Experimental and Cost Analyses of a One Kilowatt-Hour/Day Domestic Refrigerator-Freezer

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ABSTRACT

Over the past 10 years, government regulations for energy standards, coupled with the utility industry's promotion of energy-efficient appliances, have prompted appliance manufacturers to reduce energy consumption in refrigerator-freezers by approximately 40%. Global concerns over ozone depletion have also required the appliance industry to eliminate R-12 and R-11 while concurrently improving energy efficiency to reduce greenhouse emissions. In response to expected future regulations that will be more stringent, several design options were investigated for improving the energy efficiency of a conventionally designed domestic refrigerator-freezer. The options, such as cabinet and door insulation improvements and a high-efficiency compressor, were incorporated into a prototype refrigerator-freezer cabinet and refrigeration system. Baseline energy consumption of the original 1996 production refrigerator-freezer, along with cabinet heat load and compressor calorimeter test results, were extensively documented to provide a firm basis for experimentally measured energy savings.

The goal for the project was to achieve an energy consumption that is 50% below the 1993 National Appliance Energy Conservation Act (NAECA) standard for 20-ft^3 (570-L) units. Based on discussions with manufacturers to determine the most promising energy-saving options, a laboratory prototype was fabricated and tested to experimentally verify the energy consumption of a unit with vacuum insulation around the freezer, increased door thicknesses, a high-efficiency compressor, a low-wattage condenser fan, a larger counterflow evaporator, and adaptive defrost control. The resulting energy consumption was 0.928 kWh/day, a substantial energy efficiency improvement of 45% compared to the 1996 model baseline unit (1.676 kWh/day) and 54% better than the 1993 NAECA standard for 20-ft^3 (570-L) units (2.006 kWh/day). The cost for these improvements was estimated to be approximately \$134 (manufacturer's cost). Since the cost was determined to be so high as to render the improvements infeasible, a second design was investigated that was more cost-efficient. The second unit eliminated the vacuum panel insulation and larger counterflow evaporator. The cost-improved design resulted in an energy consumption of 1.164 kWh/day at a manufacturer's cost increase of \$53. Assuming that there is a 100% markup from manufacturer's cost, the payback for this unit is approximately 6.6 years.

INTRODUCTION

In an effort to significantly reduce energy consumption in refrigerator-freezers, an industry/government Cooperative Research and Development Agreement (CRADA) was established to evaluate and test design concepts for a domestic unit that is representative of approximately 60% of the U.S. market. The stated goal of the CRADA is to demonstrate advanced technologies that reduce by 50% the 1993 NAECA standard energy consumption for a 20-ft^3 (570-L) top-mount, automatic-defrost refrigerator-freezer. For a unit this size, the goal translates to an energy consumption of 1.003 kWh/day. The general objective of the research is to facilitate the introduction of efficient appliances by demonstrating design changes that can be effectively incorporated into new products.

A 1996, 20-ft^3 (570-L) top-mount, automatic-defrost refrigerator-freezer was selected as the baseline unit for testing. Since the unit was required to meet the 1993 NAECA standards, the energy consumption was quite low (1.676 kWh/day), thus making further reductions in energy consumption very challenging. Among the energy-saving features incorporated into the design of the baseline unit were a low-wattage evaporator fan, increased insulation thicknesses, and liquid-line flange heaters.

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Background

Greenhouse gases and their damaging effects on the atmosphere have received increased attention following the release of scientific data by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) that show carbon dioxide (CO_2) to be the main contributor to increased global warming (UNEP 1991). For domestic refrigerator-freezers operating on alternative refrigerants such as R-134a, the indirect contribution to global warming potential resulting from the amount of carbon dioxide produced by the power plant in generating electricity to operate a unit over its lifetime is approximately 100 times greater than the direct contribution of the refrigerant alone. Moreover, approximately 62 million new units are manufactured worldwide each year and hundreds of millions are currently in use (UNEP 1995). It is anticipated that the production of refrigerator-freezers will substantially increase in the near future as the result of an increased demand, especially in developing countries, where growth is expected to be on the order of 10% to 15% per year for the next few years. Therefore, in response to global concerns over greenhouse gases, efforts are being made to produce refrigerator-freezers with low energy consumption (Fischer et al. 1991).

In addition to the concerns of the global community over greenhouse emissions, refrigerator-freezers are also required to meet certain minimum energy-efficiency standards set up by the U.S. Congress and administered by the U.S. Department of Energy (DOE) (NAECA 1987). The initial standards went into effect January 1, 1990, and had one revision, in 1993, that resulted in an average 25% reduction in energy consumption. In the next revision, originally scheduled for 1998, the standards were expected to require an additional 30% reduction in energy consumption. This reduction may be decreased to 23% and rescheduled for 2003, depending on the assessment of the energy penalty for using blowing agents other than hydrochlorofluorocarbons (HCFCs) for the foam used in refrigerator-freezer insulation (Appliance 1996). A historical chart showing actual and projected improvements in the electrical energy use of refrigerator-freezers is shown in Figure 1.

Customer expectations and competitive pressures impose an unwritten set of constraints on refrigerator-freezers produced in the United States. The excellent characteristics of R-12 and its use over the past 50 years have led to highly efficient and reliable compressors and other refrigeration system components (UNEP 1991). Studies have shown that refrigerator-freezers give satisfactory performance for approximately 14 years on average (*Appliance* 1994). This high degree of reliability has caused consumers to expect long lifetimes and trouble-free operation from refrigerator-freezers and all appliances in general. Additionally, refrigerator-freezers have become a relatively low cost commodity item. Therefore, increased costs associated with efficiency improvements must be justified on the basis of an improved environment and lower operating costs to the consumer. Unless consumers are motivated to spend more for efficiency, further improvements will be hard for manufacturers to justify based on existing market conditions. External forces, such as rebates, new selling techniques, or standards will be required to further reduce refrigerator-freezer energy consumption from existing levels and generate markets for high-efficiency products.

EXPERIMENTAL PLAN

In previous work on this project, a phase 1 prototype refrigerator-freezer achieved an energy consumption of 1.413 kWh/day (Vineyard et al. 1995). The baseline unit for phase 1 was a 1993 vintage model with an initial energy consumption of 1.801 kWh/day. Design changes incorporated into the unit to reduce energy consumption consisted of thicker insulation around the entire cabinet, a high-efficiency compressor, low-wattage evaporator and condenser fans, an enhanced evaporator, and a liquid-line shut-off valve. The cabinet heat loss rate was determined to be 224.1 Btu/h (65.7 W), a 9% reduction from the baseline unit (246.0 Btu/h) (72.1 W).

Following discussions with an advisory group composed of all the major refrigerator-freezer manufacturers, several options (Table 1) were considered for the phase 2 effort. The options fall into three main categories: (1) cabinet heat load reductions, (2) refrigeration system improvements, and (3) parasitic power reductions. Options 1 and 2, improvements to the cabinet/door insulation and door gasket, reduce the power requirement by lowering the heat gain to the refrigerated space. Options 3 through 6 deal primarily with improving the thermodynamic refrigeration cycle efficiency by using a high-efficiency compressor, improving heat exchanger effectiveness, and utilizing a different thermodynamic cycle, such as the Lorenz-Meutzner. Options 7 and 8 reduce the parasitic power requirements by substituting electrically commutated direct-current (DC) motors for those presently used in the evaporator and condenser and by using a long-term defrost control scheme to initiate defrost based on demand. In the previous phase 1 effort, most of these options were investigated both analytically and

TABLE 1
Design Options for Improving the Energy Efficiency of a Refrigerator-Freezer

Option Number	Design Change
Option 1	Improved cabinet and door insulation
Option 2	Reduced door gasket losses
Option 3	High-efficiency compressor substitution
Option 4	Increased evaporator size with counterflow arrangement
Option 5	Increased condenser size with counterflow arrangement
Option 6	Advanced cycle with zeotropic hydrocarbon mixture
Option 7	Low-wattage fan motors
Option 8	Adaptive defrost control

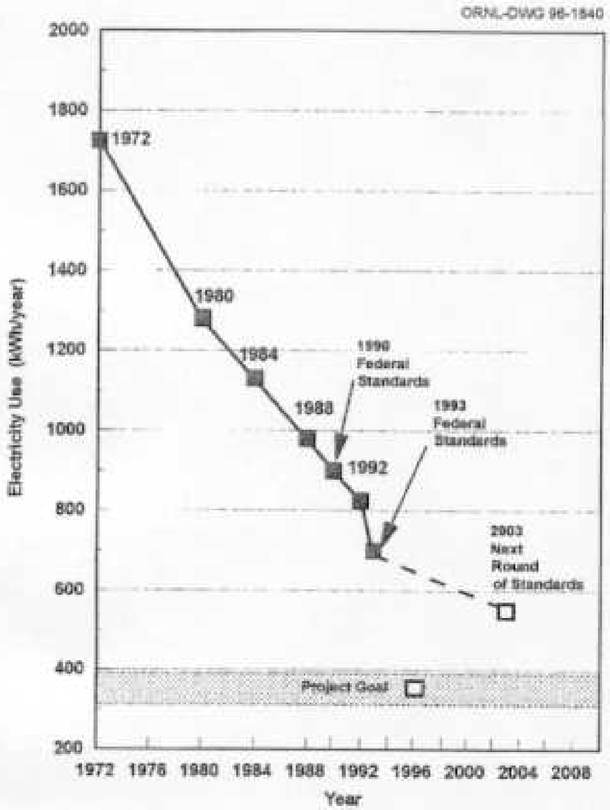

Figure 1 *Refrigerator-freezer energy improvements for 20-ft^3 (570-L) models (sales-weighted average).*

experimentally. The results showed that major improvements in energy saving came from cabinet insulation improvements, the high-efficiency compressor, and the low-wattage fan motors. Therefore, the priorities for this study were those same options along with adaptive defrost control and heat exchanger improvements. Advanced cycles were the lowest priority and would not be experimentally investigated unless the project goal could not be achieved otherwise.

TEST PROCEDURES

Several tests were conducted to quantify the effects on energy consumption of refrigeration system and cabinet design changes. All tests were performed on a 20-ft^3 (570-L) top-mount, automatic-defrost refrigerator-freezer with a forced-air condenser and evaporator. The testing included reverse cabinet heat loss rate measurements, standard nine-point compressor calorimeter mappings, and 90°F (32.2°C) closed-door energy consumption tests as specified in section 8 of the Association of Home Appliance Manufacturers (AHAM) standard for Household Refrigerators and Household Freezers (AHAM 1985). The tests were performed in environmental chambers with airflows and temperature fluctuations within the specifications of the AHAM standard or according to manufacturers' recommendations for tests where no standard is specified, such as the reverse heat loss rate tests.

Reverse Cabinet Heat Loss Rate Measurements

Reverse cabinet heat loss rate measurements were made to assess the improvements in cabinet thermal performance from changes such as vacuum insulation or increased insulation thickness in the freezer section or doors. The procedure for measuring heat loss rate involves placing a cabinet in a cold chamber with controlled heat sources and small electrical chassis fans to maintain desired temperatures in both the freezer and fresh food compartments. The fans are run continuously during the test to prevent temperature stratification. Each fan draws approximately 6 to 7 watts of electricity and has an air circulation rate of 30 cfm (14 L/s), which is assumed to have negligible effects on the inside surface heat transfer of the refrigerator-freezer. Temperature and watt measurements for both refrigerator-freezer compartments along with ambient temperature are recorded as the cabinet temperatures achieve desired levels. Once the cabinet temperatures achieve steady state, data are compiled and averaged for a 30-minute interval to determine overall heat loss rates for both compartments.

The heat loss rate is calculated in Btu/h (W) and plotted against the difference between temperatures inside each compartment and ambient air temperature. Heat loss rates for the freezer compartment were determined from the following equation:

$$Q_{FRZ} = UA_{FRZ} \times (T_{FRZ} - T_{AMB}) + UA_{MUL} \times (T_{FRZ} - T_{FF}) \quad (1)$$

where Q_{FRZ} is the heat loss rate for the freezer in Btu/h (W), UA_{FRZ} is the overall freezer compartment thermal resistivity in Btu/h·°F (W/°C), $(T_{FRZ} - T_{AMB})$ is the temperature difference between the freezer and ambient in °F (°C), UA_{MUL} is the thermal resistivity of the mullion in Btu/h·°F (W/°C), and $(T_{FRZ} - T_{FF})$ is the temperature difference between the freezer and fresh food compartments in °F (°C). In a similar manner, the fresh food heat loss rate was determined from the following equation:

$$Q_{FF} = UA_{FF} \times (T_{FF} - T_{AMB}) - UA_{MUL} \times (T_{FRZ} - T_{FF}) \quad (2)$$

where Q_{FF} is the heat loss rate for the fresh food compartment in Btu/h (W), UA_{FF} is the overall fresh food compartment thermal resistivity in Btu/h·°F (W/°C), and $(T_{FRZ} - T_{AMB})$ is the temperature difference between the fresh food compartment and ambient in °F (°C).

Tests were initially run with the temperatures in both compartments essentially equal. This allowed the mullion heat transfer term to be dropped from both Equations 1 and 2 so that freezer and fresh food compartment resistivities could be determined from dividing the power measurement (Q) by the temperature difference in each compartment $(T_{FRZ} - T_{AMB})$ or $(T_{FF} - T_{AMB})$. Once the compartment thermal resistivities were known, tests were then performed with large temperature differences between the freezer and fresh food compartments to determine the mullion thermal resistivity. Plots were then generated using Equations 1 and 2 to represent the heat loss rates in both compartments for each cabinet and door configuration.

The tests were conducted using temperature differences across the cabinet walls comparable to those attained in the 90°F (32.2°C) closed-door test procedure where the refrigerator-freezer works to maintain cold internal temperatures in a warm room. In order to achieve the temperature differences, it was necessary to maintain the chamber at 0°F (−17.8°C). Since the thermal conductivity of insulating foam generally decreases with decreasing temperatures, this procedure could slightly underestimate actual cabinet heat loss rates (ASHRAE 1989). In addition, the reverse cabinet heat loss measurement employed in this study may not accurately measure the heat leakage through the gasket region. Heat leakage in the gasket area is a function of the airflow inside the freezer. Since the evaporator fan was not running, the heat leakage rate might be higher than the measured values for all the tests. However, the relative differences between the test results for the different insulation configurations should be approximately the same. The procedure used in this study was chosen because it allowed a determination of heat leakage rates for both the freezer and fresh food compartments.

Compressor Calorimeter Mappings

Reductions in the total cabinet heat load along with efficiency improvements required corresponding changes in the capacity and design of the compressor. In order to determine the extent of these changes, the original and high-efficiency compressors were tested using a nine-point compressor calorimeter procedure to generate compressor maps. In this procedure, compressor operating characteristics, including refrigeration capacity and energy efficiency ratios (EERs), are determined at each point in a matrix of 110°F (43.3°C), 120°F (48.9°C), and 130°F (54.4°C) condensing temperatures and −20°F (−28.9°C), −10°F (−23.3°C), and 0°F (−17.8°C) evaporating temperatures. Also specified in the test procedure are a 90°F (32.2°C) ambient temperature for the compressor, superheating of the suction gas to 90°F (32.2°C), and subcooling of the liquid refrigerant line to 90°F (32.2°C) before throttled expansion. The nine-point maps generated from the tests are used to estimate changes in refrigerator-freezer energy consumption when using the high-efficiency compressor.

Energy Consumption Tests

System performance for the baseline and enhanced cabinets was assessed using the standard 90°F (32.2°C) closed-door test procedure. In this procedure, the refrigerator-freezer is operated at two different control settings in a 90°F ± 1°F (32.2°C ± 0.6°C) environmental chamber. Energy use and compartment temperatures are measured from the onset of one defrost cycle to the beginning of the next defrost. The test points are then used to calculate the energy consumption over a 24-hour period based on a reference 5°F (−15.0°C) freezer temperature and 45°F (7.2°C) fresh food temperature. Other requirements of the test procedure are an outlet voltage level of 115 ± 1 volt AC to the refrigerator-freezer and an air circulation rate of less than 50 ft/min (15 m/min) in the environmental chamber. The high ambient temperature, 90°F (32.2°C) is used to simulate the contribution of door openings and food loadings. Comparisons of field performance to closed-door test ratings indicate the laboratory procedure is a valid indication of energy use in field service (Meier and Jansky 1993). Previous refrigerator-freezer testing indicated that the test procedure with two different thermostat settings gives a broader indication of appliance performance at different ambients and internal operating conditions than a single-point test (Sand et al. 1993).

EXPERIMENTAL RESULTS

The experimental approach emphasized hardware changes that can be incorporated into a conventional refrigerator-freezer design, which is defined as a unit with a single, fan-forced evaporator and condenser and a single-speed compressor and operating with a pure refrigerant. Changes centering on a conventional design are considered to be more acceptable to manufacturers because they would require less retooling and have greater reliability. In addition, a conventional design is more likely to be accepted by consumers since it would cost less to implement than a nonconventional design change, such as a dual-evaporator system with nonazeotropic refrigerant mixtures.

Reverse Heat Loss Results

Steady-state heat loss measurements were performed on two separate cabinets—a baseline refrigerator-freezer cabinet and an enhanced cabinet with vacuum insulation panels foamed around the freezer section. In addition to the standard doors, which were 1 in. (2.5 cm) thick, three sets of doors with varying degrees of insulation improvements were tested on the baseline cabinet. The door improvements consisted of the following: thick doors (2 in. [5.1 cm]), 1 in. (2.5 cm) thick vacuum insulation panels foamed into standard doors, and 1 in. (2.5 cm) thick vacuum insulation panels foamed into thick doors. For the tests with the enhanced cabinet, standard doors and thick doors with no vacuum insulation panels were investigated.

Cabinet heat loss rates for the baseline cabinet with the standard doors and door insulation improvements are shown in Figure 2. The heat loss rates are determined from Equations 1 and 2 using compartment and mullion *UA*s calculated from measurements made under steady-state conditions. The compartment heat loss rates are in Btu/h (W) and plotted for temperature differences between the ambient and compartment of 45°F (25°C) in the fresh food section and 85°F (47.2°C) in the freezer section. These temperature differences are representative of those for the freezer and fresh food compartments when using the 90°F (32.2°C) closed-door test procedure. Figure 3 shows the cabinet heat loss results for the enhanced cabinet with the standard and thick doors.

The cabinet heat loss rates are summarized in Table 2 along with Q_{FRZ}/Q_{TOT} ratios for a refrigerator-freezer. The experimental results indicate that the baseline cabinet heat loss rate was reduced 6.4% (195.2 to 182.7 Btu/h) (57.2 to

TABLE 2
Summary of Reverse Heat Loss Tests 90°F (32.2°C) Ambient, 5°F (−15°C) Freezer, 45°F (7.2°C) Fresh Food Compartment

Description	$Q_{freezer}$ (Btu/h)	$Q_{fresh\ Food}$ (Btu/h)	Q_{total} (Btu/h)	$Q_{freezer}/Q_{total}$ (Btu/h)	Percent Reduction
Base Cabinet:					
w/standard doors (1 in. [2.5 cm])	103.4	91.8	195.2	0.53	—
w/thick doors (2 in. [5 cm])	94.8	87.9	182.7	0.52	6.4
w/vacuum panels in standard doors (1 in. [2.5 cm])	95.1	78.6	173.7	0.55	11.0
w/vacuum panels in thicker doors (2 in. [5 cm])	98.4	72.8	171.2	0.57	12.3
Enhanced Cabinet:					
w/vacuum panels around freezer section	86.4	79.5	165.9	0.52	15.0
w/vacuum panels around freezer section + doors (2 in. [5 cm])	80.3	75.0	155.3	0.52	20.4

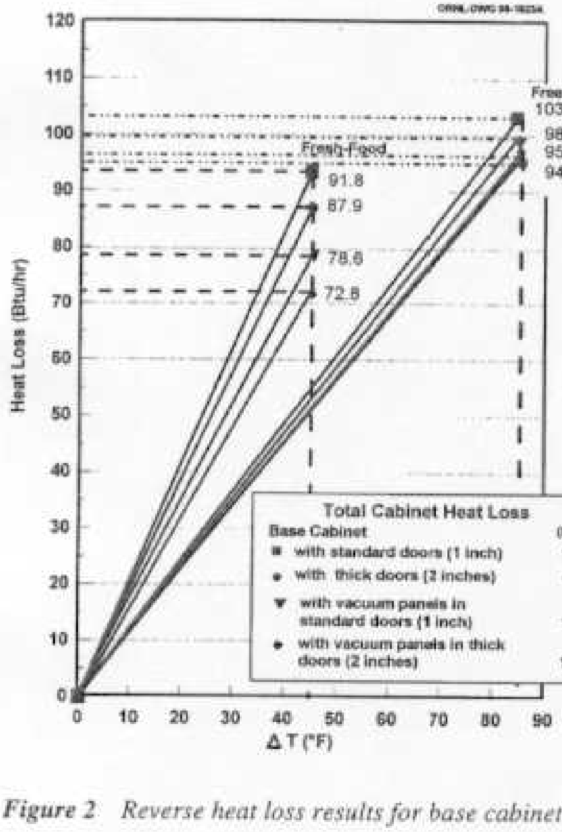

Figure 2 Reverse heat loss results for base cabinet.

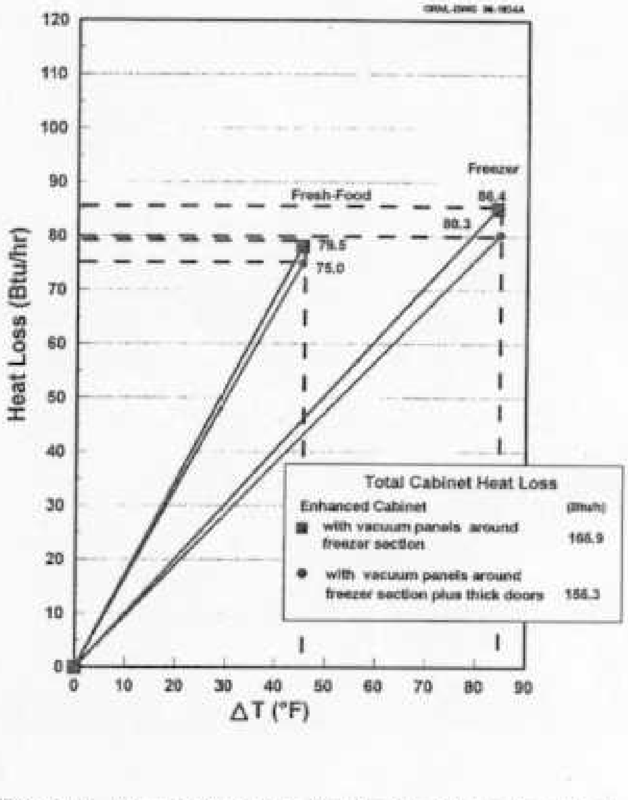

Figure 3 Reverse heat loss results for enhanced cabinet.

53.5 W) by replacing the standard doors with thick doors. Using 1 in. (2.5 cm) thick vacuum panels and foaming them into standard doors resulted in the cabinet heat loss rate being reduced from 195.2 to 173.7 Btu/h (57.2 to 50.9 W), an 11.0% reduction. Finally, when 1 in. (2.5 cm) thick vacuum panels were foamed into a thick door, the cabinet heat loss rate was reduced by 12.3%.

Examining the individual compartments, the additional insulation and vacuum panels appear to have the most benefit in the fresh food section, lowering the heat loss rate by as much as 20.7%. By contrast, the maximum improvement in the freezer section was less than half that amount (8.3%).

For the enhanced cabinet, vacuum panels foamed around the entire freezer section resulted in an overall cabinet heat loss rate of 165.9 Btu/h (48.6 W), 15.0% lower than the baseline cabinet. Tests were also performed with thick doors on the enhanced cabinet, resulting in a 20.4% reduction in the overall cabinet heat loss rate (195.2 vs. 155.3 Btu/h) (57.2 vs. 45.5 W). While the cabinet heat loss rate could have been reduced even further by using vacuum panel doors, the additional cost ($53.52) would have been prohibitive. Therefore, that configuration was not tested.

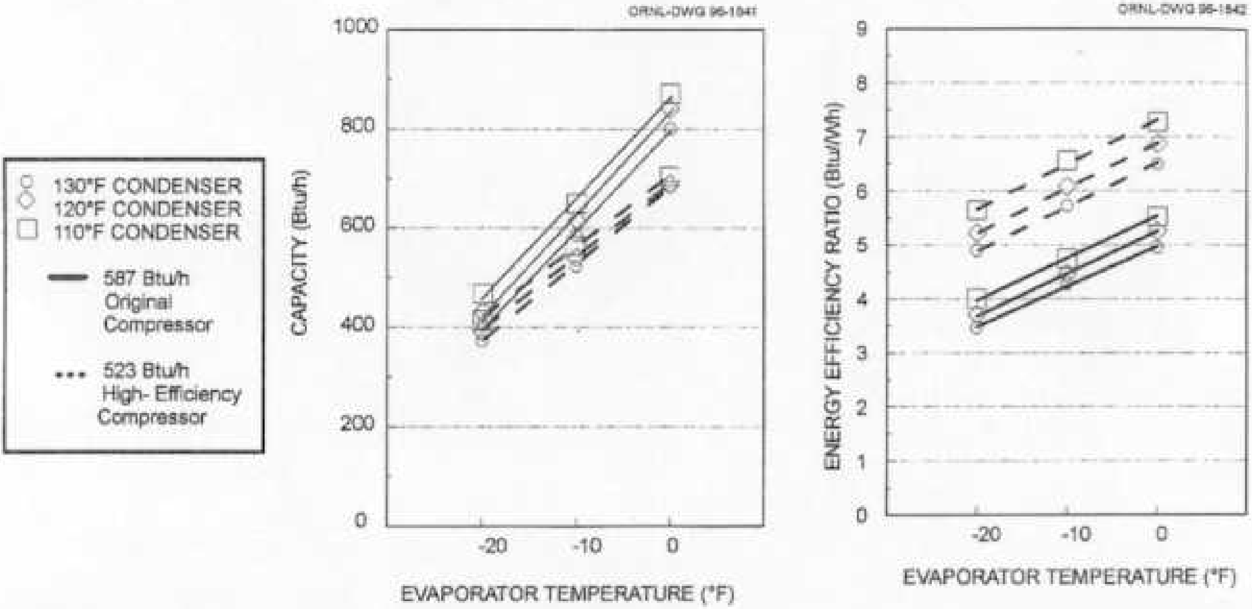

Figure 4 Compressor calorimeter results.

Compressor Calorimeter Results

Nine-point calorimeter tests were used to determine the performance over a range of operating temperatures for the baseline compressor used in the production refrigerator-freezer and the high-efficiency compressor used in the modified units. The high-efficiency compressor is a variable-speed model that can be run at speeds from 2,200 to 3,600 rpm with only minor variations in EER. For these tests, the compressor was run at the lowest speed (2,200 rpm). The resulting compressor maps, shown graphically in Figure 4, are used as inputs for modeling analyses. From the data in Figure 4, one can determine that, at the standard rating point for a −10°F (−23.3°C) evaporator and a 130°F (54.4°C) condenser, the EER for the baseline compressor is 4.28 while that of the high-efficiency compressor is 5.73, a 33.9% increase in EER.

The refrigeration capacity of the high-efficiency compressor was approximately 523 Btu/h (153.2 W), 10.9% less than the baseline compressor (587 Btu/h) (172.0 W) it replaced. The high-efficiency compressor was run at the lowest speed possible in attempts to achieve reasonable run times once additional insulation was added to the cabinet doors and vacuum panel insulation was added to the freezer section. Using a compressor with a capacity much greater than the load would have resulted in short, frequent compressor runs that increase system cycling losses.

System Results

Of the eight options under consideration for reducing the energy consumption of the refrigerator-freezer, only five were required to achieve the goal of a 50% energy saving. Those five options were: (1) cabinet and door insulation enhancements, (2) a high-efficiency compressor, (3) a low-wattage condenser fan, (4) adaptive defrost control, and (5) a larger evaporator with a counterflow arrangement. Option 5, a larger condenser with a counterflow arrangement, would have been the next design change to be introduced had it been necessary to achieve further savings. The other modifications, door gasket improvements and an advanced cycle design, were low-priority items due to their additional complexity and difficulties in incorporating them into a commercially manufactured cabinet. However, they would have been addressed if the goal had not been achieved.

Energy consumption tests were initially performed on the baseline cabinet according to section 8 of the *AHAM Standard for Household Refrigerators and Household Freezers* (AHAM 1985). The results (Table 3) show that the energy consumption was 1.676 kWh/day. The DOE standard for a unit of this type and size is 2.006 kWh/day. Thus, the baseline cabinet is 16.5% below the DOE standard.

Next, an enhanced cabinet with vacuum insulation panels foamed around the freezer section was tested. In addition to the vacuum insulation, the unit also was assembled with a larger counterflow evaporator. The daily energy consumption for that unit was 1.533 kWh/day, an 8.5% reduction from the baseline unit and 23.6% lower than the DOE standard.

Following completion of the energy consumption tests on the enhanced cabinet, the unit was modified by exchanging the standard doors for ones that were 2 in. (5.1 cm) thick and by replacing the existing condenser fans and compressor with a low-wattage fan and a high-efficiency compressor (5.73 EER). In addition, a long-term defrost control algorithm was used to further reduce the energy consumption. The results for all the improvements, listed in Table 3, show that the energy consumption was reduced from 1.533 kWh/day to 0.928 kWh/day, a savings of 39.5%. Relative to the baseline unit and NAECA stan-

TABLE 3
Energy Consumption and Cost Information

Description	Energy Consumption (kWh/day)	Percent Run Time	Manufacturer's Cost Increase (dollars)
Baseline unit	1.676	44.2%	—
Baseline unit with 2 in. (5 cm) thick doors, 5.73 EER compressor, low-wattage condenser fan, and adaptive defrost	1.164	47.6%	53.38
Enhanced cabinet (vacuum panels around freezer section) with 2 in. (5 cm) thick doors, 5.73 EER compressor, low-wattage condenser fan, larger evaporator, and adaptive defrost control	0.928	36.5%	134.33

TABLE 4
Manufacturer's Cost Increase for Design Changes

Design Change	Manufacturer's Cost Increase (dollars)
Low-wattage condenser fan	$4.50
Increased evaporator area	$3.11
Vacuum panels around freezer section	$77.84
2 in. (5 cm) thick doors	$6.73
High-EER compressor	$35.00
Adaptive defrost control	$7.15

dards, the results represent a 44.6% improvement (1.676 to 0.928 kWh/day) and a 53.8% improvement (2.006 to 0.928 kWh/day), respectively.

An additional design configuration was assembled by replacing the existing compressor and condenser fan on the baseline unit with the high-efficiency compressor and low-wattage condenser fan. In addition, the standard doors were replaced with the 2 in. (5.1 cm) thick doors, and a long-term defrost control algorithm was utilized. Although the energy consumption for this configuration was expected to be moderately higher than for the enhanced cabinet model, the design changes were expected to be more cost-effective. The resulting energy consumption for the unit was 1.164 kWh/day, a 30.5% reduction from the baseline unit and 42.0% lower than NAECA standards.

Cost Analysis

In order to obtain a cost/benefit ratio of the energy-saving features, it was necessary to estimate the cost for each design change (Table 4). Most of this information was obtained from a study on the cost-efficiency of design options in support of the proposed 1998 DOE standards (Hakim and Turiel 1996). In that study, costs were collected from several refrigerator-freezer manufacturers and averaged to protect the confidentiality of the data. In addition to that information, manufacturers' costs were estimated by the suppliers for the high-efficiency compressor and vacuum panel insulation based on the added electronics and square footage of insulation added to the freezer section.

Using the information from Table 4, the estimated manufacturer's cost increase for the 0.928 kWh/day design is $134.33. This estimate is based on using a high-efficiency condenser fan ($4.50), adaptive defrost control ($7.15), an increased evaporator area ($3.11), 2 in. (5.1 cm) thick doors ($6.73), a 5.73 EER high-efficiency compressor ($35.00), and vacuum panel insulation around the freezer section ($77.84). The energy saving from all these features is 273 kWh/yr relative to the baseline unit (1.676 vs. 0.928 kWh/day). Based on an average cost for electricity of $0.0867/kWh, the annual saving is $23.67. Doubling the manufacturer's cost to arrive at an estimated cost to the consumer gives a payback of 11.4 years ($268.66/$23.676 per year), which is considered too long for most consumers.

A breakdown of the energy savings from each design change is shown in Table 5. The magnitude of the energy savings is affected by the order in which improvements are made. The order shown in Table 5 is the order in which changes were actually made to the baseline unit. Two of the entries, the condenser fan and adaptive defrost energy savings, were calculated rather than experimentally tested. The condenser fan savings were determined by multiplying the difference in the fan wattages of the production fan (11.6 W) and the low-wattage fan (2.7 W) by the number of hours of run time (44.2%). The savings for the adaptive defrost control were calculated from experimental data using the procedure outlined in section 8 of the *AHAM Standard for Household Refrigerators and Household Freezers*. The results show that the low-wattage condenser fan, thicker doors, and adaptive defrost control had paybacks in the range of 3.0 to 4.1 years. The high-efficiency compressor required 7.7 years to pay back. The worst payback period was for the vacuum panel insulation/increased evaporator area combination, which needed almost 36 years to payback, clearly an unacceptable alternative. For all the scenarios, it was assumed that the consumer cost was twice the manufacturer's cost.

Since the payback was determined to be too long for the unit to be economically feasible, a second unit was assembled at a much lower cost. The estimated manufacturer's incremental cost for this unit is $53.38 based on using a high-efficiency condenser fan ($4.50), adaptive defrost control ($7.15), 2 in. (5.1 cm) thick doors ($6.73), and a 5.73 EER high-efficiency compressor ($35.00). The energy saving for this unit is 187 kWh/yr (1.676 vs. 1.164 kWh/day). Using a cost for electricity of $0.0867/kWh, the annual saving is $16.22. The payback, assuming the consumer cost is twice that of the manufacturer's cost, is 6.6 years.

TABLE 5
Cost Analysis for Design Options

Case	Design Changes	Annual Energy Use (kWh/yr)	Annual Energy Savings (kWh/yr)	Cost Savings ($/yr)	Consumer Cost ($)	Payback (years)
A	Baseline Unit	612	—	—	—	—
B	A+ vacuum insulation around freezer, increased evaporator area	560	52	4.51	161.90	35.9
C	B+ low-wattage condenser fan	525	35	3.03	9.00	3.0
D	C+ 5.73 EER compressor	420	105	9.10	70.00	7.7
E	D+ 2 in. (5 cm) thick doors	379	41	3.55	13.46	3.8
F	E+ adaptive defrost control	339	40	3.47	14.30	4.1

CONCLUSIONS

Two significant accomplishments were realized from the project. First, it was shown to be technically feasible to build an extremely low energy-consuming 20-ft^3 (570-L) refrigerator-freezer. It would have been possible to reduce the energy consumption even further had the vacuum panel doors been used. There were, however, two drawbacks to the unit: (1) the costs were prohibitively high, and (2) the compressor run time was too low, indicating that we needed a much smaller compressor, probably in the 400 to 450 Btu/h (117 to 132 W) range. Compressors in this capacity range traditionally have much lower EERs than those in the 700 to 800 Btu/h (205 to 234 W) range. Thus, improving the efficiency of small-capacity compressors would appear to be a high priority for reducing energy consumption in future refrigerator-freezers. This assumes that some form of cabinet improvement, such as vacuum insulation, thicker insulation, or door gasket improvements, will be used to significantly reduce the cabinet heat gain. At present, vacuum insulation, while an excellent technology, still appears too costly. In addition, vacuum panel insulation remains unproven in terms of long-term reliability and heat transfer degradation over time; these two factors must be addressed. Instead of being used to reduce energy consumption, a more appropriate application for vacuum panel insulation in refrigerator-freezers appears to be in the area of gaining additional food storage volume by reducing the insulation volume in areas where it is thickest, such as the doors.

The second, and most promising, accomplishment was the cost-improved refrigerator-freezer, resulting in energy consumption of 1.164 kWh/day. Based on the results from the low-energy refrigerator-freezer (Table 5), which indicated that the vacuum panel insulation and increased area evaporator were not cost-effective, a second unit was assembled without these features. The new unit achieved low energy consumption with a reasonable additional cost. The cost of this unit could be reduced even more by using a production compressor with a slightly lower EER than the high-efficiency compressor. Using a compressor with an EER in the 5.2 to 5.3 range would increase the energy consumption to approximately 1.25 kWh/day. The additional cost for the unit would be around $18 or $36 to the consumer. The unit would save 155 kWh/yr for a savings of $13.44 annually. The payback on a unit like this would be less than 3 years, which should be even more appealing to consumers than the 6.6-year payback for the 1.164 kWh/day version.

American manufacturers of domestic refrigerator-freezers have established an enviable record of consistent improvements in the energy efficiency of their product. Widespread use of this appliance as a result of its efficiency, convenience, and reliable performance has made it a target for additional refinement, but clearly, the margins for improving performance are reaching a point of diminishing returns. Switching to a design that performs well in standardized energy-consumption tests but sacrifices many of the convenient and dependable features of this essential appliance would be a mistake for an established industry.

Clearly, there is a rationale for retaining many familiar aspects of a product design that has been refined and used for 30 years. However, some changes are needed to further reduce energy consumption and produce appliances that are more environmentally acceptable. Many of the design options that could have a significant effect on the energy use of a refrigerator-freezer have been clearly identified and are technologically available. In virtually every instance, however, substitution of components with improved efficiency is accompanied by increases in unit hardware cost. In addition, a proven product is being replaced with one whose reliability has not been determined.

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