COST-EFFICIENCY ANALYSIS IN SUPPORT OF THE ENERGY CONSERVATION STANDARDS FOR REFRIGERATOR/FREEZERS

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ABSTRACT:

The National Appliance Energy Conservation Act (NAECA) of 1987 requires the Department of Energy (DOE) to consider new or amended energy efficiency standards for refrigerators and freezers along with several other appliances. This paper describes the cost-efficiency analysis of design options carried out in support of the proposed 1998 standards for refrigerator/freezers. These proposed standards are unique in that they have been reached by a consensus of various interested parties including the trade association of refrigerator and freezer manufacturers, environmental groups, state energy offices, and utility companies. In large part, these consensus standards are based on the analysis described in this paper. The analysis shows that, for example, for a 515 litre (18.2 ft^3) top-mount automatic-defrost refrigerator-freezer, the annual energy consumption can be reduced from 700 kWh/y (2.52 GJ/y) to 484 kWh/y (1.74 GJ/y) (30.9%) by the use of more efficient fan motors and compressor, improved gaskets and half inch thicker insulation. The energy use can be further reduced to 422 kWh/y (1.52 GJ/y) (39.8%) by employing improved heat exchangers, switching to adaptive defrost and employing vacuum panel insulation instead of thicker walls and doors.

INTRODUCTION

The National Appliance Energy Conservation Act (NAECA) of 1987 established energy-efficiency standards for 11 types of consumer products including domestic refrigerator/freezers (NAECA 1987). The legislation requires the Department of Energy (DOE) to consider new or amended standards for these and other types of products at specified times. **The average energy consumption of refrigerators and freezers has steadily decreased over the past two decades resulting in significant energy savings as well as reducing emissions of SO_2, CO_2 and No_x and helping in the fight against global warming. Figure 1 shows how the energy consumption of top-mount automatic-defrost refrigerator-freezers, the most popular product class of refrigerators and freezers (AHAM 1994), has changed over the years.** This article describes the engineering analyses performed for and considered by the DOE and the representatives of the **trade association of refrigerator and freezer manufacturers, environmental groups, state energy offices, and utility companies (henceforth referred to as the** Refrigerator Standards Group, that is, RSG) to develop 1998 proposed standards for refrigerators and freezers. **Figure 1 also shows the projected maximum allowable energy consumption for top-mount automatic-defrost refrigerator-freezers if the 1998 Proposed Standards are finalized in their present form.** This paper presents the methodology and results of analysis of design options to improve the efficiency of refrigerators and freezers. The analysis was performed in several steps: (1) selection of appliance classes, (2) selection of baseline units, (3) selection of design options within each class, (4) determination of maximum technical feasible energy factors, (5) development and implementation of performance models, (6) development of cost estimates, and (7)

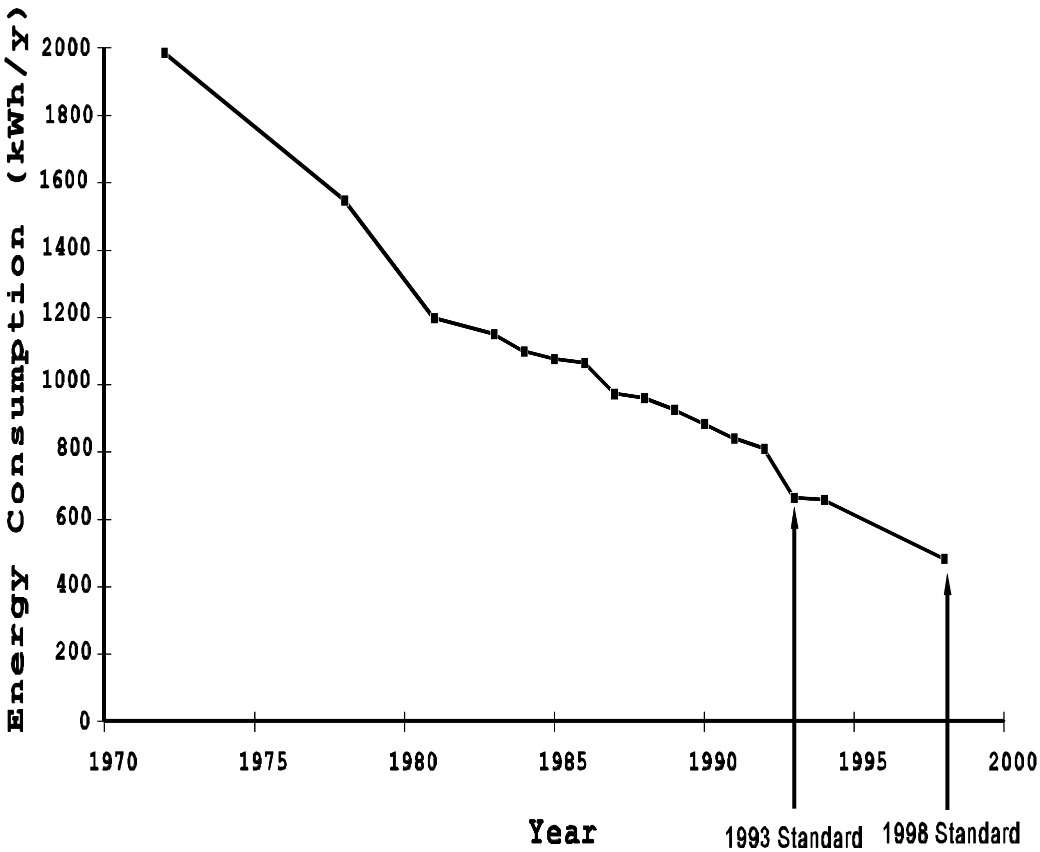

Figure 1. Annual Energy Consumption Trend for Top-Mount Automatic-Defrost Refrigerator-Freezers.

generation of price-efficiency relationships. For a detailed discussion of these steps refer to the Technical Support Document (DOE July, 1995).

Refrigerators, refrigerator-freezers, and freezers are major household appliances designed for the refrigerated storage of food products. A refrigerator consists of a refrigerated cabinet at 0°C (32°F) or above. A freezing compartment below 0°C (32°F) may also be available as long as it does not provide long-term storage below -9.4°C (15°F). A refrigerator-freezer includes a separate compartment for freezing and storing foods at temperatures below -15°C (5°F). A freezer consists of a cabinet for the storage and freezing of foods at -17.78°C (0°F) or below. A refrigerator, freezer or refrigerator-freezer with volume less than 220 litres (7.75 ft^3) and height less than 91.4 cm (36 inch) is classified as a Compact unit. Units that do not fall under the compacts category will be termed as Standard units.

The energy consumption of refrigerators and freezers is highly dependant upon the inside volume and the temperature at which it is maintained. For the same volume, more energy is spent to maintain a lower temperature inside. In order to take this fact into account, the concept of "adjusted volume (AV)" is used. For refrigerator-freezers, AV = fresh-food volume plus 1.63 times freezer volume. For freezers, AV = 1.73 times freezer volume; and for all others AV = fresh-food volume plus 1.44 times freezer volume.

JOINT COMMITTEE CONSENSUS

From the very beginning, in 1992 when this standards analysis began, there was an unprecedented level of cooperation between the refrigerator and freezer manufacturers, DOE, and its contractor responsible for conducting this analysis. There was free exchange of information between the parties and the results were made available to the manufacturers at various stages of the analysis and their comments, suggestions and recommendations incorporated in the analysis. Rulemaking procedures, as are conducted under NAECA, tend to cause participants to take relatively rigid, adversarial, and ideological positions. The free exchange of information and the ability to enter into constructive dialogue are limited. In contrast, negotiations offer the opportunity for open, candid, and collegial in-depth discussion and exchange of ideas and data (Joint Comments November 1994). The 1998 refrigerator and refrigerator-freezer proposed standards are unique in that they have been arrived at by a consensus between the industry and the representatives from various environmental groups and utilities. Since the 1970's these parties have been the primary parties in DOE and state appliance standards, research and development, utility incentive and demand side management activities. They represent a broad spectrum of interests and points of view. The analysis presented in this article and published in the Technical Support Document (DOE July, 1995) was considered by the participants in arriving at the consensus. This consensus was presented to the Department of Energy as a recommendation for an energy conservation standard that would meet the requirements of the NAECA for refrigerator/freezers.

Table 1. Consensus Standards for Refrigerator/Freezers and Freezers

Product Class	Energy Standards Equation (kWh/y)	Energy Standards Equation (kWh/y)
Standard Units		
Manual/Partial Defrost Refrigerators and Refrigerator/Freezers		
Manual Defrost	E = 0.31AV* + 248.4	E = 8.82AV** + 248.4
Partial Automatic Defrost	E = 0.31AV + 248.4	E = 8.82AV + 248.4
Automatic Defrost Refrigerator/Freezers		
Top-Mount Automatic Defrost Without Dispenser	E = 0.35AV + 276.0	E = 9.80AV + 276.0
Top-Mount Automatic Defrost With Dispenser	E = 0.36AV + 356.0	E = 10.20AV + 356.0
Side-Mount Automatic Defrost Without Dispenser	E = 0.17AV + 507.5	E = 4.91AV + 507.5
Side-Mount Automatic Defrost With Dispenser	E = 0.36AV + 406.0	E = 10.10AV + 406.0
Bottom-Mount Automatic Defrost	E = 0.16AV + 459.0	E = 4.60AV + 459.0
Freezers		
Upright Automatic Defrost	E = 0.44AV + 326.1	E =12.43AV + 326.1
Upright Manual Defrost	E = 0.27AV + 258.3	E = 7.55AV + 258.3
Chest Manual Defrost	E = 0.35AV + 143.7	E = 9.88AV + 143.7
Compact Units		
Refrigerators and Refrigerator/Freezers		
Manual Defrost	E = 0.38AV + 299.0	E = 10.70AV + 299.0
Partial Automatic Defrost	E = 0.25AV + 398.0	E = 7.00AV + 398.0
Top-Mount Automatic Defrost	E = 0.45AV + 355.0	E = 12.70AV + 355.0
Side-Mount Automatic Defrost	E = 0.27AV + 501.0	E = 7.60AV + 501.0
Bottom-Mount Automatic Defrost	E = 0.46AV + 367.0	E = 13.10AV + 367.0
Freezers		
Upright Automatic Defrost	E = 0.40AV + 391.0	E = 11.40AV + 391.0
Upright Manual Defrost	E = 0.35AV + 250.8	E = 9.78AV + 250.8
Chest Manual Defrost	E = 0.37AV + 152.0	E = 10.45AV + 152.0

*AV means the adjusted volume in litres.
** AV means the adjusted volume in ft

The consensus standard, which is the same as the DOE proposed standard, is projected to save 20 billion kWh/y (72 EJ/y) or 0.23 Quads/year of primary energy by 2010 while preserving the quality and functionality of the product. The consensus standards for maximum allowable annual energy consumption for various types of refrigerators and freezers (called product classes) are listed in Table 1.

PRODUCT CLASSES

Different types of refrigerators and freezers offer different utility to the consumer and as such may have features which affect their energy use in different ways. For example, a refrigerator with automatic defrost would use more energy than one without; or one with an ice dispenser would consume more energy than a similar unit without the dispensing feature. For this reason refrigerators and freezers have been divided into various product classes. Table 1 also lists the existing product classes for refrigerator/freezers.

DESIGN OPTIONS

Table 2 lists the design options considered in this study. The design options are changes that can be incorporated into the design of a refrigerator-freezer or freezer to improve its efficiency. Some of the design options listed are found in existing products; others are being developed. Only the design options which were found to be technologically feasible and not yet adopted by the majority of manufacturers are discussed. A discussion of all design options can be found in the Technical Support Document (DOE July, 1995).

Increased Insulation Thickness for Walls and Doors

75% to 90% of the energy required by a refrigeration unit may be attributed to the thermal performance of the insulated shell. Hence, by improving the performance of the shell, significant savings are possible. One way of improving the overall thermal resistance of the shell is to increase its thickness.

Adding 1.27 cm to 2.54 cm (0.5 to 1.0 inch) more insulation results in improvements ranging from a few percent to over 10% relative to the previous

Table 2. Design Options for Refrigerators and Freezers

Increased Cabinet Insulation Thickness	Improved Fan Motors for Evaporator and Condenser
Increased Door Insulation Thickness	Improved Fans for Evaporator and Condenser
Improved Resistivity of Insulation	Variable-Speed Fan
Vacuum Panel Insulation	Two-Stage Two-Evaporator System
Gas-Filled Panels	Other Refrigerant Cycles
Improved Gaskets	Improved Heat Exchange in Evaporator
Double Door Gaskets	Improved Heat Exchange in Condenser
Reduced Heat Load for Through-the-Door Feature	Alternative Refrigerants
Reduced Energy for Electric Anti-Sweat Heaters	Improved Expansion Valve
Condenser Hot Gas for Anti-Sweat Heaters	Fluid Control Valve
Reduced Energy for Automatic Defrost	Location of Compressor, Condenser, and Evaporator Fan Motor
Condenser Hot Gas for Automatic Defrost	Use of Natural Convection Currents
Adaptive Defrost	Electrohydrodynamic Enhancement of Heat Exchangers
Improved Compressor Efficiency	Voltage controller
Two-Compressor System	Variable-Speed Compressor

design level. The technology to implement this change is readily available and the efficiency improvements are significant. Two scenarios were analyzed for door and cabinet insulation thickness increases; they are an increase of 1.27 cm (0.5 inch) and an increase of 2.54 cm (1 inch), respectively. The market served by each product class will be impacted by insulation increases. The magnitude of the impact depends upon the dimensions of the baseline model. For compact refrigerators and freezers, which are often used in undercounter configurations, space constraint considerations have led to a decision not to employ insulation increases for the sides or door.

The cost estimates for these changes were obtained from the manufacturers of refrigerators and freezers and the energy savings were obtained from the EPA Refrigerator Analysis Program[1] (ERA) (Merriam March, 1993).

Vacuum Panel Insulation (VPI)

Evacuated insulation panels reduce heat transfer because of the low pressures inside. VPIs offer very low conductances and have been applied in small numbers; some major U.S. manufacturers have tested the panels in refrigerators and freezers. Evacuated panels are filled with low-conductivity powders that prevent collapse. Silica-filled panels with conductivity value of 0.006 to 0.008 W/m·K have been developed and are available to the manufacturers.

Evacuated insulation panels of 2.54 cm thickness and k-value of 0.00576 W/m·K (0.04 hr-ft^2-°F/Btu-in) are assumed to cover 50% of the wall and door surface area. Using this assumption, the equivalent resistivity of the walls and doors was calculated and used in the ERA program to determine the energy savings. The cost of replacing foam with VPI was derived from Vacuum Panel

[1] The EPA Refrigerator Analysis Program is a public domain software.

and Thick Wall Foam Insulation for Refrigerators: Cost Estimates for Manufacturing and Installation (Waldron October, 1992). This cost includes the savings that result from using 2.54 cm thinner foam.

Improved Gaskets

As much as 25% of the total thermal load enters the cabinet through the gaskets on the door edges (Flynn October, 1992). If the insulating value of the gasket is improved and heat leakage through the gasket is reduced, the efficiency of the refrigerator can be increased.

An EPA report describes theoretical modeling and experimental research on gasket heat loads (Flynn October, 1992). The report concludes that replacing about half of either the metal door flange or cabinet flange with plastic can reduce the heat flow through the gasket region by 25%.

The gasket heat leaks in the ERA program were reduced. The cost and efficiency improvements for this design option were based on estimates by refrigerator and freezer manufacturers.

Reduced Heat Load of Through-the-Door Feature

Through-the-door (TTD) features like ice makers displace insulation in the door. These features also make it very difficult to apply foam in the doors. Air leaks around the dispenser also contribute to the heat gain by the cabinet. With this design option, however, foam insulation as well as improved methods of reducing air leakage can be used to reduce the heat load of TTD features.

The ancillary heat leak in the ERA program was reduced. The cost and efficiency improvements for this design option were based on estimates by refrigerator and freezer manufacturers.

Adaptive Defrost

One way to reduce the energy used for defrost would be to better control the time and amount of defrost heat by using adaptive defrost. Adaptive defrost systems makes use of "smart" controls to adjust the time between defrost cycles as well as the duration of defrost itself so that the minimum amount of energy is used. Refrigerators and freezers now usually use a timer that initiates defrost after a certain constant time span, usually around 10 to 12 hours of compressor on-time. However, the frost build-up on an evaporator can vary significantly depending on the refrigerator-freezer or freezer type, its usage, and the ambient conditions. By limiting the number of defrost cycles and their duration, energy use can be reduced. It is believed that approximately 3-4% energy can be saved with adaptive defrost. There are refrigerators available today with adaptive defrost control, but these units are top-of the-line models with other electronic convenience features.

The defrost heater wattage was reduced in the ERA program to simulate adaptive defrost. The cost and efficiency improvements for this design option were based on estimates by refrigerator and freezer manufacturers.

High-Efficiency Compressors

Data have been obtained on efficiency and costs of HFC-134a compressors from four compressor manufacturers, from refrigerator manufacturers, and other sources. Compressor efficiencies have improved significantly during the last ten years and advances continue to be made. Since the compressor is the major energy-consuming component in a refrigerator, advances in **compressor efficiency have a significant effect on overall refrigerator efficiency.**

Most Table 3. Estimated 1998 Compressor COPs (using HFC 134a)

Product Class Served	Capacity Range		Maximum by 1998	
	(W)	(Btu/h)	COP	EER

The Five Standard Auto-Defrost Refrigerator-Freezers	220 to 278	750 to 950	1.64	5.60
	176 to 205	600 to 700	1.60	5.45
Auto Defrost Upright Freezers	250 to 278	850 to 950	1.64	5.60
Manual Defrost Upright Freezers	161 to 176	550 to 600	1.51	5.15
Manual Defrost Chest Freezers	147 to 161	500 to 550	1.45	4.95
Compacts	117	400	1.38	4.70
	103	350	1.26	4.30
	59	200	1.04	3.55
	41	140	0.76	2.6

models today have compressor COPs ranging between 0.73 (2.50 EER) for small 57 L (2 ft^3) all-refrigerator to 1.58 (5.40 EER) for the larger 629 L (22 ft^3) refrigerator-freezer.

Many manufacturers purchase the compressors for refrigerators and freezers from compressor manufacturers although some manufacturers produce their own compressors. As more efficient compressors become available, refrigerator manufacturers can incorporate them into their products. Conversion to a high-efficiency compressor is fairly straightforward for manufacturers to implement as long as the compressors are available or can be produced at a reasonable cost. Information (see Table 3) collected in this analysis, suggests that a 1.64 COP (5.6 EER) compressor for refrigerators will be available within the next few years.

Table 3 shows the maximum COP of the compressors expected to be available to the refrigerator manufacturers before the proposed standard goes into effect. All the compressor data used for the simulations are either maps of actual compressors or extrapolations from such maps. Costs were obtained by averaging the data received from compressor manufacturers.

Fan and Fan Motor Improvement

Fans are used to increase evaporator heat transfer and condenser heat transfer in units that have bottom-mount condensers. If the efficiency of the fans, in particular the fan motors, is increased the energy use of the refrigerator-freezer can be reduced. Typical evaporator and condenser fan motors presently require 10 to 16 W of power. Power can be reduced with improved magnets and capacitor-run motors. Dry film capacitor motors could provide additional efficiency improvements in the near future. Refrigerator manufacturers purchase fans and motors from outside vendors. Therefore, conversion to more efficient fan motors can be easily accomplished when more efficient units are available. By replacing both the condenser and evaporator fan motor significant efficiency improvement for the refrigerator could be achieved. The costs for the new motors are higher than for current models.

Based on input from three motor manufacturers, the fan motor power demand was chosen to be 4.50 W for the more efficient evaporator and condenser fan motors. The cost of switching to better motors was also obtained from the motor manufacturers. The cost and efficiency improvements for the more efficient fan design were based on estimates by refrigerator and freezer manufacturers.

Improved Evaporator and Condenser Heat Exchange

The evaporator and condenser are key components of the refrigeration system. Heat exchanger performance can be enhanced by increasing face area, adding more tube rows, increasing the thermal mass, or by integrating the heat exchanger with the outer shell of the unit. These measures are limited by the geometry of the refrigerator-freezer. There is a tradeoff between increasing the volume occupied by the heat exchanger and reducing the interior volume of the refrigerator.

The cost and efficiency improvements for this design option were based on estimates by refrigerator and freezer manufacturers.

ENERGY USE DATA

Data used in this analysis are for refrigerators and freezers presently being manufactured by nine major manufacturers. These data were obtained from the refrigerator-freezer manufacturers and were used to establish the energy consumption and the characteristics of the baseline models. The only exception is the bottom mount auto defrost refrigerator-freezer. For this case, data for only one 566 L (20 ft^3) unit were available and it was found to be almost 25% more efficient than required by the 1993 Standard. In order to bring the energy use closer to the 1993 Standard, the wall thickness was decreased by 1.27 cm (0.5 inch). In all, data for approximately 50 units of refrigerators, refrigerator-freezers, and freezers were obtained and used as input to the ERA program (Merriam March, 1993). Out of these 50 units, approximately 90% showed the simulated energy consumption to be within 20% of the DOE Test energy use and about 70% were within 10% of the DOE Test energy use. For each product class, the baseline models chosen were those 1) which were close to the 1993 Standard, and 2) whose simulated energy use was close to their actual energy use. Following are the steps used in arriving at the baseline energy consumption in this analysis. It should be kept in mind that the actual models used CFCs at the time this analysis was carried out and that they would be phased out by the time the proposed standard goes into effect. This required two changes: 1) CFC11 being replaced by HFC141b as the foam-blowing agent (no change in conductivity assumed[2]); and 2) CFC12 being replaced by R134a (compressor maps for compressors using R134a used in place of the R12 compressor maps)

(I) Run the simulation on ERA with the data provided by the manufacturer (with the CFCs present) and determine the simulated energy consumption.

(ii) Compare the simulated energy use to the DOE Test energy use and determine the calibration factor (Test Energy/ ERA Energy).

(iii) Make changes for the CFC phaseout (R12 compressor map replaced by R134a map of same COP and similar capacity) and find the simulated energy use.

(iv) Determine the baseline energy consumption as non-CFC energy times the calibration factor[3].

Table 4 lists a comparison of measured and ERA predicted energy consumption for the baseline models for the product classes analyzed. These numbers are obtained at the end of the first step of the four step process listed above and hence are different from the baseline energy use number listed in Table 6. Table 5 summarizes some of the important data for the baseline refrigerator-freezers and

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[2] Except for the case of side-by-side refrigerator-freezer and chest freezer where the conductivity was changed from 0.0159 W/m·K to 0.0175 W/m·K and 0.0182 W/m·K, respectively. It is believed that H141b cannot attain a conductivity of 0.0159 W/m·K.

[3] The energy use is further multiplied by 0.7 for chest freezers and 0.85 for upright freezers as specified in the DOE test procedure for freezers.

freezers. In addition to the data shown in Table 5, detailed geometric and refrigeration system information is needed to perform energy use simulations.

Simulations are carried out using the ERA model. This steady-state energy model calculates heat leakage into a cabinet and then determines the energy needed by the refrigeration system to maintain interior temperatures as specified in the DOE test procedure. Internal loads from heaters and evaporator fans are added to the

external heat gain. Total energy used to run the compressor, fans, anti-sweat heaters, and defrost heaters is calculated. Detailed information on the cabinet dimensions, insulation levels, compressor performance, heat exchanger effectiveness, and auxiliary electrical equipment is needed to run the simulation model.

The component energy use for a typical 515 L (18.2 ft^3) top-mount auto-defrost refrigerator-freezer has been estimated. The adjusted volume is 606 L (21.4 ft^3). For the baseline case, about 80% of the total energy is used by the compressor. The rest of the energy use is divided among fans, anti-sweat heaters, and defrost heaters. About 15% of the compressor energy use is for removal of internal heat generated by the evaporator fan motor, defrost heater, and anti-sweat heaters. These results indicate that the greatest energy conservation opportunity lies with reductions in compressor energy use. This can be accomplished by using more efficient compressors or by reducing heat gain into

the cabinet.

Table 4. Comparison of Measured and Predicted Energy Use for Baseline Units

Product Class	Measured Energy Use (kWh/y)	ERA Predicted Energy Use (kWh/y)
Standard Units		
<u>Manual/Partial Defrost Refrigerators and Refrigerator/Freezers</u>		
Manual Defrost	No Data	No Data
Partial Automatic Defrost	No Data	No Data
<u>Automatic Defrost Refrigerator/Freezers</u>		
Top-Mount Automatic Defrost Without Dispenser	689.9	686.2
Top-Mount Automatic Defrost With Dispenser	799.4	733.7
Side-Mount Automatic Defrost Without Dispenser	737.3	788.4
Side-Mount Automatic Defrost With Dispenser	793.1	733.7
Bottom-Mount Automatic Defrost	612.1	543.9
<u>Freezers</u>		
Upright Automatic Defrost	878.0	939.5
Upright Manual Defrost	598.0	655.0
Chest Manual Defrost	615.9	701.2
Compact Units		
<u>Refrigerators and Refrigerator/Freezers</u>		
Manual Defrost	308.0	350.0
Partial Automatic Defrost	433.0	565.4
Top-Mount Automatic Defrost	No Data	No Data
Side-Mount Automatic Defrost	No Data	No Data
Bottom-Mount Automatic Defrost	No Data	No Data
<u>Freezers</u>		
Upright Automatic Defrost	558.8	830.4
Upright Manual Defrost	400.0	461.7
Chest Manual Defrost	371.3	407.7

Table 5. Characteristics of Baseline Refrigerators and Freezers

Product Class	Adjusted Volume L (ft^3)	Insulation Thickness in cm (inch)				Comp. COP (EER)	Evap. Fan W (Btu/h)	Cond. Fan W (Btu/h)
		Fresh-Food		Freezer				
		Side*	Door	Side*	Door			
Refrig-Freezers								
Top Mount Auto Defrost	606.0 (21.4)	4.32 (1.70)	3.81 (1.50)	5.46 (2.15)	3.81 (1.50)	1.37 (4.68)	9.1 (31.1)	12.0 (41.0)
Top Mount Auto Defrost with Dispenser	726.8 (25.7)	3.99 (1.57)	3.81 (1.50)	5.08 (2.00)	3.81 (1.50)	1.58 (5.40)	9.1 (31.1)	12.0 (41.0)
Side-by-Side Auto Defrost	737.8 (26.1)	5.21 (2.05)	5.08 (2.00)	5.38 (2.12)	5.08 (2.00)	1.48 (5.13)	10.0 (34.1)	10.0 (34.1)
Side-by-Side Auto Defrost with Dispenser	740.9 (26.2)	5.13 (2.02)	3.81 (1.50)	5.84 (2.30)	3.81 (1.50)	1.52 (5.18)	8.0 (27.3)	11.6 (40.0)
Bottom Mount Auto Defrost	686.0 (24.2)	4.04 (1.59)	4.29 (1.69)	6.27 (2.47)	5.08 (1.50)	1.51 (5.15)	10.5 (35.8)	10.0 (34.1)
Freezers								
Upright Auto Defrost	716.3 (25.3)	-	-	4.90 (1.93)	7.01 (2.76)	1.54 (5.24)	9.0 (30.7)	-
Upright Manual Defrost	685.4 (24.2)	-	-	6.35 (2.50)	3.81 (1.50)	1.29 (4.40)	-	-
Chest Manual Defrost	723.1 (25.5)	-	-	6.41 (2.52)	5.48 (2.16)	1.22 (4.15)	-	-
Compacts								
Partial Defrost Refrigerator-Freezer	105.7 (3.73)	3.20 (1.26)	2.44 (0.96)	5.81 (2.29)	3.85 (1.52)	0.91 (3.11)	-	-
Manual Defrost Refrigerator-Freezer	46.2 (1.6)	2.67 (1.05)	2.59 (1.02)	-**	-**	0.80 (2.73)	-	-
Auto Defrost Refrigerator-Freezer	104.7 (3.7)	3.81 (1.50)	3.81 (1.50)	-**	-**	0.91 (3.10)	-	12.0 (41.0)
Compact Freezers								
Chest Manual Defrost	254.1 (9.0)	-	-	6.38 (2.51)	4.60 (1.81)	1.14 (3.88)	-	-
Upright Manual Defrost	258.0 (9.1)	-	-	4.19 (1.65)	5.49 (2.16)	1.07 (3.65)	-	-

* Average thickness of all the sides except the door.
** Contains an ice box whose walls do not act as insulators.

However, auxiliary electric equipment accounts for about 30% (resulting from direct electric power consumption and contribution to heat inside the refrigerator) of the total energy use; thus, there are also significant opportunities for conserving energy by using more efficient fans and reducing heater use.

Compressor data were obtained directly from four major compressor manufacturers. Table 3 shows the maximum COP for compressors expected to be available to the refrigerator manufacturers before the proposed standard goes into effect in 1998. All the compressor data used for the simulations are either maps of actual compressors or extrapolations from such maps. The extrapolation consisted of multiplying the power requirements in the compressor map by a constant factor to make the compressor COP equal to that of the baseline or the highest achievable (as the case may be). For example, for the case of the 622 L (22 ft^3) side-by-side refrigerator-freezer without through-the-door features, the baseline compressor had a COP of 1.50 (5.13 EER) at the nominal conditions whereas the R134a compressor of similar capacity had a COP of 1.54 (5.27 EER). In order to reconcile the difference in the performance of the two compressors at the nominal condition, the power requirement of the R134a compressor was multiplied by the factor 1.54/1.50 for each combination of the evaporator and condenser temperatures. The fan motor power demand is chosen to be 4.50 W for the more efficient evaporator and condenser fan motors. The evacuated panel thermal conductance value is 0.00576 W/m·K (0.04 hr-ft^2-°F/Btu-in) and it is assumed that 50% of the total surface area is covered by 2.54 cm (1 inch) thick vacuum panels.

The heat leak into the cabinet can be reduced by either increasing the insulation thickness or improving the resistivity of the insulation (vacuum insulation panels). Two possible levels of insulation increase have been considered, 2.54 cm (1 inch) increase and a 1.27 cm (½ inch) increase. Since a manufacturer would either increase insulation thickness or use vacuum panels, the two options are mutually exclusive. This results in three branches in the analysis for each product class; first where the insulation is increased by 2.54 cm (1 inch), second where the insulation increase is

limited to 1.27 cm (½ inch), and the third where 50% of the surface area is covered by 2.54 cm (1 inch) thick insulation vacuum panels. These options were not considered feasible for compacts or units with volume of 220 L (7.75 ft^3) or less. Most of the compacts are "under the counter" units. This requires that the exterior dimensions do not exceed 61 cm (24 inch) depth and 86.4 cm height (34 inch). Since most units already have the maximum allowable depth and height, any increase in insulation thickness would result in reduced consumer utility. If insulation is added on the outside, the units will not fit in the space provided for them, and if insulation is added on the inside, the refrigerated volume will decrease. For compacts, the chest freezer is an exception because it does not belong to the "under the counter" category and hence insulation increase on the outside does not decrease consumer utility. VPI was not considered for compacts.

The design options are ordered by their cost-effectiveness (the first option being the most cost-effective and the last one being the least cost-effective). The DOE test procedure is run both with and without the anti-sweat heaters in operation and the annual energy use is calculated from the average of the two daily energy use values. To take this into account, the simulations are performed with only half the anti-sweat heater power.

Detailed Energy-Use Data for Top-mount Auto-Defrost Refrigerator-freezer

Of all the product classes that were analyzed in this study, simulation results for a top-mount auto-defrost refrigerator-freezer only are presented here. Table 6 shows the design options that were employed in analyzing a top-mount auto-defrost refrigerator-freezer along with the manufacturing cost, duty cycle, heat loads and the break-out of power consumed by the fan motors and the compressor. Table 7 quantifies the individual changes made for each design option relative to the baseline.

Table 6. Energy Use of a Top-Mount Auto-Defrost Refrigerator-Freezer

Design Opt. Level	Option	Mfg. Cost (1992$)	Duty Cycle (%)	Cab. Heat Load (W)	Comp. Power (W)	Evap. Fan Power (W)	Cond. Fan Power (W)	Ann. Energy Use (kWh/y)
0	BASELINE	259.53	43	86.32	145.15	9.10	12.00	700.86
1	0 + 1.60 COP (5.45 EER) Compressor	270.59	43	86.30	125.36	9.10	12.00	620.13
2	1 + Reduce Condenser Fan Motor Power	275.09	43	86.30	125.36	9.10	4.50	594.45
3	2 + Add 1.27 cm (½") Insulation to Doors	278.71	42	83.32	123.45	9.10	4.50	572.43
4	3 + Reduce Evaporator Fan Motor Power	285.21	41	81.23	123.45	4.50	4.50	543.07
5	4 + Improve Evaporator Fan Efficiency	286.02	40	81.18	124.73	4.50	4.50	539.40
6	5 + Add 1.27 cm (½") Insulation to Walls	297.37	37	74.06	123.79	4.50	4.50	495.37
7	6 + Reduce Gasket Heat Leak	300.34	36	72.23	123.82	4.50	4.50	484.36
8	7 + Add 1.27 cm (½") Insulation to Doors	303.45	35	70.40	123.85	4.50	4.50	473.35
9	8 + Add 1.27 cm (½") Insulation to Walls	312.35	33	65.79	123.92	4.50	4.50	444.00
10	9 + Increase Condenser Area	315.61	32	65.74	125.27	4.50	4.50	436.66
11	10 + Adaptive Defrost	322.76	32	64.91	123.99	4.50	4.50	425.65
12	11 + Increase Evaporator Area	325.86	31	64.80	125.38	4.50	4.50	421.98
13	7 + Increase Evaporator Area	303.45	35	72.08	126.22	4.50	4.50	477.02
14	13 + Increase Condenser Area	306.71	34	72.02	127.55	4.50	4.50	469.69
15	14 + Adaptive Defrost	313.86	34	71.14	125.15	4.50	4.50	458.68
16	2 + Reduce Evaporator Fan Motor Power	281.59	42	84.15	124.43	4.50	4.50	561.42
17	16 + Improve Evaporator Fan Efficiency	282.40	42	84.09	123.66	4.50	4.50	557.75
18	17 + Reduce Gasket Heat Leak	285.37	41	82.30	123.68	4.50	4.50	546.74
19	18 + Increase Evaporator Area	288.47	40	82.13	124.76	4.50	4.50	539.40
20	19 + Increase Condenser Area	291.73	39	82.06	125.90	4.50	4.50	532.07
21	20 + Vacuum Panels on Walls & Doors	338.48	32	66.05	124.02	4.50	4.50	432.99
22	21 + Adaptive Defrost	345.63	31	65.25	126.70	4.50	4.50	421.98

Assumptions:

(1) Energy consumptions forthe baseline and for each design option were obtained from an ERA simulation of an actual 515.06 L (18.2 ft^3) refrigerator. A correction factor of 1.005 was applied to the ERA values in order to account for the difference between the simulated and the actual baseline usage.

(2) Manufacturer cost of the baseline unit was interpolated from the industry provided manufacturer cost vs kWh curve for this product class. Using a linear interpolation between the two closest points onthe industry provided curve to the ERA baseline consumption of 700.86 kWh, the ERA baseline cost is $259.53.

(3) Baseline: Compressor COP=1.37 (4.68 EER); Evaporator fan motor power = 9.10 W; Condenser fan motor power = 12.00 W; Defrost = 400 W for 18 minutes every 14 hours of compressor run time. Insulation thicknesses: freezer & fresh-food doors 3.81 cm (1.50"); freezer sides (avg of, top, side and back) 5.46 cm (2.15"); fresh-foods sides (avg of bottom, sides and back) 4.32 cm (1.70"). Foam conductivity is 0.017 W/mC in the doors, sides, top and bottom. Evaporator and condenser areas: 2.22 m^2 and 0.64 m^2, respectively.

(4) Vacuum panel option assumes that 50% of total wall and door surface area is covered by 2.54 cm (1") thick vacuum panels. The increase in cost (compared to foam insulation) assumes a variable cost of $3.24/$m^2$ ($1.20 per board foot), which includes materials, installation, labor, and shipping. A depreciated investment cost of $10/unit was also assumed. Both costs are derived from Waldron, J.M., "Vacuum Panel and Thick Wall Foam Insulation for Refrigerators: Cost Estimates for Manufacturing and Installation," prepared for US EPA Global Change division, EPA Project No. X818749-01-0, October 1992.

Table 7. Design Changes for the Top-Mount Auto-Defrost Refrigerator-Freezer

Level No.	Design Option	Increased Mfg. Cost (1992$)	Base Case	Efficient Case	Percent Change (%)
1	1.60 COP (5.45 EER) Compressor	11.06	1.37 COP (4.67 EER)	1.60 COP (5.45 EER)	16.80
2	Reduce Condenser Fan Motor Power	4.50	12.0 W (40.95 Btu/h)	4.50 W (15.36 Btu/h)	62.50
3	Add 1.27 cm (½") Insulation to Doors	3.62	FZ: 3.81 cm (1.50") FF: 3.81 cm (1.50")	FZ: 5.08 cm (2.0") FF: 5.08 cm (2.0")	33.33 33.33
4	Reduce Evaporator Fan Motor Power	6.50	9.10 W (31.06 Btu/h)	4.50 W (15.36 Btu/h)	50.55
5	Improve Evaporator Fan Efficiency	0.81	23.6 L/s (50.0 cfm)	26.0 L/s (55.1 cfm)	10.16
6	Add 1.27 (½") Insulation to Walls	11.35	FZ: 5.46 cm (2.15") FF: 4.32 cm (1.70")	FZ: 6.73 cm (2.65) FF: 5.59 cm (2.20)	23.26 29.40
7	Reduce Gasket Heat Leak	2.97	FZ: 0.1125 W/m °C FF: 0.1108 W/m °C	FZ: 0.1046 W/m °C FF: 0.1030 W/m °C	7.00 7.00
8	Add 2.54 cm (1") Insulation to Doors	6.73	FZ: 3.81 cm (1.50") FF: 3.81 cm (1.50")	FZ: 6.35 cm (2.50") FF: 6.35 cm (2.50")	66.67 66.67
9	Add 2.54 cm (1") Insulation to Walls	20.24	FZ: 5.46 cm (2.15") FF: 4.32 cm (1.70")	FZ: 8.00 cm (3.15") FF: 6.86 cm (2.70")	46.52 58.80
10	Increase Condenser Area	3.26	0.64 m^2 (6.89 ft^2)	0.70 m^2 (7.53 ft^2)	9.37
11	Adaptive Defrost	7.15	8.58 W (29.28 Btu/h)	6.19 W (21.13 Btu/h)	27.85
12	Increase Evaporator Area	3.11	2.22 m^2 (23.90 ft^2)	2.66 m^2 (28.63 ft^2)	19.82
13	Vacuum Panels on Walls & Doors	46.75	Doors: 0.017 W/m °C Walls: 0.017 W/m °C	Doors: 0.0116 W/m °C Walls: 0.012 W/m °C	31.76 29.41

where FF refers to fresh food section and FZ to the freezer section.

Compact Refrigerators and Refrigerator-freezers

This set of classes includes all refrigerator products less than 220 litres (7.75 ft^3) and 91.4 cm (36 inches) or less in height. The total energy consumption of compact refrigerators is less than 2.6% of the total energy consumed by all sizes of refrigerator products.

The ERA predictions for energy consumption for compacts were found to be off by as much as 48% (see Table 4). This, along with the lack of data limited the analysis for these product classes. Also, for or these product classes the efficiency improvement is limited by various constraints including their size and the fact that most are designed to fit under the kitchen counters. Also, many of these units do not employ fan motors, mullion, auto-defrost or through-the-door features and, as such, design strategies which relate to these components or technologies are not available for improvement. In addition, most compact refrigerator and refrigerator-freezer manufacturers are small companies with limited research and development funding and capital resources. This is why only three options were identified as feasible from a design and marketing point of view. These options are: improved gaskets, improved fan motor efficiency and improved compressor efficiency.

Because of the special design constraints and limited number of options applicable to compact refrigerator-freezers and freezers, it was difficult to develop life-cycle cost analyses that reflected the real marketing situation for these products. An assessment using industry provided inputs showed that an energy saving of 2% to 3% below the 1993 standard would result in a minimum five-year payback for the consumers.

Energy Use Versus Adjusted Volume

The energy consumption of refrigerator-freezers and freezers depends, among other factors, on the volume of the fresh-food and freezer compartments. The relationship between energy consumption and adjusted volume is investigated by modeling products of different capacity but otherwise identical characteristics.

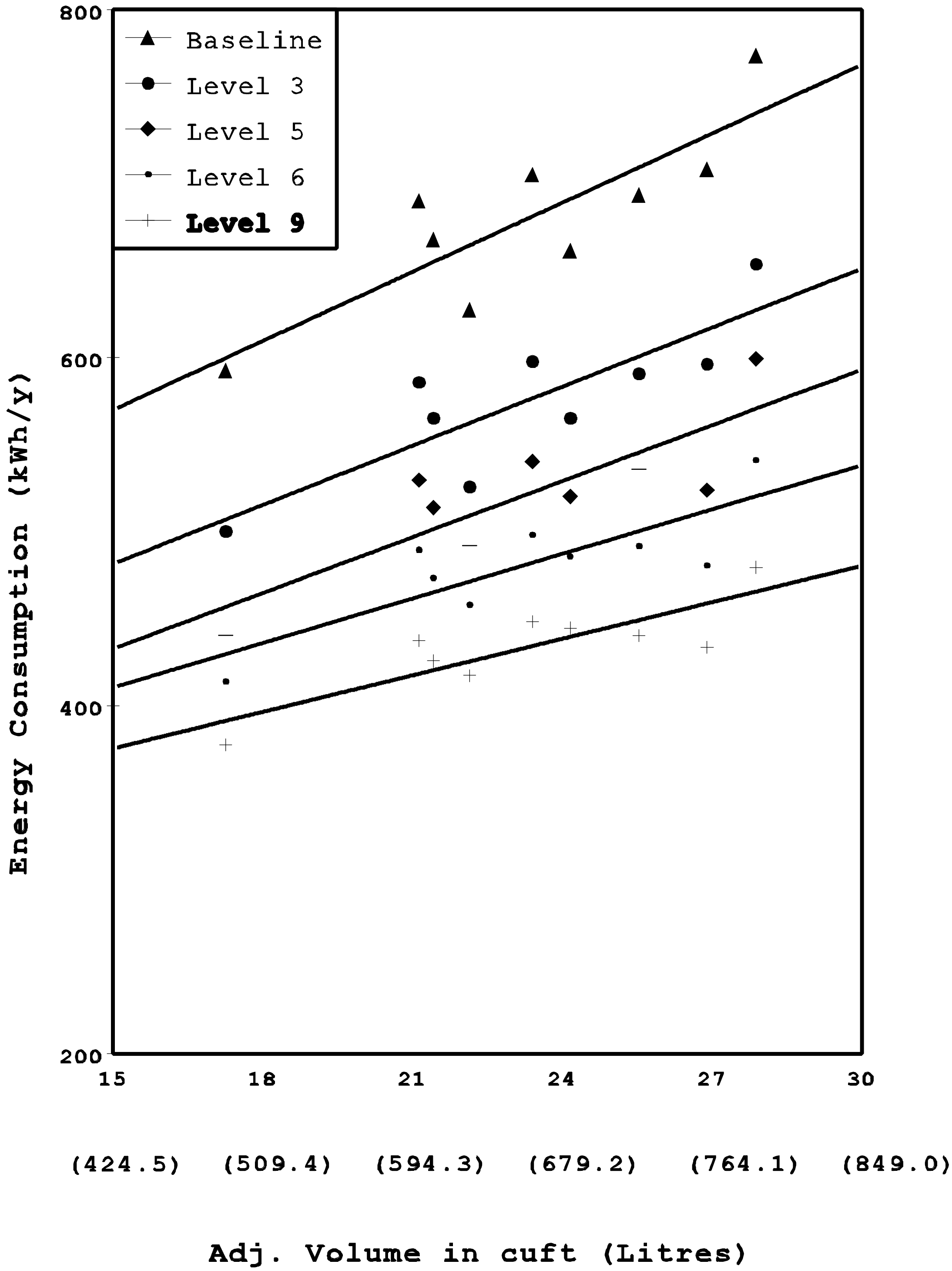

Figure 2. Annual energy use versus adjusted volume for top-mount auto-defrost

refrigerator-freezer.

Table 8. Regression Coefficients for Top Mount Auto-Defrost Refrigerator-Freezers

Design Opt. Level	Design Option	% Energy Savings*	Intercept	Slope		R^2
			kWh/y	kWh/yL	(kWh/hft^3)	
0	Baseline	-----	374.23	0.46	(13.10)	0.70
1	0 + 1.59 COP Compressor	11.80	349.50	0.44	(12.40)	0.70
2	0 + 1.7 COP Compressor	16.50	327.90	0.42	(11.90)	0.69
3	2 + Reduce Condenser Fan Motor Power	20.60	314.20	0.40	(11.20)	0.69
4	3 + Reduce Evaporator Fan Motor Power	26.11	277.80	0.39	(11.10)	0.63
5	4 + Add 1.27 cm Insulation to Doors	23.10	274.50	0.37	(10.60)	0.69
6	5 + Add 1.27 cm Insulation to Walls	33.30	284.40	0.30	(8.46)	0.67
7	6 + Reduce Gasket Heat Leak	34.70	269.60	0.31	(8.68)	0.67
8	7 + Add 2.54 cm Insulation to Doors	36.20	268.20	0.29	(8.27)	0.69
9	8 + Add 2.54 cm Insulation to Walls	39.70	272.04	0.25	(6.95)	0.70
10	9 + Increase Evaporator Area	40.70	261.37	0.25	(7.10)	0.71
11	10 + Increase Condenser Area	41.40	252.51	0.26	(7.30)	0.72
12	11 + Adaptive Defrost	43.30	246.21	0.25	(6.97)	0.69

* Relative to 1993 standard energy use at an adjusted volume of 605.9 litres (21.41 ft^3)

The relationship between adjusted volume and energy use was studied for the case of the top mount automatic defrost refrigerator-freezer only. After having chosen one particular model as the baseline and ordering the options by their cost-effectiveness, the same options were applied to eight other top mount automatic defrost refrigerator-freezers with adjusted volumes ranging from 488 L (17.25 ft^3) to 789 L (27.88 ft^3) in the same order. This analysis was done using an earlier life-cycle cost analysis. This earlier analysis assumed a 1.46 COP (4.98 EER) compressor for the baseline and also assumed a maximum of 1.70 COP (5.8 EER) to be achievable. This results in a slightly different ordering of options and a difference in the energy use associated with each level as compared to the previously described analysis for top mount refrigerator-freezers. A regression equation resulting from fitting energy use to adjusted volume was obtained for each level of design change, as shown in Figure 2. Table 8 shows the coefficients for the linear regression lines for each design level. For example, the regression equation for level 3 is the following:

$$\text{Energy Use} = 314.2 + 11.2AV$$

where AV is in ft^3 and Energy Use is in kWh/y.

An example shows how to use Table 8. Level 5 (E = 274.5 + 10.6 AV) results in a 28.1% energy savings relative to the 1993 standard energy use (at an adjusted volume of 605.9 L [21.4 ft^3]). Level 6 (E = 284.4 + 8.46 AV) results in 33.26% energy savings. The Energy Savings column in Table 8 shows the percent energy savings from the baseline for a top mount refrigerator freezer with adjusted volume of 606.0 L (21.4 ft^3) for each level of regression line. The 1993 standard energy use for this unit is 698 kWh/y.

COST-EFFICIENCY DATA

Manufacturer cost and energy efficiency data for all product classes analyzed are presented in Tables 3.5 to 3.13 in the Technical Support Document (DOE July, 1995). The manufacturer cost is the cost to the manufacturer of producing

products with the design options shown, and does not include any markups to wholesalers or retailers.

Table 9. Payback and Life-Cycle Cost for Top-Mount Auto-Defrost Refrigerator-Freezers

Level	Option	Retail Price (1992$)	Annual Energy Use (kWh)	Annual Energy Cost (1992$)	Cumulative Payback (yrs)	Lifecycle Costs (1992$)		
						2%	6%	15%
0	BASELINE	$554.67	700.86	$61.68	-	$1521.65	$1242.85	$936.95
1	0 + 5.45 EER Compressor	$572.89	620.13	$54.57	2.56	$1428.49	$1181.81	$911.14
2	1 + Reduce Condenser Motor Power	$580.39	594.45	$52.31	2.75	$1400.55	$1164.08	$904.63
3	2 + Add ½" Insulation to Doors	$586.46	572.43	$50.37	2.81	$1376.24	$1148.54	$898.69
4	3+ Reduce Evaporator Motor Power	$597.37	543.07	$47.79	3.08	$1346.65	$1130.62	$893.59
5	4 + Improve Evaporator Fan Efficiency	$598.69	539.40	$47.47	3.10	$1342.91	$1128.34	$892.90
6	5 + Add ½" Insulation to Walls	$618.88	495.37	$43.59	3.55	$1302.35	$1105.29	$889.08
7	6 + Reduce Gasket Heat Leak	$623.89	484.36	$42.62	3.63	$1292.17	$1099.49	$888.08
8	7 + Add ½" Insulation to Doors	$629.24	473.35	$41.66	3.72	$1282.33	$1094.03	$887.43
9	8 + Add ½" Insulation to Walls	$645.43	444.00	$39.07	4.02	$1258.02	$1081.40	$887.61
10	9+ Increase Condenser Area	$651.50	436.66	$38.43	4.16	$1253.96	$1080.26	$889.67
11	10 + Adaptive Defrost	$663.67	425.65	$37.46	4.50	$1250.94	$1081.62	$895.84
12	11 + Increase Evaporator Area	$668.81	421.98	$37.13	4.65	$1251.02	$1083.16	$898.98
13	7 + Increase Evaporator Area	$628.99	477.02	$41.98	3.77	$1287.14	$1097.39	$889.18
14	13 + Increase Condenser Area	$635.06	469.69	$41.33	3.95	$1283.09	$1096.25	$891.25
15	14 + Adaptive Defrost	$647.23	458.68	$40.36	4.34	$1280.07	$1097.61	$897.41
16	2+ Reduce Evaporator Motor Power	$591.26	561.42	$49.41	2.98	$1365.85	$1142.53	$897.48
17	16 + Improved Evaporator Fan Efficiency	$592.58	557.75	$49.08	3.01	$1362.11	$1140.24	$896.80
18	17 + Reduce Gasket Heat Leak	$597.59	546.74	$48.11	3.16	$1351.93	$1134.44	$895.81
19	18 + Increase Evaporator Area	$602.68	539.40	$47.47	3.38	$1346.90	$1132.33	$896.89
20	19 + Increase Condenser Area	$608.75	532.07	$46.82	3.64	$1342.84	$1131.19	$898.96
21	20 + Vacuum Panels on Walls & Doors	$688.52	432.99	$38.10	5.68	$1285.92	$1113.68	$924.69
22	21 + Adaptive Defrost	$700.69	421.98	$37.13	5.95	$1282.90	$1115.04	$930.86

Average lifetime = 19 years
All costs are in 1992 dollars
Electricity rate is $0.088/kWh (average cost in 1998 obtained from an interpolation of the 1995 and 2000 prices of electricity forecast in DOE’s Annual Energy Outlook 1993, inflated to 1992 dollars). This interpolated value (for 1998) is 0.082$/kWh (1991$). After adjusting for inflation from 1991 to 1992, it becomes 0.085 $/kWh. The electricity price was then adjusted by an enduse factor of 1.04
There are no installation and maintenance costs

The energy use data are annual unit energy consumption in kWh. All costs, except those for fan motors, compressors, and VPI, were obtained from refrigerator manufacturers. The data were collected from several refrigerator-freezer manufacturers and averaged in order to protect the confidentiality of data received from individual manufacturers. Independent estimates of the cost of purchased parts were obtained from compressor and fan motor manufacturers. Estimates for vacuum panel insulation were derived from Vacuum Panel and Thick Wall Foam Insulation for Refrigerators: Cost Estimates for Manufacturing and Installation (Waldron October, 1992).

Appendix A of the Technical Support Document (DOE July, 1995) contains disaggregated costs for nine product classes. Total costs are divided between variable and fixed costs. The variable cost is further subdivided into material, labor, burden, and shipment. The fixed part of the cost is divided into tooling, building and equipment, and research and development. Variable costs for compacts were not subdivided into their components; instead these categories were combined under the heading "variable costs".

Table 9 shows the life-cycle cost and the simple payback periods for different design option levels for the case of a 515.1 litres (18.2 ft^3) top-mount refrigerator-freezer.

CONCLUSION

The analysis shows that for a 515 litre (18.2 ft^3) top-mount automatic-defrost refrigerator-freezer, the annual energy consumption can be reduced by 31% by the use of more efficient fan motors and compressor, improved gaskets and half inch thicker insulation. The cumulative payback for the consumer is approximately 4 years. On a national level, for all the product classes combined, the proposed 1998 Standards will result in the savings of 20 billion kWh/year (72 EJ/y) or 0.23 Quads/year of primary energy by the year 2010 (Joint Comments November 1994). They will also result in a cumulative reduction in SO_2 emissions of 1017 kt (1120 thousand short tons), No_x emissions of 966 kt (1065 thousand short tons) and CO_2 emissions of 540 Mt (595 million short tons) by the year 2030 (DOE July, 1995).

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REFERENCES

1. AHAM 1994. Energy Efficiency and Consumption Trends for Refrigerators and Freezers provided by AHAM to Lawrence Berkeley Laboratory.
2. Flynn S., Rouch K., Fine A. October 1992. *Finite Element Analysis of Heat*

Transfer Through the Gasket Region of Refrigerators/ Freezers, **EPA/430/R-92/009.**

3. **Joint Comments of The Association of Home Appliance Manufacturers, The Natural Resources Defense Council, The American Council for An Energy Efficient Economy, the New York State Energy Office, the California Energy Commission, Pacific Gas and Electric, and Southern California Edison, relating to Energy Conservation Standards for Refrigerator/Freezer., November 15, 1994. Docket No. EE-RM-93-801,.**

4. **Merriam R., Verone A., Feng H. March 1993.** *EPA Refrigerator Analysis (ERA) Program: User's Manual Version 1.0*, **Cambridge, MA: Arthur D. Little Inc.**

5. **Public Law. March 1987.** *National Appliance Energy Conservation Act 1987.*

6. **U.S. Department of Energy July 1995.** *Technical Support Document: Energy Efficiency Standards for Consumer Products: Refrigerators, Refrigerator-Freezers, & Freezers*. **DOE/EE-0064**

7. **Waldron J.M. October 1992.** *Vacuum Panel and Thick Wall Foam Insulation for Refrigerators: Cost Estimates for Manufacturing and Installation*, **prepared for US EPA Global Change Division, EPA Project No. X818749-01-0**