United States
Enviromental Protection
Agency

Office of Atmospheric
and Indoor Air
Programs

EPA-430-R-94-011
June 1994

EPA

Energy-Efficient Refrigerator Prototype Test Results

ACKNOWLEDGMENTS

This report has been compiled by H. Alan Fine and Jean Lupinacci of the Global Change Division of the U.S. Environmental Protection Agency and Professor Reinhard Radermacher of the Center for Environmental Energy Engineering at the University of Maryland. The authors wish to thank the many students at the University and technicians and engineers at the many companies who worked to develop the prototypes tested in this report. Particular thanks must go to Admiral Company, Frigidaire Company, GE Appliances, Haier Group, ShangLing Refrigerator Company, W.C. Wood Company Ltd., and Whirlpool Corporation for their donation of refrigerators and/or help in the manufacture of the prototypes. Many component suppliers, including Aladdin Industries, Inc., AMERICOLD, Degussa AG, Owens-Corning, and Thermalux, are also gratefully acknowledged for their donations and help on this project.

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Working prototype refrigerator/freezers demonstrating a wide variety of existing and emerging technologies for energy conservation have been built and tested.

Energy-efficiency gains resulting from improvements to individual components can be grouped as follows:

% Energy Reduction	Improvement
5-10	improved gasket region design inverter hydrocarbon refrigerants
10-15	50% coverage advanced insulation linear compressor Lorenz cycle in side-by-side R/F
15-20	Lorenz cycle in top-freezer R/F Kopko Cycle
25-30	Adding 1.5 inches of foam insulation

Substantial energy-efficiency gains resulting from a combination of improvements can be grouped as follows:

% Energy Reduction	Improvements
30-40	Adding 1.5 inches of insulation and Kopko cycle
40-50	Adding 1.5 inches of insulation, better compressor, Lorenz cycle, and improved gasket Adding insulation, better compressor, and HFC-152a refrigerant to a Chinese R/F
> 50	Adding insulation, better compressor, and hydrocarbon refrigerants to a Chinese R/F

The EPA Refrigerator Analysis (ERA) model predictions agree with measurements made on the prototypes.

I. INTRODUCTION

Many factors have driven industry to implement energy-efficiency improvements in household refrigerator/freezers (R/Fs). The 1993 DOE Energy Efficiency Standards have been in effect for a little more than one year, and many manufacturers have models on the market that exceed this standard. In fact, the winner of The Golden Carrot Competition for $30 million, Whirlpool Corporation, will be selling R/Fs in 1994 that exceed the standard by more than 25 percent, without using ozone-depleting CFCs. Other manufacturers are expected to offer similar energy efficient products in the near future.

There appears to be dramatic changes occurring in consumer buying preferences. Consumer acceptability is an important factor to selling refrigerators. Based on the marketing perception that consumers are only first cost driven and place high value on internal volume, manufacturers were reluctant to explore cost-effective design changes to increase energy efficiency, particularly by adding more insulation to the refrigerator walls.

The recent success of Sears's program to prominently market the "Energy Efficient" 1993 models may change the idea that energy efficiency would not drive the sale of refrigerators. The Sears program consisted of training, advertising, point-of-sale identification, and charts that helped customers understand the substantial savings and environmental benefits from purchasing energy-efficient refrigerators. Early indications from Sears showed that many customers would ask for the new models and were even willing to wait and pay more for them.

There is not just one path or design approach that leads to super-efficient refrigerators but rather multiple pathways to achieve large energy savings. Each refrigerator manufacturer will decide on the most cost-effective set of options and technologies based on its current products' energy efficiency, design, size class, cost-structure, and other factors.

In evaluating the potential energy savings in R/Fs, EPA has conducted a wide variety of analyses, including technical evaluations, model development and analysis, cost analyses, marketing and consumer preference analysis, and prototype development and testing. All are necessary to determine the ultimate acceptability of the various options. Manufacturers will conduct similar analyses pertaining to their own product lines and circumstances as they commercialize new energy-efficient products.

I.A PURPOSE OF REPORT

This report will summarize the test results for the numerous R/Fs built by EPA and our partners to evaluate a wide variety of technologies to increase energy efficiency and to eliminate the use of CFCs. The results for many of the prototypes represent the joint efforts of EPA, the University of Maryland, and various equipment and refrigerator manufacturers. In many cases, the prototypes were tested at both the University and the individual companies. The partnerships were a critical component of the success of the prototypes. The interaction between the various experts was useful to define realistic parameters, resolve problems, and make modifications to the prototypes on the production line.

The prototypes were developed to test technologies that increase energy efficiency and eliminate CFCs. The refrigerators that were built and tested are not meant to showcase all combinations of technologies, but rather to demonstrate significant energy savings that could be achieved with existing and emerging technologies.

Some of the prototypes were built to test the performance of a single technology. Other prototypes combined technologies that demonstrated substantial energy savings to identify any interactive effects between the different technologies and different systems.

The report is divided into four sections.

- The *Introduction* describes the purpose of the report, the testing methodology, and comparison with ERA energy calculations.
- The *Cabinet Improvements* section summarizes the test results from refrigerator/freezers that demonstrate improvements to the thermal envelope of the unit.
- The *Cycle Improvements* section summarizes the test results from refrigerator/freezers that demonstrate improved components, alternate refrigerants, and alternate cycles.
- The *System and Cabinet Modifications* section provides a summary of test results from units that combined both improvements to the cycle and the cabinet.

Many technologies have shown great promise for future development, but further evaluation will need to be conducted for commercialization. Continued applied research, manufacturability, long-term reliability, and cost analyses may be required by the manufacturers.

I.B ENERGY TEST PROCEDURE

Except as noted, refrigerator energy tests were performed at the University of Maryland (U. Md.) according to the DOE test procedure, with some minor modifications. The modifications were necessary to arrive at well optimized refrigeration cycles in a short period of time. For those tests that included a defrost cycle and the anti-sweat heaters, the outcome is the same as for the DOE procedure.

During testing at U. Md., all compartment temperatures and the room temperature are measured and maintained as prescribed by DOE. The compartment temperatures, however, are maintained with an independent temperature controller, not the original refrigerator thermostat. Generally, the temperature controller controls the freezer temperature, while the food compartment temperature is adjusted by either a second controller (Kopko and dual loop systems) or by adjusting charge and capillary tube length. The instantaneous power and energy consumption are measured with watt and watt-hour transducers, respectively.

The defrost is normally deactivated during testing at U. Md. and tests are conducted for one day (24h). The system, however, is defrosted regularly to maintain system performance. When a defrost cycle is included in the measurement at U. Md., the energy consumption is measured from the onset of one defrost cycle to the onset of the next. The energy consumption is then extrapolated to 24h. When defrost cycles and anti-sweat heaters in the on and off positions are included, the U. Md. method is the same as the DOE method, except it is faster and more accurate. The refrigerator performance is determined at a freezer temperature of 5°F rather than measuring above and below this temperature and then interpolating to it.

Modifications to the defrost cycle were not tested. In certain instances, such as the incorporation of either the Lorenz or Kopko cycle into the R/F, additional energy savings could be achieved by modifying the defrost cycle.

Table I.1 reports refrigerator tests that were repeatable within ±1 percent when repeated under the same conditions and at the same laboratory, and within ± 5 percent when compared to other laboratories. The table also shows a comparison of the U. Md. test results and the test results of the manufacturers conducted according to the DOE standard.

Table I.1 University of Maryland and Manufacturer Test Results

Model Tested	Test Location and Conditions	FF Temperature (°F)	FZ Temperature (°F)	Energy Consumption (kWh/24h)
Admiral RB19xx with vacuum insulation	U. Md. w/o defrost	5.3	38.5	1.96
	U. Md. with defrost	4.9	38.3	2.16
	Admiral DOE Test	5	38	2.12
Whirlpool ET20ZK	U. Md. with anti-sweat heaters on	5.0	41.9	2.17
	Whirlpool with anti-sweat heaters on	5.0	40.0	2.31
Thick-wall 20 ft^3 Whirlpool	U. Md. with anti-sweat heaters on	5.0	37.4	1.91
	Whirlpool with anti-sweat heaters on	5.0	38.1	1.85
	U. Md. with anti-sweat heaters off	5.0	37.1	1.38
	Whirlpool with anti-sweat heaters off	5.0	36.6	1.44

I.C ERA ENERGY CALCULATIONS

The EPA Refrigerator Analysis (ERA) computer model can be used to estimate the impact on energy consumption of a wide variety of modifications to the refrigerator cabinet and components. ERA predicts the performance (energy consumption) of household R/Fs and is capable of simulating various cabinet, auxiliary, and cycle configurations. It consists of four major components:

1. A menu-driven input processor;

2. Estimation of the cabinet loads;

3. Thermodynamic cycle simulation; and

4. Energy-consumption calculations.

Additional details are provided in the ERA User's Manual. [1]

The results of a variety of ERA calculations have been presented in *Multiple Pathways to Super-Efficient Refrigerators*. [2] These results have been compared to the test results of applicable prototype models.

II. CABINET MODIFICATIONS

A series of prototype refrigerator/freezers (R/Fs) were produced that contained improvements to the thermal envelope of the units. These improvements included:

- Improvements to the foam insulation system,
- The addition of vacuum insulation, and/or
- Improvements to the gasket system.

Details of the prototypes and the resulting energy savings are presented in the following section.

II.A FOAM INSULATION ENHANCEMENTS

The overall thermal performance of the cabinets was improved by increasing the thickness of the R/F cabinet or by reducing the thermal conductivity of the foam. The results of these tests are described next.

II.A.1 Thick-Wall Foam Insulation

Polyurethane foam insulation was added to the walls of a refrigerator to reduce heat flow into the refrigerated volume. The internal volume was maintained by adding the insulation to the exterior of the unit, at the expense of slightly larger exterior dimensions. Alternatively, insulation can be added to the interior surfaces, but at the expense of internal volume.

Baseline Unit The baseline unit was a standard 20 ft^3 automatic-defrost top-freezer refrigerator, Whirlpool model number ET20DK. Dimensions and daily energy consumption are presented in ***Table II.1.***

Thick-Wall Unit The "double-insulated" refrigerator was manufactured by installing the liner for the standard 20 ft^3 model into the shell of a standard 25 ft^3 unit, model ET25DK. The unit was then foamed and completed with components identical to those for the standard ET20DK. Special doors did, however, have to be manufactured to fit the unit.

Two units were built and tested at Whirlpool.

Table II.1 Double-Insulated Refrigerators

		Baseline Unit	Thick-Wall Unit
Volume (ft^3)			
Freezer		5.5	5.5
Fresh Food		14.4	14.4
Exterior Dimensions (in)			
Height		66	69
Width		32	35
Depth		28	31
Insulation Thickness (in)			
Doors		1.5	2.8
FF Sides		1.8	3.3
FF Back		1.8	3.6
FF Bottom		1.8	3.3
FZ Sides		2.2	3.6
FZ Back		2.2	4.0
FZ Top		2.2	3.6
Mullion		2.5	2.5
Energy Consumption (kWh/24h)	Whirlpool		1.63 ± 0.03
	U.Md.	2.33	1.73
	EPA-RTP		1.72

Discussion As can be seen from the above table, approximately 1.5 inches of foam were added to all exterior surfaces of the unit. Interior volume was maintained, while exterior dimensions were increased by 3 inches on each dimension.

A measured 27 percent decrease in energy consumption was achieved. The ERA model predicts a 19 percent energy reduction for the addition of 1 inch of insulation to the exterior of 18 ft^3 R/Fs and 29 percent for the addition of 2 inches. [2] ERA is thus in good agreement with the measurements.

II.A.2 Lower Thermal Conductivity Foam Insulation—Carbon Black

The thermal performance of foam insulation is a complex function of three modes of heat transfer that occur within the insulation: heat conduction in the solid and vapor phases and thermal radiation through the composite. Reducing the amount of heat transferred by any of these mechanisms should reduce the thermal conductivity of the foam and the rate of heat flow through the foam for a given set of conditions.

The addition of carbon black particles to polyurethane foam reduces thermal radiation transport and the thermal conductivity of the foam. Black foams have been developed for the construction industry and are under development for appliance applications by Miles Inc. and the Center for Applied Energy Research Inc. [3]

Baseline Unit The baseline model was a standard 17 ft^3 automatic-defrost top-freezer model, Admiral Co. model number RB17OPW. Foaming of pre-assembled empty cabinets with an HCFC-141b-blown foam was done at Miles Inc. The foam formulation was developed by Miles for this trial. After foaming, the units were returned to Admiral for final build-up and testing. Foam properties and energy test results are shown in *Table II.2*. [3]

Black-Foam Units Foam with the same formulation but containing 6.3 percent carbon black was used for these units. All other processing and testing protocols were identical.

Table II.2 Carbon-Black Foam Refrigerators

	Baseline Units	Black-Foam Units
Foam Thermal Conductivity (BTU*in/(h*ft^{2}*°F))	0.129	0.12
Foam Density (lb/ft^3)	1.75	1.87
Energy Consumption (kWh/24h)	1.84 $\pm$ 0.03	1.83 $\pm$ 0.01

Discussion The thermal conductivity of the carbon-black loaded foam was eight percent lower than the baseline HCFC-141b foam. Computer model simulations made by Admiral predicted a 3.2 percent lower energy consumption for the refrigerator. ERA predictions for 18 ft^3 models [2] show energy reductions ranging from 3.4 to 4.3 percent with an average of 4.0 percent.

The actual energy consumption of the black-foam prototype refrigerator was less than one percent lower than the baseline. Tests, including reverse heat flow measurements, are being performed to determine why larger energy savings were not observed. One hypothesis for why the eight percent lower thermal conductivity black-foam did not reduce the energy consumption of the unit was that the black-foam units were made in February 1993 and the baseline models in May. Small improvements in components over this period may have lowered the energy consumption of the baseline models and masked the effect of the improved foam.

II.B VACUUM INSULATION

A number of advanced insulation systems are currently under development. These systems generally consist of a filler material contained in a gas-tight barrier. All of the concepts, except for gas-filled panels, attain their lower thermal conductivity at reduced pressure (under vacuum). Filler materials incorporated into these advanced insulations include ceramic spacers, precipitated silica or other powders, fiberglass, aerogel tiles, and open-cell foams. Barrier materials range from laminated polymer structures to stainless steel.

High thermal resistance (low thermal conductivity) elements can be combined with foam insulation in the walls of R/Fs to improve their thermal performance, without effecting their structural integrity. Four types of advanced insulation systems were tested in R/Fs and/or freezers. Typical center-of-panel properties for the vacuum insulations employed in the prototypes are summarized in ***Table II.3***. It is important to note that the conductivities of panels used in the prototypes may be substantially higher than those given in the table, as edge effects may substantially change the thermal performance of small panels, especially those fabricated with metallic barriers.

Table II.3 Typical Vacuum Insulation Thermal Conductivities

Description	Manufacturer	Thermal Conductivity (BTU*in/(h*ft^2*°F))
Precipitated Silica in Plastic Laminate (VIPs)	Degussa AG	0.050 ± 0.003[1]
Aerogel Tiles in Plastic Laminate	Thermalux	0.051 ± 0.001[1]
Fiberglass in Stainless Steel	Owens-Corning	0.018 ± 0.002[2]
Precipitated Silica and Carbon Black in Stainless Steel	Aladdin Industries, Inc.	0.042[1]

[1] Measurements made by Materials Thermal Analyses Group at Oak Ridge National Laboratory.
[2] Measurements made by Owens-Corning.

II.B.1. VIP Insulation

II.B.1.a VIP Insulation—Chest Freezers

Vacuum insulation panels (VIPs) consisting of precipitated silica filler in a plastic-laminate barrier/container were installed in three chest freezers at W. C. Wood Co. Ltd. in November 1991. The balance of the composite insulation system consisted of W. C. Wood's standard foam formulation blown with CFC-11.

Baseline Units Two production model chest freezers were employed as baseline units: WC42-xx and WE46-xx. Storage capacity, insulation thickness, and energy consumption data for these models are listed in ***Table II.4***.

VIP Units VIPs were mounted on styrofoam inserts adjacent to the cold-wall evaporators on the sides and bottom of the three prototype units. The cabinets were then assembled, foamed, and built-up on the production line without any additional modifications. The percentages of area covered by VIPs and energy consumption results are presented in the following table. Additional details on panel sizes and locations are available in reference [4].

Table II.4 VIP Insulated Chest Freezers

	WC42-xx #1	WC42-xx #2	WE46-xx
Capacity (ft^3)	14.8	14.8	16.5
Insulation Thickness (in)	2.5	2.5	3.0
Baseline Energy Consumption (kWh/24h)	1.16	1.16	1.24
% Area Covered by VIPs	54	54	44
Energy Consumption (kWh/24h)	1.04	0.99	1.08
% Energy Reduction	11	15	13

Discussion An average 13 percent reduction in energy consumption for an average 50 percent area of coverage was obtained. The baseline models were relatively high-efficiency models incorporating thick insulation walls. The impact of VIPs on energy consumption would thus be less than that for freezers or R/Fs with thinner walls.

Measurements performed on the WC42-xx units approximately 18 months after production showed 13 and 16 percent increases in energy consumption with 12 and 7 percent increases in run time for units 1 and 2, respectively. The increase for unit one is much higher than that which would be expected from the aging of the foam alone. Either a panel failure or aging of the panels must have occurred. The increase in run time for unit two would be consistent with foam aging. The significant increase in energy consumption, as compared to the increase in run time, has not been explained.

II.B.1.b VIP Insulation—Upright Freezers

VIPs were installed in upright freezers at W. C. Wood Co. Ltd. in February 1992. The balance of the composite insulation system consisted of W. C. Wood's standard CFC-11 blown foam insulation formulation, with the exception of fiberglass doors.

Baseline Units Two production model upright freezers were used as baseline models: WVF47-xx and WV58-xx. Data on these models are presented in *Table II.5.*

VIP Units VIPs were mounted on the sides, back, and top of the smaller unit and on the sides, back, top, and bottom of the larger model. Cabinets were then assembled, foamed, and built-up on the production line without any other modifications. Percentages of area covered and test results follow. Additional details on panel sizes and locations can be found in reference [4].

Table II.5 VIP Insulated Upright Freezers

	WVF47-xx	WV58-xx
Capacity (ft^3)	16.7	20.3
Insulation Thickness (in)	2.5	2
Baseline Energy Consumption (kWh/24h)	2.15	2.34
% Area Covered by VIPs	56	53
Energy Consumption (kWh/24h)	2.02	2.05
% Energy Reduction	6	12

Discussion The approximately 10 percent energy reduction is lower than that achieved for the chest freezers even though the walls are thinner. This probably results from the fiberglass insulated door, which allow a disproportionate amount of heat to flow into the cabinet.

Retests on the prototypes performed approximately 14 months after production showed a 5 percent increase in energy consumption and compressor run time. This is consistent with aging of the foam insulation, alone, over this period.

II.B.1.c VIP Insulation—Top-Freezer Refrigerators

VIPs were installed in 19 ft^3 automatic-defrost top-freezer refrigerators produced by the Admiral Company in 1991 and 1992. The balance of the insulation system was either Admiral's standard foam formulation blown with CFC-11 or a special CO_2-blown formulation.

Baseline Units The 1991 baseline units were standard Model RB19xx production units built during the last quarter of the year. The 1992 baseline models were RB19K2A production models, modified with a flat back to accommodate larger VIPs. Foam insulated doors also replaced the standard fiberglass insulation in all baseline models. DOE energy test results for the various units are presented in ***Table II.6.***

VIP Units VIPs were mounted on the sides and top adjacent to the steel cabinet and on the back adjacent to the plastic liner on all prototype units. Panels were also mounted adjacent to the steel cabinet bottom on the 1992 units. Cabinets were then assembled, foamed, and built-up without any additional modifications. Three sets of cabinets and doors were generally produced. These components were tested together or in combination with doors or cabinets from the baseline models to generate the data presented below. Additional information on the panel sizes and locations can be found in references [5] and [6].

Table II.6 VIP Insulated Top-Freezer Refrigerators

Year	1991	1992	1992
Foam Blowing Agent	CFC-11	CFC-11	CO_2
Baseline DOE Energy Consumption (kWh/24h)	2.36 ± 0.12	2.26 + 0.06	2.58 ± 0.10
VIPs in Cabinet and Doors			
% Area	47	68	68
DOE Energy	2.12 ± 0.05	2.08 ± 0.06	2.26 ± 0.09
% Reduction	10	8	13
VIPS in Cabinet only			
DOE Energy	2.27 ± 0.06	2.15 ± 0.06	
% Reduction	4	5	
VIPs in Doors Only			
DOE Energy	2.23 ± 0.07	2.21 ± 0.01	
% Reduction	5	2	

Discussion

The energy reduction results for the 1992 prototypes were less than expected. The results for the units made with CFC-11 foam are based on only two sets of cabinets and doors. Two additional sets were made but found to have very poor energy performance. These units were disassembled after testing and found to have punctured panels. The percentage reduction for the poorer insulating CO_2-blown foam was as expected. Measurements were not made for the cabinet-only and door-only configurations, as rapid aging of these foams would have produced confusing results.

The average 10 percent energy reduction is smaller than the 14 to 16 percent predicted by ERA for 50 percent area of coverage of several 18 ft^3 refrigerators. [2] The ERA calculations were based on 1-inch thick panels, while the tests were performed with 0.5- and 0.75-inch thick panels. Linear extrapolation of the test results for the 1991 prototypes to 1-inch thick panels yields a 14 percent energy reduction. Similar calculations for the 1992 prototypes yields 12 and 19 percent reductions for the CFC-11 and CO_2 foams, respectively. Only the results for the 1992 prototypes with CFC-11 foam are not in good agreement with ERA. As mentioned previously, there may have been problems with punctured panels in these tests.

II.B.1.d VIP Insulation—Side-by-Side Refrigerators

A set of 22 ft^3 side-by-side refrigerators were built at Admiral Co. in 1991. The insulation system in these units consisted of VIPs and Admiral's standard CFC-11 foam formulation.

Baseline Units The baseline units were standard production models built in late 1991, model CNS22V8A. All walls and doors of the baseline units contained foam insulation.

VIP Units VIPs were mounted on the top, sides, and doors of the prototype units. All panels were attached to the steel case, except the back panels that were attached to the liner. Cabinets were then assembled, foamed, and completed without any additional modifications on the production line. Additional details on panel sizes and location can be found in reference [5]. Test data are presented in the following table.

Table II.7 VIP Insulated Side-by-Side Refrigerators

Baseline DOE Energy Consumption (kWh/24h)	2.98 ± 0.08
VIPs in Cabinet and Doors	
% Area Covered by VIPs	49
DOE Energy	2.96 ± 0.07
% Energy Reduction	1
VIPS in Cabinet only	
DOE Energy	2.82 ± 0.07
% Energy Reduction	5
VIPs in Doors Only	
DOE Energy	3.06 ± 0.15
% Energy Reduction	-3

Discussion The presence of the VIPs in the long slender doors of the side-by-side units resulted in warpage and poor sealing. Thus the energy consumption went up for the doors-only case and only went down one percent for the cabinet and doors case. Foam voids were also observed in the cabinet. These were patched prior to energy testing but may have contributed to the small reduction in energy that resulted for the cabinet-only tests.

Similar vacuum panels at approximately 55 percent area of coverage have been installed in a 25 ft^3 side-by-side model. [7] These panels resulted in a 17 percent reduction in energy consumption.

II.B.2 Aerogel Insulation

Panels consisting of aerogel tiles encapsulated in a plastic laminate barrier/container were installed in top-freezer automatic-defrost refrigerators. The panels were manufactured by Thermalux from 12 in. by 12 in. by 0.5 in. silica aerogel tiles, which were cut and assembled into the desired panel sizes. The refrigerators were made at Admiral Co., and the remainder of the insulation composite was their standard foam formulation blown with CFC-11.

Baseline Units The baseline units were standard Admiral production models manufactured in 1992, model RB19K2A. Several indentations in the backs of the units were eliminated to allow a higher coverage of vacuum panels. Foam-insulated doors were also used to replace the standard fiberglass insulation. All other dimensions and components were unchanged from the standard production models.

Aerogel Units Three prototype units containing aerogel panels were fabricated. Aerogel panels were attached to all surfaces of the prototypes, including the bottom. All panels except those on the back were attached to the steel case. The panels were 1-inch thick, except those on the fresh food compartment sides, bottom, and back, which were 0.5 inches thick. The units were assembled, foamed, and completed on the normal production line without any additional modifications. Additional details on panel sizes and locations can be found in reference [6]. Test results follow.

Table II.8 Aerogel Insulated Top-Freezer Refrigerators

Baseline DOE Energy Consumption (kWh/24h)	2.26 ± 0.06
Panels in Cabinet and Doors	
% Area Covered by Aerogel	67
DOE Energy	2.10 ± 0.09
% Energy Reduction	7
Panels in Cabinet only	
DOE Energy	2.12 ± 0.07
% Energy Reduction	6
Panels in Doors Only	
DOE Energy	2.24 ± 0.05
% Energy Reduction	1

Discussion

The aerogel panels were very fragile, and several were broken during shipment. After energy testing, one prototype was disassembled and also found to have panels that had lost their vacuum. The panels located on the bottom of the units also blocked foam flow, resulting in voids that had to be patched. These two problems account for the poor performance of these prototypes.

Additional tests of this insulation are not currently possible, as Thermalux has gone out of business, and they were the only known supplier of large aerogel tiles.

II.B.3 Owens-Corning Evacuated Insulation

Vacuum panels consisting of fiberglass in a stainless steel container are produced by Owens-Corning (OC). As noted earlier, these panels may have center-of-panels thermal resistivities higher than 50 $h*ft^{2}*°F/(BTU*in)$, but edge effects may substantially lower their performance in refrigerators.

Baseline Units Baseline units were 1992 Admiral RB19K2A models with flat backs and foamed doors as described in section II.B.1.c.

OC Units Four prototypes were built with OC panels. Panels were 0.75 inches thick, except for the fresh food back, which was 0.5 inches thick. Small panels were used in two of the prototypes to cover the machine compartment. All four units had panels on the other five sides. After mounting the panels, the cabinets were assembled, foamed with Admiral's standard CFC-11 foam formulation, and completed on the production line. Test results follow.

Table II.9 OC Insulated Top-Freezer Refrigerators

Baseline DOE Energy Consumption (kWh/24h)	2.26 ± 0.06
Panels in Cabinet and Doors	
% Area Covered	69
DOE Energy	1.92 ± 0.05
% Energy Reduction	15
Panels in Cabinet only	
DOE Energy	1.99 ± 0.05
% Energy Reduction	12
Panels in Doors Only	
DOE Energy	2.18 ± 0.04
% Energy Reduction	4

Discussion The energy reduction results were the best of the advanced insulations tested. This is probably reflective of the higher thermal resistances of the panels, measured by Owens-Corning to average almost R-40 per inch including edge effects.

The two units with panels over the machine compartments did not have significantly different energy consumption than those without these panels. This is indicative of the fact that small panels will not have an improved performance over foam, especially for panels with metallic edges.

One unit was also known to have a panel that had lost its vacuum. Again, the performance was not significantly different than that of the other units. This is probably indicative of the small number of prototypes and the variability in the other components of the refrigerator masking the effect of one bad panel.

II.B.4 Aladdin Insulation

Evacuated panels containing a blend of precipitated silica and carbon black contained in stainless steel are produced by Aladdin Industries. These panels have slightly higher center-of-panel thermal resistance than the panels contained in plastic, but edge effects may substantially lower their effectiveness.

Baseline Units The baseline models were 1993 RB193PW refrigerators produced by Admiral. The only modification to the standard units was the use of 2-inch thick doors. At the request of Admiral, only percentage changes from the baseline are presented in this report.

Aladdin Units Three prototype units were built with Aladdin panels. All panels were 1-inch thick, except for 0.5 in. panels on the fresh food back. Panels were not placed over the machine compartment. Except for the panels and 2-inch thick doors, the prototypes were identical to standard production models. Foam blown with CFC-11 was used for the balance of the insulation system. [6]

Table II.10 Aladdin Insulated Top-Freezer Refrigerators

Baseline DOE Energy Consumption	100%
Panels in Cabinet and Doors	
% Area Covered	57
% Energy Reduction	6
Panels in Cabinet only	
% Energy Reduction	5

Discussion The Aladdin panels had approximately 15 percent higher areas of coverage and 25 percent higher center-of-panel thermal resistances than the panels contained in plastic. The energy reductions were, however, lower. Edge effects are clearly very important. Higher center-of-panel thermal resistances and larger panels can overcome this problem, as demonstrated by the Owens-Corning insulation results.

II.C Improved Gaskets

Heat flow through the gasket region of the cabinet contributes significantly to the total load. Finite element analysis (FEA) of this region of the refrigerator cabinet has shown that heat flow in this region can be reduced by 50 percent by minor changes to the design of the flanges on the door and cabinet. [8] Test results for two prototype units with gasket modifications are presented in the next section and section IV.A.

II.C.1 Improved Gasket—VIP Insulated Refrigerator

Heat flow in the gasket region occurs by conduction down the flanges and then by convection from the ends of the flanges and the gasket. Replacing a portion of the flanges on the inside of the refrigerator with plastic can reduce the total amount of heat flow in this region by one-half. In many cases, the cabinet flange does not extend into the cabinet as far as the gasket. Unless the small gap between the gasket and interior liner is sealed, convection from the end of the flange will still occur as if the flange extended into the refrigerated volume.

Baseline Unit One of the Admiral RG19xx prototype units built in 1991 and containing VIPs was used in this test program (see II.B.1.c.). The energy tests were performed at U. Md. with the anti-sweet heaters off (one portion of the standard DOE test).

Modified Unit A cross section of the gasket region is shown in ***Figure II.1***. The cabinet flange was modified by adding a piece of foam insulating tape adjacent to the flange on the inside of the refrigerated volume. The door flange was modified by removing the metal that protruded through the flange region. A front view of these modifications is shown in ***Figure II.2.***

Table II.11 VIP Insulated Refrigerator with Improved Gasket

Baseline Energy Consumption (kWh/24h)	2.18 ± 0.02
Energy consumption with door flange modification % Reduction	2.11 3
Energy consumption with both flanges modified % Reduction	2.01 ± 0.01 8

Discussion Slightly greater energy reductions could be achieved by redesigning the door flange, as opposed to removing the flange from between the screw holes.

ERA predicted energy reduction of 7 and 11 percent for 25 percent and 50 percent reductions in heat flow through the gasket region, respectively. The FEA results indicate that an approximately 40 percent reduction in heat flow should have occurred, with the modifications performed. Thus agreement between ERA and the test results is very good.

Figure II.1 Cross Section of Gasket Region

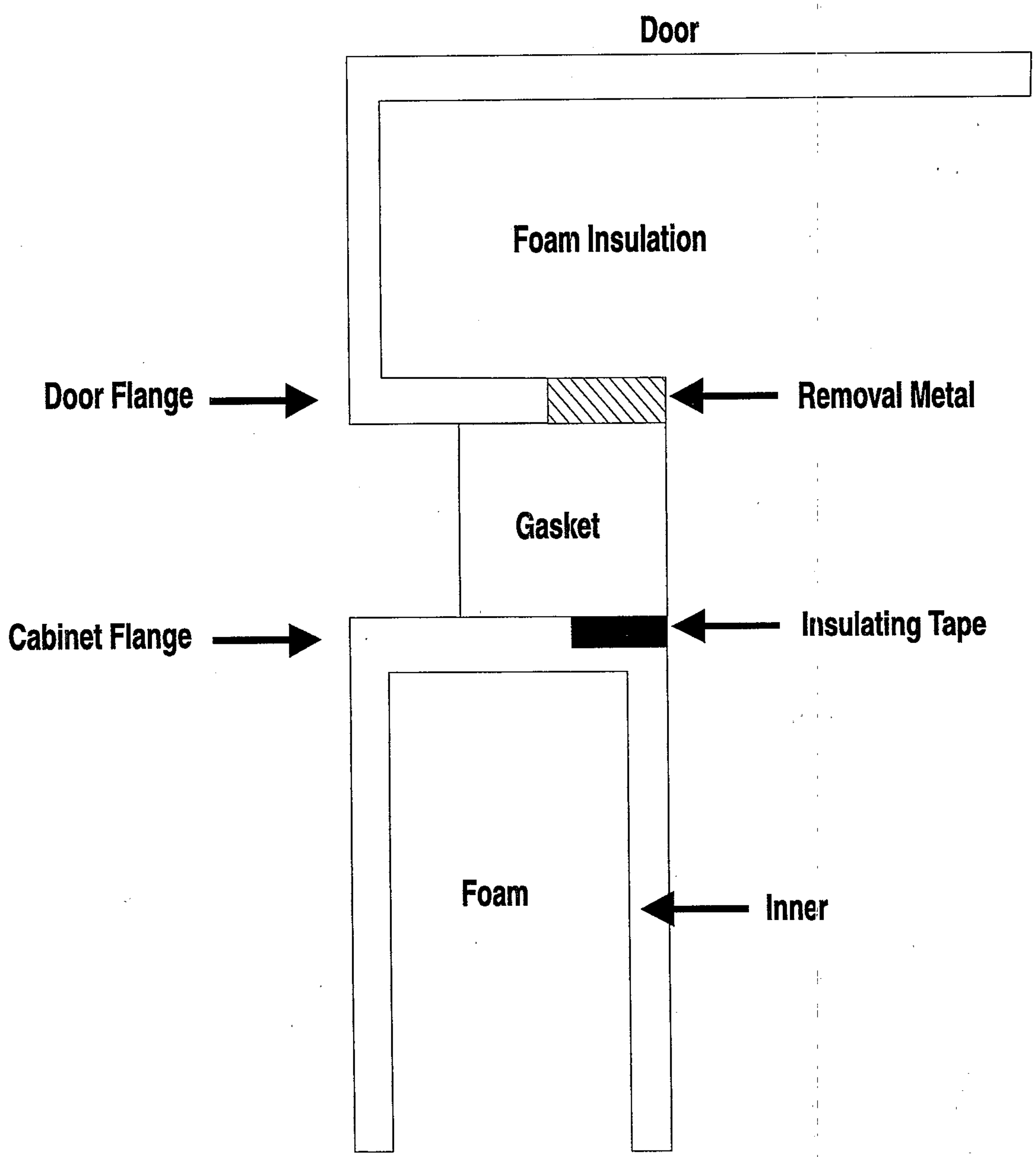
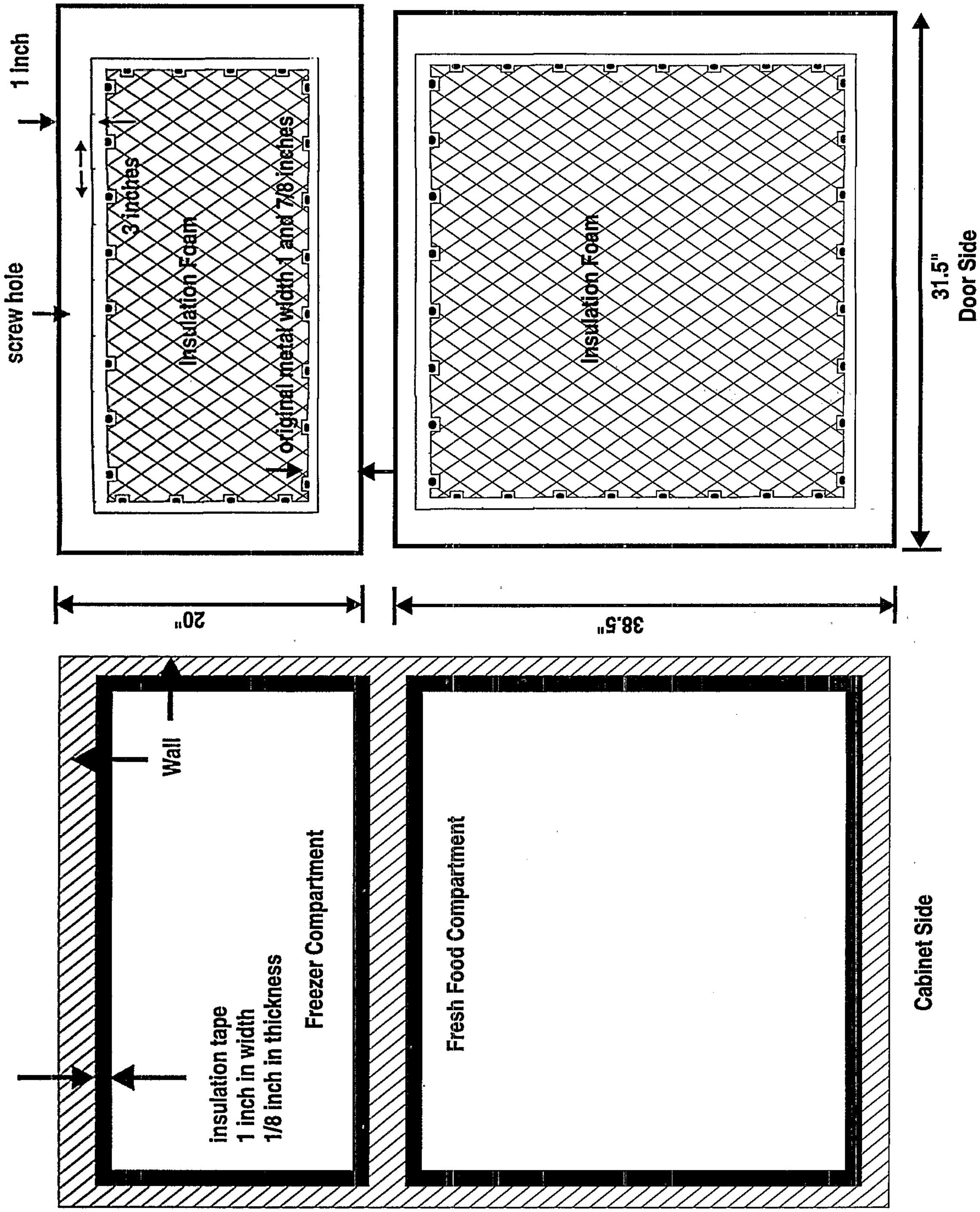


Figure II.2 Front View of Gasket Region



III. Cycle Improvements

A series of prototype refrigerators was also produced with improved cycle components. Improvements included:

- Improved components,
- Alternate refrigerants, and
- Alternate cycles.

The results of tests on these prototypes are presented in this section.

III.A. IMPROVED COMPONENTS

III.A.1 Linear Compressor

A linear compressor differs from a conventional reciprocating compressor in that the motor drives the piston directly. This feature eliminates the crank mechanism and simplifies the design. In the linear compressor developed by SunPower Inc., gas bearings guide the piston as it resonates on a spring. Use of gas bearings and elimination of the crank greatly reduces friction losses and eliminates the need for lubricating oil. The resonant piston reduces motor size and improves motor efficiency. Reducing the input voltage to the linear motor reduces the stroke of the piston and allows for easy capacity control. The net result of these improvements is a simple, efficient, oil-free, variable-capacity design. Compressor calorimeter tests with the SunPower compressor have shown a 15 percent improvement in design efficiency compared to a conventional reciprocating design. [9]

Baseline Unit The baseline unit was an 18.6 ft^3 top-freezer automatic-defrost refrigerator produced by Frigidaire, model number FPGS19TSWO.

Prototype Unit The compressor was replaced with the linear compressor. The capillary tube and refrigerant charge were optimized for minimum energy consumption. Thermocouples were installed. The remainder of the baseline unit remained unchanged.

Table III.1 Linear Compressor

	Baseline	Linear Compressor
Compressor EER	5.5	6.2
Charge (g)	156	200
Energy Consumption (kWh/24h)	1.94	1.73
FF/FZ Temperature (°F)	45.2/4.6	46.1/4.4
Duty Cycle	0.52	0.48
% Energy Reduction		11

Discussion

The linear compressor was more efficient than the original compressor and produced an 11 percent energy savings. The savings were smaller than expected when compared on an EER basis because the fans also consume electricity.

ERA predicted a 10 percent energy savings when the linear compressor replaced a 6.0 EER reciprocating compressor in an 18 ft^3 R/F. [2] The linear compressor in the ERA analysis was assumed to have an EER of 6.5 and variable capacity control. The test did not include capacity control, and the linear compressor had an EER of 6.2 and replaced the Frigidaire unit, which had a 5.5 EER.

III.A.2 Inverter

An inverter is a variable-frequency power source that can be used to vary the speed of electric motors. The inverter used in the experiments is a proprietary design. It works with conventional permanent split capacitor (psc) motors such as those used in refrigerator compressors.

Baseline Unit The baseline unit was an 18 ft^3 top-freezer automatic-defrost refrigerator manufactured by Whirlpool.

Prototype Unit A 90 V inverter was added to the power supply to the compressor. The fan voltage and frequency was not changed.

Table III.2 Inverter

	Baseline	Inverter
FF/FZ Temperature (°F)	42.3/4.4	42.3/4.8
Energy Consumption (kWh/24h)	2.49	2.36
Duty Cycle	0.57	0.69
% Energy Reduction		5

Discussion The best result with the inverter was achieved at an inverter frequency of 45 Hz. The test results demonstrate that there may exist an optimum duty cycle, which is not 100 percent, when an inverter is used. In addition to using the inverter, the supply voltage was optimized and found to be 90V.

III.A.3. Voltage Regulator

III.A.3.a Green Plug—New Top-Freezer Refrigerator

The "Green Plug" is a commercially available voltage regulator.

Baseline Unit The baseline unit was a 20 ft^3 top-freezer automatic-defrost R/F manufactured by Whirlpool in 1992, model number ET20ZKXZW.

Prototype Unit Baseline R/F was connected to a 115V and 120V power supply via the Green Plug.

Table III.3 Green Plug—New Top-Freezer Refrigerator

	Baseline	Green Plug
Input Voltage (V)	115	115
Energy Consumption (kWh/24h)	2.47	2.37
FF/FZ Temperature (°F)	37.1/4.0	35.2/4.9
Duty Cycle	0.54	0.54
% Energy Reduction		4

	Baseline	Green Plug
Input Voltage (V)	120	120
Energy Consumption (kWh/24h)	2.41	2.40
FF/FZ Temperature (°F)	38.2/8.4	38.7/8.6
Duty Cycle	0.48	0.45
% Energy Reduction		0

Discussion Generally, test results with this refrigerator showed performance changes of about 2±3 percent when the Green Plug was used. Similar results have been found by Consumers Union. [10]

III.A.3.b Green Plug—Side-by-Side Refrigerator

The Green Plug is a commercially available voltage regulator.

Baseline Unit The baseline unit was a 1975 Sears 19 ft^3 side-by-side R/F, model number 106-7650511.

Prototype Unit The baseline unit was connected to a 115V and 120V power supply via the Green Plug.

Table III.4 Green Plug—Side-by-Side Refrigerator

	Baseline	Green Plug
Input Voltage (V)	120	120
Energy Consumption (kWh/24h)	5.34	5.35
FF/FZ Temperature (°F)	34.1/8.2	34.4/8.4
Duty Cycle	0.67	0.69
% Energy Reduction		0

	Baseline	Green Plug
Input Voltage (V)	120	120
Energy Consumption (kWh/24h)	6.11	5.75
FF/FZ Temperature (°F)	30.1/3.8	30.9/4.2
Duty Cycle	0.75	0.68
% Energy Reduction		6

Discussion Generally, test results with this refrigerator showed performance changes of about minus two to six percent when the Green Plug was used. Only at 120V and under severe operating conditions (high temperature lift) were savings of 6 percent found. These results are also consistent with results found by Consumers Union. [10]

III.A.4 Hot Water Refrigerator

Baseline Unit The baseline R/F was an 18 ft^3 top-freezer automatic-defrost unit produced by Whirlpool, model number ET18ZKXZW00.

Prototype Unit A water-cooled condenser was added before and in series with the condenser of the baseline R/F. The water loop for the water-cooled condenser was equipped with a 5-gallon water tank and a circulation pump. Whenever the refrigerator was in operation, the pump operated and the condenser fan was turned off. If the water temperature in the tank rose above the set point, the pump would turn off, and the condenser fan would come on. The water-cooled condenser was a tube-in-tube, counter-flow heat exchanger with refrigerant in the inside tube. Outside and inside tubes were 0.375" and 0.125" in diameter, and the condenser was about 120" long.

Table III.5 Hot Water Refrigerator

	Baseline	Prototype
Energy Consumption (kWh/24h)	1.86	2.09
FF/FZ Temperature (°F)	38.9/3.5	36.0/4.1
Water Flow Rate (g/s)	n/a	14.5
Initial Temperature in Water Tank (°F)	n/a	72
Final Temperature in Water Tank (°F)	n/a	118
Heat Recovered to Water Tank (kWh/24h)	n/a	1.26
Duty Cycle	0.46	0.33

Discussion While the energy consumption of the prototype R/F was higher than for the baseline, the heat recovered by the water-cooled condenser reduced the energy requirement of the water heater. Results of a simulation of a domestic water heater combined with the measured refrigerator performance show net energy savings of 10 to 15 percent for the combined system.

III.B. IMPROVED REFRIGERANTS

III.B.1 Improved Refrigerants—Hydrocarbon Blends

Baseline Unit The baseline unit was a 20 ft^3 top-freezer automatic-defrost R/F produced by Whirlpool, model number ET20ZKXZW.

Prototype Unit A mixture of n-butane (R-600) and propane (R-290) was used as a refrigerant in the original refrigerator. The capillary tube length and charge were optimized. A sight glass at the condenser outlet and two pressure transducers were also added. The additional capillary tube had a diameter of 0.026".

Table III.6 Hydrocarbon Blends

	Baseline	R-600 and R-290
Charge (g)	240	80 (30/70)
Extra Cap. Tube (ft)	0	5
Energy Consumption (kWh/24h)	2.47	2.30
FF/FZ Temperature (F)	37.1/4.0	39.4/3.3
Duty Cycle	0.54	0.33
% Energy Reduction		7

Discussion There are a number of advantages that result from hydrocarbon use: energy savings up to seven percent compared to R-12 as the refrigerant, charge reduction to a third of that of R-12, and a lower pressure ratio than that of R-12. The energy savings can be improved by taking advantage of the temperature glide (which was not done here). The charge can also be reduced further with better designs, thereby reducing the flammability risk. It should be noted that the mixture concentration may vary considerably due to preferential oil solubility and storage effects in components. [11]

III.B.2 Improved Refrigerants—Cyclopropane

Baseline Unit The baseline R/F was an 18.0 ft^3 top-freezer automatic-defrost unit manufactured by Whirlpool.

Prototype Unit Only the refrigerant, amount of charge, and the length of the capillary tube were changed.

Table III.7 Cyclopropane

	Baseline	Cyclopropane
Charge (g)	156	100
Energy Consumption (kWh/24h)	2.20	2.05
FF/FZ Temperature (°F)	38.5/4.4	38.9/4.4
Duty Cycle	0.52	0.47
% Energy Reduction		7

Discussion Cyclopropane showed a seven percent decrease in energy consumption compared to the baseline with R-12. The volummetric capacity of cyclopropane is 17 percent higher than that of R-12. Since the compressor remained unchanged, the higher volummetric capacity resulted in a reduction of the compressor run time. The discharge pressure of cyclopropane increased by 10 percent, while the suction pressure was similar to that of R-12. [12]

ERA predicted a four percent energy reduction when HFC-134a was replaced by cyclopropane. [2]

III.B.3 Improved Refrigerants—HFC-134a and HFC-152a

Original Unit The original unit was an 18.0 ft^3 top-mounted automatic-defrost R/F built by GE, model number TBX18P.

Prototype Unit The original compressor was replaced with a RG108-1 compressor for HFC-134a tests. It was then replaced with a TG108-1 compressor for HFC-152a tests. Both compressors came from AMERICOLD.

Table III.8 Minimum Energy Consumption of the Optimized Systems

System Type	HFC-134a	HFC-152a
Min. energy consumption (kWh/day)	1.83	1.79
Avg. instantaneous power (on time) (W)	172.4	174.0
Compressor on-time (min)	23.0	21.0
Total cycle time (min)	52.0	49.0
Additional capillary tube length (ft)	7.0	18.0
Refrigerant charge (g)	200	120.
Avg. freezer comp. temperature (°F)	5.6	5.1
Avg. food comp. temperature (°F)	40.8	40.3
Avg. evap. pressure during on time (psia)	15.1	13.3
Avg. cond. pressure during on time (psia)	174.0	163.3

Table III.9 Calorimeter Data for the Two Compressors

Refrigerant	HFC-134a	HFC-152a
Compressor model #	RG108-1	TG108-1
Oil type	RL212B (Ester)	100DL (alkylbenzene)
Evaporation temperature (°F)	-10.4	-9.4
Evaporation pressure (psia)	16.5	15.4
Condensing temperature (°F)	129.9	129.8
Condensing pressure (psia)	213.4	190.3
Capacity (BTU/h)	759.9	824.7
EER	4.78	4.93

Discussion The HFC-152a R/F test has two percent lower energy consumption than the HFC-134a R/F test. The calorimeter tests show a three percent lower EER and an eight percent lower capacity for the HFC-134a compressor. The lower capacity of the compressor is reflected in the longer run time for the HFC-134a R/F. When the lower EER of the HFC-134a compressor is considered, both systems have the same performance. [13]

III.B.4 Improved Refrigerants—HCFC-22 and HFC-152a Blends

Baseline Unit The baseline R/F was a GE 18 ft^3 top-freezer automatic-defrost unit.

Prototype Unit There were essentially no changes made to the refrigerator, except changes to the capillary and the addition of measurement probes (two pressure transducers and one sight-glass).

Table III.10 HCFC-22 and HFC-152a Blends

	Baseline	13% HCFC-22 and 87% HFC-152a
Charge (g)	350	207 (27&180)
Energy Consumption (kWh/24h)	2.11	2.03
FF/FZ Temperature (°F)	44.3/5.0	43.7/4.8
Duty Cycle	0.48	0.48
% Energy Reduction		4

Discussion Several mixture compositions were tried to find the mixture of 13 percent HCFC-22 and 87 percent HFC-152a. This best mixture led to an optimum energy savings of four percent. [12]

III.C. IMPROVED CYCLE

III.C.1 Lorenz-Meutzner Cycle

III.C.1.a Lorenz-Meutzner Cycle—Zeotropic Refrigerant Mixtures

Baseline Unit The baseline R/F was a 20.0 ft^3 side-by-side unit produced by Whirlpool.

Prototype Unit The original evaporator was replaced by a counter-cross-flow evaporator, and a natural convection evaporator was added to the fresh food compartment. The total internal volume of the two evaporators was 72 percent of the original evaporator volume, resulting in a reduction of the charge. The original 10W freezer evaporator fan was replaced with a 7W unit, and a small 1W DC fan was placed in the fresh food cabinet to eliminate temperature gradients. A combination of two counter-current tube-to-tube heat exchangers (high and low temperature) and an adiabatic capillary tube replaced the conventional suction line heat exchanger. The original reciprocating compressor and condenser were used. The original compressor oil, a 150 SSU mineral oil (naphthenic), was used for tests involving R-12. A synthetic oil (alkylbenzene) was used with the zeotropic refrigerant mixture. A commercial filter dryer was installed in the liquid line after the condenser. Additional details on the various components can be found in reference [14].

Table III.11 Lorenz-Meutzner Cycle—Zeotropic Refrigerant Mixtures

	Baseline (R-12)	65% HCFC-22 and 35% HCFC-123	71% HCFC-22 and 29% HCFC-141b	60% HCFC-22 and 40% HCFC-123
Energy Consumption (kWh/24h)	2.44	2.17	2.20	2.26
FF/FZ Temperature (°F)	36.6/4.5	36.2/5.0	40.0/4.9	38.0/4.9
Duty Cycle	0.57	0.53	0.51	0.58
% Energy Reduction		11	10	7

Discussion This prototype demonstrates that the Lorenz-Meutzner cycle works well in a side-by-side refrigerator/freezer. The natural-convection food-compartment evaporator caused significant temperature stratification that could be eliminated with a 1W fan. Consequently, a forced-convection evaporator is recommended for the food compartment in a side-by-side unit.

III.C.1.b Lorenz-Meutzner Cycle—Hydrocarbon Blends

Baseline Unit The baseline unit was an 18.0 ft^3 top-freezer automatic-defrost R/F built by Whirlpool, model number WT18NKYO.

Prototype Unit A natural convection food compartment evaporator, a counter-flow freezer evaporator, and a suction line heat exchanger were added to the baseline R/F.

Table III.12 Lorenz-Meutzner Cycle—Hydrocarbon Blends

Cycle	Baseline	Baseline LM 1	Baseline LM 2	L-M	L-M	L-M	L-M
Refrigerant	R-12	R-12	R-12	R-290/ C_5H_{12}	R-290/ HCFC-123	R-290/ R-600	R-290/ R-600/ C_5H_{12}
Charge (g)	300	310	360	180 (50/50)	180 (50/50)	145 (48/52)	157 (42/39/ 19)
Energy Consumption (kWh/24h)	1.83	1.69	1.84	1.54	1.52	1.52	1.50
FF/FZ Temperature (°F)	38.1/ 4.7	38.5/ 5.0	38.1/ 4.7	40.4/ 4.8	38.9/ 4.7	38.8/ 5.1	40.2/5.1
% Energy Reduction		8	-1	16	17	17	18
Test Date	10/91 original	* 09/92	* 05/93				

* After conversion to Lorenz-Meutzner cycle

Discussion Hydrocarbon mixtures in the Lorenz cycle save energy in the range from 16 to 18 percent as compared to R-12 in a top-freezer automatic-defrost refrigerator. If it is considered that the refrigerator insulation tends to age over time (increasing of thermal conductivity), which may be indicated by the difference in the baseline tests LM1 and LM2 with otherwise identical hardware, then the savings will reach 23 to 25 percent.

ERA predicted 18 percent energy reductions for similar R/Fs with natural convection evaporators in the fresh food compartment. This is in agreement with the test results.

III.C.1.c Lorenz-Meutzner Cycle

Baseline Unit The baseline R/F was a 19.8 ft^3 top-freezer automatic-defrost unit produced by Whirlpool, model number ET20ZKXZW.

Prototype Unit A counter-cross-flow condenser (forced convection), counter-flow freezer evaporator (forced convection), counter-flow food compartment evaporator (natural convection) were added. An inter-cooler between the freezer and fresh food evaporators was not used.

Table III.13 Lorenz-Meutzner Cycle

Heater	On	Off	Off	Off	On	On
Refrigerant	R-12	R-12	Mixture 1*	Mixture 2*	R-12	Mixture 2*
FF/FZ Temperature (°F)	41.9/5	38.6/5	38.5/4.5	42.0/5.2	41.8/4.8	42.3/4.8
Energy Consumption (kWh/24h)	2.17	2.05	1.74	1.66	2.28	1.92
% Energy Reduction**			15	19		16

* Mixture 1 is HFC-134a (56%)/HCFC-123 (31%)/R-290 (4%)/HFC-32 (9%), and (Mixture) 2 is R-290 (65 %)/HCFC-123 (35%).

** Compared with the test result using R-12.

Discussion The R-12 test was repeated (second to last column) to account for the aging of the cabinet and any other deterioration of the insulation that may have occurred during the numerous modifications. The energy savings are calculated based on the respective baseline test (either with the heater on or off). The savings of the last test are based on the latest baseline. Test results show that at least 15 percent energy savings can be achieved with this version of the Lorenz-Meutzner cycle.

III.C.2 Modified Lorenz-Meutzner Cycle

III.C.2.a Modified Lorenz-Meutzner Cycle—U.S. Refrigerator

The modified Lorenz-Meutzner cycle has three-way internal heat exchangers in the food and freezer compartments, where heat is mutually exchanged between the compartment air, refrigerant condensate, and evaporating refrigerant. In the original Lorenz-Meutzner Cycle, heat is internally exchanged between the compartment air and refrigerant vapor, while the refrigerant condensate line is bypassed.

Baseline Unit The baseline R/F was a 19.8 ft^3 top-freezer automatic-defrost Whirlpool (Kitchen Aid) unit, model number KTRS20KXWH10.

Prototype Unit A modified Lorenz-Meutzner cycle with internal heat exchange in the evaporators, counter-cross-flow condenser and freezer evaporator, natural-convection food evaporator, and intercooler added. The refrigerator/freezer was equipped with the original rotary compressor and energy-saving valve.

Table III.14 Modified Lorenz-Meutzner Cycle—U.S. Refrigerator

	Baseline	Prototype
Refrigerant	R-12	R-290/HCFC-123
Energy Consumption (kWh/24h)	1.86	1.55
FF/FZ Temperature (°F)	38.1/5.1	38.6/4.1
% Energy Reduction		17

Discussion The results indicate that the daily energy consumption decreased by up to 17 percent without considering the defrost cycle. Many other CFC-free refrigerant mixtures were also tested with significant energy savings, in the same 17 percent savings range.

III.C.2.b Modified Lorenz-Meutzner Cycle—Chinese Refrigerator

Baseline Unit The baseline R/F was a top-freezer 6.4 ft^3 automatic-defrost model produced by the ShangLing Refrigerator Co., model number BCD-180.

Prototype Unit Modification similar to those described in Section III.C.2.a were made. The evaporator was constructed of 5/16 inch O.D. aluminum/copper tubing in a cross-counter-flow pattern with 40-45 plate fins. The resulting heat exchanger was 9 inches deep in the direction of air flow with 12.5 inch x 2 inch cross-sectional area.

Table III.15 Modified Lorenz-Meutzner Cycle—Chinese Refrigerator

	Baseline	Prototype
Refrigerant	R-12	R-290/ HCFC-123
Energy Consumption (kWh/24h)	1.29	1.16
FF/FZ Temperature (°F)	38.7/5.0	38.1/5.0
% Energy Reduction		10

Discussion The results indicate that the daily energy consumption decreased by up to 10 percent. Since this Chinese refrigerator had much smaller internal volume, there was not much room for optimizing the evaporators. Also, the condenser was located in the foam insulation and was not a counter-flow design. Considering these limitations, the energy savings were quite good, although not as high as found in the American R/F. [15]

III.C.3 Dual-Loop System

Baseline Unit The baseline R/F was a 19.8 ft^3 top-freezer automatic-defrost unit manufactured by Whirlpool.

Prototype Unit A dual-loop system with two separate vapor compression cycles, one for the freezer and one for the food compartment, were added. The freezer compartment cycle included a 4.0 EER reciprocating compressor, which was placed at the left outside of the cabinet, the original evaporator and fan, mounted in the original position, and a natural convection condenser located on the back of the cabinet.

The food compartment cycle consisted of a 3.65 EER reciprocating compressor, located in the original compressor compartment, a new counter-flow heat exchanger with a 6 W fan, and a new natural convection condenser.

To reduce heat transfer between the two compartments, the top side of the food and the bottom side of the freezer compartments were insulated with a 1-inch thick glass wool mat. The compressor oil was changed from a mineral oil with 3GS viscosity to a 1GS mineral oil to compensate for the lower operating temperatures. Additional details can be found in reference [16].

Table III.16 Dual Loop System

	Baseline	Dual Loop
Energy Consumption (kWh/24h)	1.98	1.87 (1.30 in FF + 0.57 in FZ)
FF/FZ Temperature (°F)	40.5/3.7	39.6/3.7
Duty Cycle	0.47	0.51 for FZ/0.22 for FF
% Energy Reduction		4

Discussion The best result achieved with the dual loop system showed a four percent improvement of the total energy consumption over the baseline. The compressors used in both cycles were smaller and lower EER than the original rotary compressor (EER = 4.9). Energy savings of more than 20 percent could be possible, if compressors with the same EER as the original compressor were available. The reported savings exclude defrost. Higher energy savings can be expected when defrost is included. This effort continued for an additional 12 months with the best result being a 4 percent reduction in energy consumption. Accounting for foam aging, the result would have been higher.

ERA calculations for the dual loop have predicted a two percent energy reduction. The savings were smaller because forced convection evaporators and condensers were used. [2]

III.C.4 Two-Stage Refrigerator

Baseline Unit The baseline model was built at U. Md. It consisted of an approximately 20 ft^3 top-freezer refrigerator that was housed in an insulated wooden box.

Prototype Unit A forced convection food compartment evaporator, forced convection freezer evaporator, and condenser were used. Two compressors were used in series. The first pumped refrigerant from the freezer evaporator to the food compartment evaporator pressure level, the second from the fresh food pressure level to the condenser pressure level.

Table III.17 Two-Stage System

	Baseline	Two-Stage
Energy Consumption (kWh/24h)	3.30	3.20
FF/FZ Temperature (°F)	43.9/5.2	38.3/5.3
Duty Cycle	0.72	0.62
FF/FZ Compressor EER	4.4	4.2/3.4
Charge (g)	480	316
% Energy Reduction		3

Discussion The test results show a three percent energy savings over the single stage configuration. Considering that the food compartment temperature was considerably lower than in the baseline test, another three percent could have been gained. Finally, accounting for the lower compressor EER would result in a total energy savings of about 20 percent.

III.C.5 Kopko Cycle

The Kopko cycle represents a method of achieving energy savings with two evaporators in a single circuit without the use of mixtures or special control valves. The basic set-up uses a freezer evaporator and fresh-food evaporator connected in series, each with its own fan. The controls run one evaporator fan at a time. Only the freezer fan operates when cooling the freezer; and only the fresh-food compartment fan operates when cooling the fresh-food compartment. The evaporators are installed to minimize natural convection of air when the fans are off. The normal sequence is to cool the fresh-food compartment first, then the freezer. This set-up uses the higher evaporator pressures that normally occur at the beginning of the compressor on time to cool the fresh-food compartment.

Baseline Unit The baseline unit was an 18 ft^3 top-freezer automatic-defrost R/F manufactured by Whirlpool, model number ET18NKXYW.

Prototype Unit A forced convection food compartment evaporator was added to the system. Capillary tube length was optimized and measurement probes were added. The control logic was changed. Lastly, the compressor was exchanged as indicated in the table below. [17]

Table III.18 Kopko Cycle

	Baseline	Kopko
Energy Consumption (kWh/24h)	1.78	1.24
FF/FZ Temperature (°F)	38.4/4.9	39.0/5.1
Duty Cycle	0.45	0.43
Compressor	FGV80AW(SINGLE)	AMERICOLD HG107
EER	4.91	5.52
Charge (g)	177	360
% Energy Reduction		30

Discussion The use of the Kopko configuration leads to considerable energy savings. When the higher compressor EER is excluded, the new configuration produces an 18 percent increase in performance.

The following six tables describe all of the intermediate modifications to the Kopko system and the respective test results.

Table III.19 Kopko Cycle—First Modification

	Baseline	First Modification
Size	18 ft^3	Same as Baseline
Compressor	FGV80AW	Same as Baseline
Freezer Evaporator Type Total Area Flow Fan	Forced Convection Plate Fin and Tube 2,500 in^2 Cross-Flow 40 - 50 cfm, 8 - 12 W	Forced Convection Spiny Fin and Tube 1,457 in^2(0.94 m^2) Counter-Flow Same as Baseline
Food Evaporator Type Total Area Flow Fan	N/A	Forced Convection Plate Fin and Tube 2,500 in^2 Cross-Flow 65 cfm, 7 W Pewee Boxer Model# 4715PS-12T-B10
Condenser	Natural Convection	Same as Baseline
Capillary Tube	~ 8′ (0.026" ID)	9′6" (0.026" ID) in FZ
SLHX	6′8" 0.026" ID by 0.313" OD	10′ (4′ located in FF) 0.125" by 0.313"OD
Fan Control	N/A	FZ Fan First with Timer
R-12 Flow Path Direction	N/A	FZ to FF Evaporator
R-12 Charge (g)	177	230
Two-Way Switch Model # Power	N/A	Potter-Brumfield KUP-5A15-120 2 W
On-time Delay Relay Model # Power	N/A	Dayton Elect. MFG. Co. 6X601F (Range 9-900sec) 3 W
Filter Dryer	Original	ALCO EK - 032
Sight-glass	N/A	Installed

Table III.20 Kopko Cycle—First Modification Test Results

	Baseline	First Modification
Energy Consumption (kWh/24h)	1.78	1.67
FZ/FF Temperature (°F)	4.9/38.4	4.7/38.2
RTD Controller Set Point, FZ/FF (°F) Hysterisis, FZ/FF	5.5/- 1.4/-	4.5/38.55 0.4/0.3
Duty Cycle	0.45	0.42
% Energy Reduction		6

Table III.21 Kopko Cycle—Second Modification

	First Modification	Second Modification
Compressor	FGV80AW	FGV80AW
Freezer Evaporator Type Total Area Flow Fan	Forced Convection Spiny Fin and Tube 1,457 in^2 Counter-Flow 40 - 50 cfm, 8 - 12 W	Forced Convection Spiny Fin and Tube 2,853 in^2 (1.84 m^2) Counter-Flow 26 cfm, 4 W
Food Evaporator Type Total Area Flow Fan	Forced Convection Plate Fin and Tube 2,500 in^2 Cross-Flow 65 cfm, 7 W Pewee Boxer Model# 4715PS-12T-B10	Forced Convection Plate Fin and Tube 3,661 in^2 (2.36 m^2) Cross-Flow 65 cfm, 7 W Pewee Boxer Model# 4715PS-12T-B10
Condenser	Natural Convection	Natural Convection
Capillary Tube	9′6" (0.026" ID) in FZ	8′0" (0.026" ID) in FZ
SLHX	10′ (4′ located in FF) 0.125" by 0.313"OD	6′8" 0.026"ID by 0.313"OD
Fan Control	FZ Fan First with Timer	FF Fan First
R12 Flow Path Direction	FZ to FF Evaporator	FZ to FF Evaporator
R12 Charge (g)	230	300
Two-Way Switch	Installed	Installed
On-time Delay Relay	Installed	N/A
Filter Dryer	Installed	Installed
Sight-glass	Installed	Installed
Special Insulation Mullion FZ Evaporator Cover	N/A	 1" Foam Glass Wool

Table III.22 Kopko Cycle—Second Modification Test Results

	First Modification	Second Modification
Energy Consumption (kWh/d)	1.67	1.56
FZ/FF Temperature (°F)	4.7/38.2	5.0/38.3
RTD Controller Set Point, FZ/FF (°F) Hysterisis, FZ/FF	 4.5/38.55 0.4/0.3	 5.9/36.9 1.0/0.2
Pressure (psia) High Side Low Side	 161.6 15.5	 158.1 16.2
Temperature (°F) Condenser FZ Evaporator FF Evaporator	 105.2 -21.3 9.5	 113.0 -15.8 -3.9
On/Off-Time (min)	12.8/18.0	13.5/19.7
FF On-Time (min)	- (Fan on once)	4.5 (Fan on twice)
Duty Cycle	0.42	0.41
% Energy Reduction from Baseline	6	12

Table III.23 Kopko Cycle—Third Modification and Test Results

	Second Modification	Third Modification
Energy Consumption (kWh/d)	1.56	1.29
FZ/FF Temperature (°F)	5.0/38.3	5.1/ 39.2
RTD Controller Set Point, FZ/FF (°F) Hysterisis, FZ/FF	 5.9/36.9 1.0/0.2	 5.35/36.25 0.7/0.7
Pressure (psia) High Side Low Side	 158.1 16.2	 152.2 15.5
Temperature (°F) Condenser FZ Evaporator FF Evaporator	 113.0 -15.8 -3.9	 97.5 -17.5 12.3
Compressor Model# Capacity EER Oil	Reciprocating FGV80AW (EMBRACO) 820 4.91 Mineral, 3GS	Reciprocating HG-107 (AMERICOLD) 700 5.5 Mineral, 1GS
R12 Charge (g)	300	320
On/Off-Time (min)	13.5/19.7	13.3/16.3
FF On-Time (min)	4.5	5.5
Duty Ctcle	0.41	45
% Energy Reduction from Baseline	12	28

Table III.24 Kopko Cycle—Fourth Modification and Test Results

	Third Modification	Fourth Modification
Energy Consumption (kWh/24h)	1.29	1.24
FZ/FF Temperature (°F)	5.1/39.2	5.1/39.0
RTD Controller Set Point, FZ/FD (°F) Hysterisis, FZ/FD	 5.35/36.25 0.7/0.7	 4.0/35.2 1.5/0.6
Pressure (psia) High/Low Side	 152.2/15.5	 150.1/16.2
Temperature (°F) Condenser FZ/FF Evaporator	 97.5 -17.5/12.3	 95.0 -15.2/42.8
Compressor Model # Capacity EER Oil	Reciprocating HG-107 (AMERICOLD) 700 5.5 Mineral, 1GS	Reciprocating HG-107 (AMERICOLD) 700 5.5 Mineral, 1GS
R12 Charge (g)	320	320
Filter Dryer	Installed	Removed
Sight-glass	Installed	Removed
On/Off-Time (min)	13.3/16.3	20.8/28.0
FF On-Time (min)	5.5	7
Duty Cycle	0.45	0.43
% Energy Reduction from Baseline	28	30

IV. SYSTEM AND CABINET MODIFICATIONS

Several super-efficient prototype units have been built and tested combining modifications to both the system and cabinet. These units are described in this section.

IV.A DOUBLE INSULATION AND LORENZ-MEUTZNER CYCLE

Baseline Unit The baseline model was a 20 ft^3 top-freezer automatic-defrost R/F produced by Whirlpool. This was the same unit described in Section II.A.1.

Prototype Unit A series of modifications were made to the prototype unit. These included adding double insulation (see II.A.1), adding a high-efficiency compressor, adding a modified Lorenz-Meutzner cycle with a HCFC-123 and R-290 refrigerant blend, and reducing the gasket region heat leak. The results of each step in the path follow. Details of individual steps are then presented. [18]

Table IV.1 Double-Insulated, Lorenz-Cycle Refrigerator

Insulation	Standard	Double	Double	Double	Double	DOUBLE
Compressor*	Standard	Standard	High Eff.	High Eff.	High Eff.	High Eff.
Cycle	Standard	Standard	Standard	Lorenz	Lorenz	Lorenz
Door Seal	Standard	Standard	Standard	Standard	Standard	Improved
Refrigerant	R-12	R-12	R-12	R-12	HCFC-123 and R-290	HCFC-123 and R-290
Charge (g)		220	220	410	210	210
FF/FZ Temp. (°F)	38/5	37.0/5.3	37.2/5.4	36.4/5.9	38.6/5.4	38.5/5.5
Duty Cycle		0.36	0.39	0.39	0.26	0.25
Energy Consump. (kWh/24h)	1.86	1.36	1.26	1.25	1.05	1.01
Energy Consump. including defrost		1.47	1.38	N/A	1.20	1.14
% Energy Reduction		27	7	1	16	4
Total % Energy Reduction		27	32	33	44	46

*See *Table IV.2.* for additional information.

Discussion The next four sections provide design details of the prototypes tested. Detailed comparison of the test results and a drawing showing the improved door seal are also attached.

IV.A.1 Double Insulation

These modifications are described in Section II.A.1.

IV.A.2 High-Efficiency Compressor

The calorimeter test data for the high-efficiency compressor were provided by the manufacturer. ***Table IV.2*** compares the original rotary compressor with the high efficiency reciprocating compressor. The EER of the new compressor was about 12 percent higher than that of the conventional compressor used in the original thick wall unit. [18]

Table IV.2 High-Efficiency Compressor

	Original Compressor	High Efficiency Compressor
Model	RA53L11RA	HG107
Type	Rotary	Reciprocating
Oil	Alkylbenzene	Mineral Oil
Oil Viscosity	3 GS	1 GS
EER (BTU/W-h)	4.80-4.86	5.50-5.54
Capacity (BTU/h)	850-867	703.2-713.4
Power (W)	177	129

IV.A.3 Modified Lorenz-Meutzner Cycle

A modified Lorenz-Meutzner cycle was incorporated into the R/F. See section III.C.1.c for additional details. *Table IV.3* compares the specifications of the standard and new cycles.

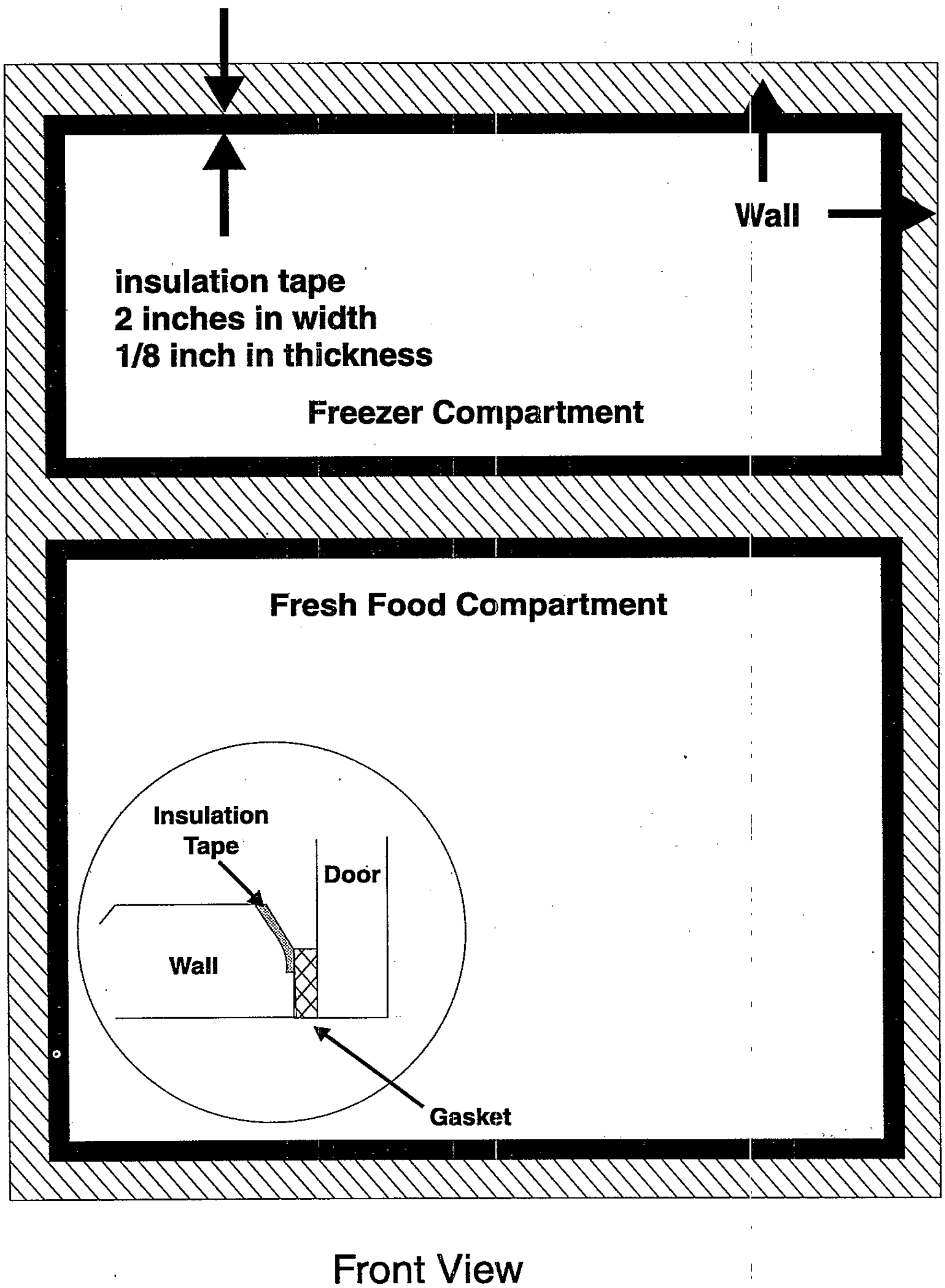
Table IV.3 Modified Lorenz-Meutzner Cycle

	Double Insulated with High Efficiency Compressor	Modified Lorenz-Meutzner Cycle
Size	19.9 cubic feet	Less than 19.9 cubic feet (considering space of cabinet evaporator)
Compressor	HG107	HG107
Compressor Oil	Alkylbenzene	Mineral oil
Freezer evaporator	Forced convection tube and fin, 18 tube passes, 26" each pass, 3/8" OD, 77 fins, cross-flow type	Forced convection tube and fin, 18 tube passes, 25" each pass, 3/8" OD counter-cross flow
Cabinet evaporator	None	Natural convection copper flat-plate, 28" by 26", copper plate two side with thickness 1/32", total surface area 1456 in^2
Condenser	Forced convection	Forced convection, modified to counter flow
Suction line HX	0.026" ID capillary tube soldered to 5/16" OD suction line	1/8" OD soldered to 5/16" OD suction tube, same length as the original length
Low temp. HX	None	25" long 3/8" OD and 1/8" OD tube soldered together, two passes

IV.A.4 Improved Gasket

The cabinet flange was modified to reduce heat leakage into the cabinet as described in Section II.C.1. A drawing of the modified gasket region follows.

Figure IV.1 Schematic Representation of Improved Gasket



IV.B DOUBLE INSULATION AND KOPKO CYCLE

Baseline Unit The baseline model was the 20 ft^3 R/F described in Section II.A.1.

Prototype Unit Double insulation (section II.A.1) and the Kopko cycle (Section III.C.5) were added to the baseline model.

Table IV.4 Double-Insulated, Kopko-Cycle Refrigerator

	Baseline	Double Insulation	Kopko
Energy Consumption (kWh/24h)	1.86	1.43	1.29
FF/FZ Temperature (°F)	38.1/5.1	38.7/5.2	38.2/5.0
Duty Cycle	0.45	0.34	0.34
Compressor	RA53L11RA(SINGLE)	RA53L11RA(SINGLE)	FN45R80T
EER	4.9	4.9	4.5
% Energy Savings		23	10
Total % Energy Savings		23	31

Discussion Accounting for the change in the compressor EER, the total energy savings based on the Kopko concept amounts to 19 percent. This would result in nearly a 40 percent reduction for the total modification. The following four tables describe all of the intermediate modifications to the system and the respective test results.

Table IV.5 Specifications for the First Modification

	Baseline	First Modification
Size	20 ft^3	Same as baseline
Wall Insulation	Thick wall	Same as baseline
Compressor Model# Capacity EER Oil	Rotary RA53L11RA 870.7 BTU/h(255.2 W) 4.91 Mineral, 4GS	Rotary RA48L83TE 787 Btu/h(230.7 W) 5.01 Mineral, 4GS
Freezer Evaporator Type Total Area Flow Fan	Forced convection Plate fin and tube 3,661in^2 Cross-flow 40 - 50 cfm, 6 - 10 W	Forced convection Plate fin and tube 4,265 in^2(3.96 m^2) Counter-flow 65 cfm, 7W
Food Evaporator Type Total Area Flow Fan	N/A	Forced convection Plate fin and tube 4,168 in^2(3.87 m^2) Counter-flow 65 cfm, 7 W
Condenser	Forced convection	Same as baseline
Capillary Tube	~ 8 ′ (0.026" ID)	7′0" (0.026" ID) in FZ
SLHX	0.026" ID by 0.313" OD	0.125" by 0.313"OD
Fan Control	N/A	FF fan first
R-12 Flow Path Direction	N/A	FZ to FF evaporator
R-12 Charge	205.5 g	410 g
Two-Way Switch Model # Power	N/A	Potter-Brumfield KUP-5A15-120 2 W
Filter Dryer	Original	Same as baseline
Sight-glass	N/A	N/A

Table IV.6 Test Result for the First Modification

	Double Insulation	First Modification
Energy Consumption (kWh/d)	1.43	1.24
FZ/FF Temperature (°F)	5.2/38.7	5.2/38.2
Total Savings (%) Net Saving	-	12.8 10.8
On/Off Time (min)	18.1/35.5	17.0/32.0
FF On-Time (min)	-	5.6
On-Time Ratio (%)	33.8	34.7
RTD Controller Set Point, FZ/FF (°F) Hysterisis, FZ/FF	 5.85/ - 1.2/ -	 4.5/39.0 1.5/0.2

Table IV.7 Compressor Comparison for Kopko Modifications

	Baseline	First Modification	Second Modification
Compressor Model # Capacity (BTU/h) EER (%) Oil	Rotary Matsushita RA53L11RA 870.7(255.2 W) 4.91 Mineral, 4GS	Rotary Matsushita RA48L83TE 787.0(230.7 W) 5.01 (+ 2.0) Mineral, 4GS	Rotary Matsushita FN45R80T 715.0(209.5 W) 4.5 (- 8.4) Mineral, 4GS

IV.C DOUBLE INSULATION AND ALTERNATE REFRIGERANTS

IV.C.1 HFC-152a

Baseline Unit The baseline model was an 8.5 ft^3 bottom-freezer R/F produced by Qingdao Haier in China, model number BCD-220. The standard cycle includes two evaporators and a single compressor with a switching valve to control refrigerant flow.

Prototype Unit Double insulation and cycle modifications were made to the unit. Added insulation was 0.8 inches on the sides, back, and bottom and 0.6 inches to the doors. Cycle improvements included adding a counter-flow condenser (natural convection), a counter-flow freezer evaporator (three-way heat exchanger, natural convection), and a food compartment evaporator (natural convection). An inter-cooler was not added between the freezer and food compartment evaporators. A high-efficiency compressor obtained from AMERICOLD (TG105-12) was also used.

Table IV.8 Increased Insulation with Refrigerants HFC-152a

Refrigerant	R-12	HFC-152a
Energy Consumption (kWh/24h)	1.70	0.96
Compressor EER	3.62	4.48
FF/FZ Temperature (°F)	38.0/5.0	38.0/5.1
% Energy Reduction		44

Discussion The results show that the combination of modifications reduced the energy consumption by about 44 percent.

IV.C.2 Hydrocarbon Mixtures

Baseline Unit The baseline unit was the same as described in the previous section.

Prototype Unit The modifications were the same as above except hydrocarbon refrigerants were used.

Table IV.9 Increased Insulation with Hydrocarbon Refrigerants

Refrigerant	R-12	R-290 (68%) and R-600 (32%)	R-290 (63%) and R-600 (37%)
Energy Consumption (kWh/24h)	1.70	0.80	0.83
FF/FZ Temperature (°F)	38.0/5.0	37.5/4.8	38.1/5.0
% Energy Reduction		53	51

Discussion Test results show that an additional 10 percent energy savings can be achieved using hydrocarbon mixtures as compared to the system using HFC-152a.

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