Measured Electricity Savings of Refrigerator Replacement: Case Study and Analysis

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There are approximately seven million refrigerator-freezers in the State of Florida. The average demand of these units is at least 1,000 MW. The average life of a residential refrigerator is approximately 20 years. At least 25% of Florida's existing stock are old inefficient units built before the advent of recent appliance efficiency standards. The least efficient are existing models of which approximately 5% of the stock is replaced each year. This represents a significant opportunity for efficiency improvement since recently established standards will greatly improve refrigerator efficiency by 1993.

In order to better define this potential, the Florida Solar Energy Center (FSEC), has conducted a case study of the potential of replacing an existing refrigerator with an energy efficient model to both save energy and alter utility load shape. We also analyzed a database of all available refrigerators manufactured in the U.S. in 1991. This statistical analysis examined differences in refrigerator size and how they may influence annual estimated energy use. Such information may be useful for utility planners who wish to realize savings from high-efficiency refrigerator programs.

Background

A number of studies have identified technologies that can dramatically improve the efficiency of new refrigerators (Turiel and Heydari 1988; U.S. DOE 1989). As an example, one analysis found that the annual electricity consumption of an 18 cubic foot refrigerator-freezer could be potentially reduced by 46% to only 515 kWh through the use of improved insulation, high efficiency compressors and fans and adaptive defrost (Turiel et al. 1990). Moreover, although refrigerators have increasing in size over the last twenty years, their efficiencies have dramatically improved. Figure 1 shows shipment weighted data for the change in size and annual electricity consumption for top-mounted freezer automatic defrost refrigerators from 1972 to 1990 (AHAM 1991b). These units represent approximately two thirds of all U.S. sales. Although average refrigerator size increased by 1.3 cubic feet, average annual energy use declined by 1,102 kWh or 55%. Units manufactured in 1993 promise to be considerably more efficient offering still greater incentive to utility programs to retire old units and replace them with newer, more efficient models.

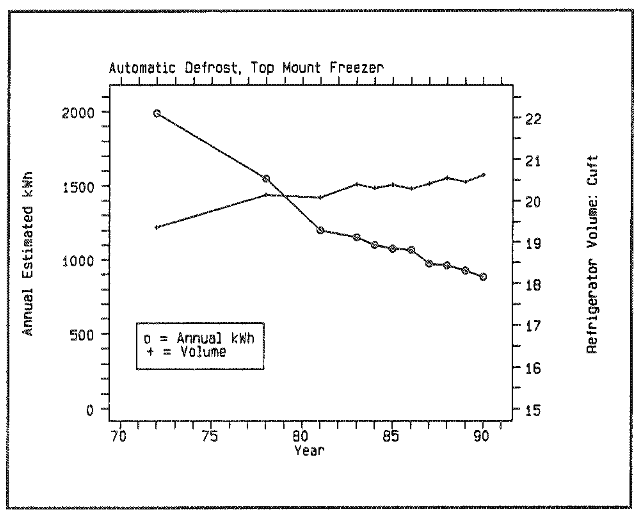

Figure 1. Change in Size and Efficiency of U.S. Automatic Defrost Refrigerator/Freezers, 1972-1990

Previous Research

The only previous study of the replacement of residential refrigerators in Florida's climate was performed by Florida Atlantic University in 1982 - 1983. The study submetered refrigerators and freezers in 25 houses for six weeks in the spring of 1982. When the results were extrapolated to a full year, the average Palm Beach household used 3,733 kWh for refrigeration--15% of total annual electricity consumption (Messenger et al. 1983). Seven of the households had a second refrigerator, which substantially increased refrigeration energy end-use. The thirty-two individually metered refrigerators used an average of 2,550 kWh per year. The average size of the existing units was 19.9 cubic feet. Of these 15 were replaced with newer more efficient units. The average consumption of the new units, which was monitored during the spring of 1983, was 1,699 kWh. With Florida's higher indoor ambient temperatures, this represented approximately 20% more electricity use than the average DOE test label estimate. Such a result is in general agreement with findings from field study surveys made of refrigerator electricity use around the country (Spolek 1985; Meier and Heinemeier 1988). These conclude that the appropriateness of the DOE test results is influenced by climate. Regardless, the refrigerator replacement program in the 15-unit sample provided a savings in refrigerator electricity end-use of 33%. The estimated reduction to the diversified peak demand from the retrofit was 97 Watts per unit.

Study Objectives

Although the above study indicated that a significant savings potential is available from refrigerator replacement, we desired to perform a more detailed comparison due to the greater efficiency of the current refrigerator models. Also, we wanted to obtain refrigerator load shape data which was unavailable from the previous work. Large sample studies of sub-metered end-use data from other regions of the country indicate that refrigerators exhibit a definite time-of-day load profile (Pratt et al. 1989; Brodsky and McNicoll 1987).

To address this need for Florida, FSEC conducted a case study of the potential of replacing an existing refrigerator with an energy efficient model to alter utility load shape. Our study objective was to give a verifiable assessment of annual electricity savings and reductions to utility peak loads arising from replacement of an existing refrigerator with a high efficiency model.

Data Collection and Acquisition

Eighteen channels of data were recorded on the project's data logger. Calibrated copper-constantan thermocouples in the fresh-food and freezer compartments recorded temperatures. Relative humidity was obtained by two solid-state bulk-polymer hygrometers. A pulse-initiating watt-hour meter provided data on electricity consumption. All the installed instruments are scanned every five seconds with integrated averages and totals output to final storage every fifteen minutes. The data was removed periodically using an on-site IBM personal computer with a direct link to the data logger. The data was then read into a statistical analysis package for analysis. Over the 20-month period of collection the data retrieval success rate has been 98%.

Consumption of the existing refrigerator was metered for an entire year from June, 1990 to June, 1991. The refrigerator is located in the conditioned space of the primary author's home, a 1,500 square foot residence in Cocoa Beach, Florida. Both kitchen, refrigerator and freezer temperatures were collected as well as recorded door openings. The original refrigerator has been in service for approximately 18 years and is similar to other automatic-defrost units which are soon to be replaced. The specific model is a 19.2 cubic foot frost-free *Sears Coldspot 106-762911* refrigerator-freezer with an automatic ice maker. Condenser coils were cleaned prior to the beginning of the year of measurement.

The existing refrigerator was replaced in August, 1991 with the most energy efficient model of its size possessing the identical conveniences (automatic ice-maker, automatic defrost), a 1991 *Frigidaire FPES19TIP*.[1] As shown in Figure 2, the two refrigerator models have a nearly identical appearance. The newer model has a DOE estimated annual energy use of 763 kWh which is within 10% of being in compliance with the more stringent 1993 appliance efficiency standards.

Refrigerator Energy Use and Load Shape

Residential refrigerator-freezers are commonly assumed to possess a relatively flat load shape. However, monitoring showed that the summertime utility peak hour (5 - 6 PM) electrical demand averaged 283 W while the demand from 4 - 5 AM when no door openings or food-loading occurred (the stand-by load) was only 198 watts. Maximum daily electrical demand tended to occur from 7 to 8 PM with a demand of 295 W.[2] This represents an hourly load variation over the course of the day of 49% even though the house was air conditioned during the hottest part of summer. Annual consumption totalled 1,963 kWh--a very substantial end-use of electricity. Based on monthly utility bills, the refrigerator represented over 25% of the total annual home electricity use. Table 1 summarizes the data. Note that most of the maximum values associated with freezer temperature and electrical demand arise from periods coincident with the defrost cycle.

The full year of data from the original refrigerator gave an indication of the magnitude of peak and annual electrical demand from older existing refrigerator stock in Florida houses. Figure 3 shows an example of data collected from the existing refrigerator over a five day period in August, 1990. The freezer compartment temperature clearly shows the periodic defrost cycles of the unit (it contains 855 Watt defrost heaters which are powered for

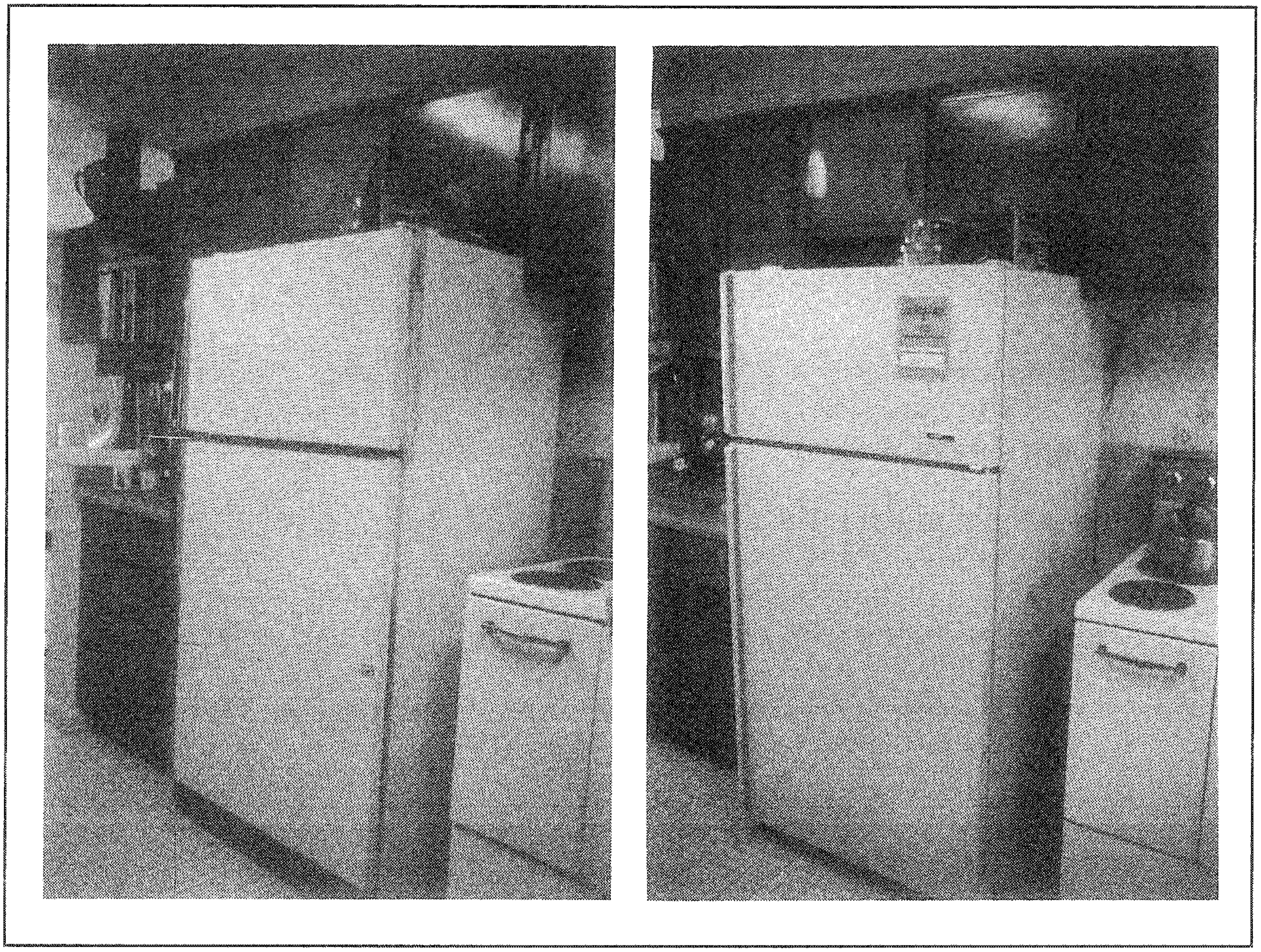

Figure 2. Existing 19 Cubic Foot Refrigerator (left) and High Efficiency Replacement Unit (right)

5-20 minutes each eight hours of compressor operation). Heavy use of the unit on August 11th during a dinner party is clearly evident.

The refrigerators were instrumented with contact switches, which recorded main door and freezer openings. A previous study of 10 refrigerators in townhouses in Twin Rivers, N.J. found an average of 48 fresh-food compartment openings per day with a further 10 freezer compartment openings (Chang and Grot 1979). Another detailed study of a single refrigerator-freezer in a three person household found 33 average fresh-food openings and 7 for the freezer compartment (Wise 1983). The refrigerator and freezer compartment in the FSEC study two-person household was opened an average of 42 times per day.

Figure 4 shows a plot of the average time-of-day frequency with which the refrigerator door was opened. As expected, door openings mirror meal preparation schedules and are heaviest after dinner when refrigerator electricity consumption is also at its peak. Kitchen temperature, on the other hand, is at its peak at approximately 3 PM during the daily cycle.

To ascertain the relative effect of environmental and usage conditions on the existing refrigerator's daily electric use, a multiple regression model was fit to the data. Similar to results obtained by Grimes et al. (1977), relative humidity was not found to exert a statistically significant influence on consumption. This also may be due to the fact that relative humidity and dry bulb temperature are correlated. Regardless, we did find kitchen temperature and door openings to account for a good part of the daily variation:

Table 1. Existing Refrigerator Performance

Value	Mean	Std. Dev	Min	Max
Fresh-Food Temp (°F)	37.8	3.07	32.2	59.5
Freezer Temp (°F)	09.3	4.33	-4.2	44.4
Kitchen Temp (°F)	82.6	5.71	65.4	97.2
Daily Door Openings	42.2	29.0	0	142.0
Daily kWh	5.38	1.17	3.24	8.28
Electrical Demand (W)	224.1	67.2	22.5	446.5
4 - 5 AM (Standby Load)	197.7	61.5	99.0	374.4
8 PM (Maximum Demand)	295.0	54.3	174.6	397.8
Summer Electrical Demand (W)				
June - September	267.7	60.7	22.5	446.5
2 - 8 PM (Utility Peak Period)	280.5	62.2	22.5	446.5
5 - 6 PM (Coincident Peak)	283.5	65.5	171.9	446.5

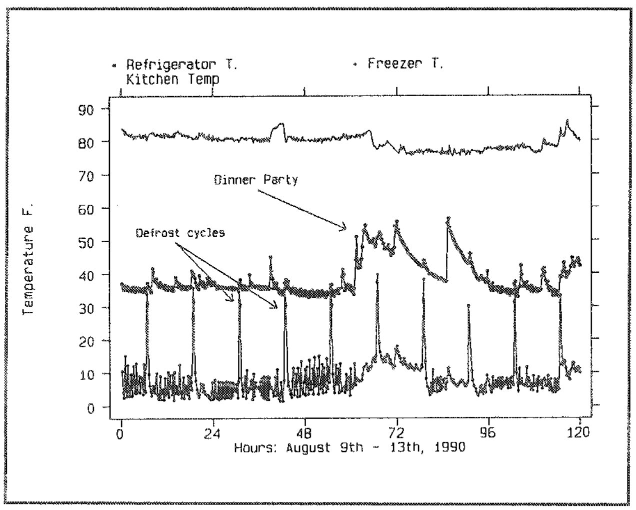

Figure 3. Example of Recorded Refrigerator and Kitchen Temperatures

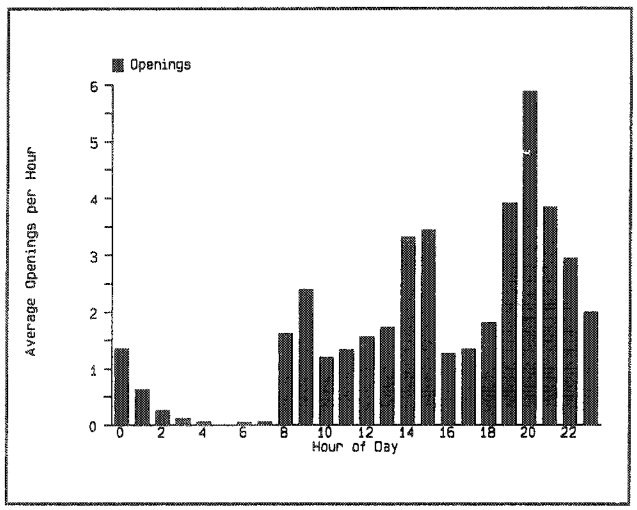

Figure 4. Average of Refrigerator Door Opening Frequency Over the Daily Cycle

$$kWh = -5.79 + \underset{[10.92]}{0.12(KitchenTemp.)} + \underset{[5.09]}{0.0095(Door\ Openings)} \quad (1)$$

where:

kWh	=	daily refrigerator energy use, kWh
Kitchen Temp	=	average daily kitchen temperature, °F
Door Openings	=	daily refrigerator and freezer door openings

$R^2 = 0.62$

R-squared indicates that about 62% of the daily variation was explained by these factors. The t-values in brackets show that all included variables were significant at better than a 99% level. Since average daily electricity use was 5.4 kWh with 42 average door openings, this indicates that refrigerator door openings were responsible for approximately 7% of overall consumption. Interestingly, the kitchen temperature turned out to be a better predictor of refrigerator energy use than did the difference between the exterior temperature and that of the freezer and/or food compartment.

In August, 1991, the existing refrigerator was replaced with the high-efficiency unit. The new model has 18.6 cubic feet, a 14.3 cubic foot fresh-food compartment and 4.3 cubic feet of freezer space. The adjusted volume of the unit is 21.3 cubic feet so that its maximum allowable annual energy use under the more stringent 1993 standards would be 696 kWh. At an estimated 763 kWh, the unit is only 10% less efficient than the standard requires for a top-mounted freezer with automatic defrost.[3] The efficiency improvements were obtained with an improved compressor design and cabinet insulation. The compressor uses more copper windings and a heavier iron core to achieve an EER of 5.3 Btu/W at standard conditions (evaporator temperature = -10°F, condenser temperature = 130°F and ambient temperature = 90°F). The improved insulation is achieved by a low-conductivity high-density urethane foam (which also contains fewer chlorofluorocarbons) and the use of the warm condenser refrigerant line to obviate the need for cabinet anti-sweat heaters. Defrost heater wattage, at 475 W, is also lower than the original unit. The defrost heater is activated every 8-hours of compressor operation for a maximum period of 21 minutes. However, defrost heater operation is usually cut-off in 6 - 8 minutes if the defrost thermostat indicates that the evaporator lines are free of frost build-up. Currently, eight months of monitored data is available with which to characterize the performance of the new unit (see Table 2).

The energy use over the first eight-months of data collection compares favorably with DOE label predicted value of 763 kWh. If the average electricity use (87 W) continued over the entire twelve month period, the refrigerator would use a total of 724 kWh. However, conditions during the two analysis periods differed. The interior temperature in the newer refrigerator was slightly warmer, although with a narrower range in the thermostat hysteresis. Attempts to lower the thermostat setting in the new unit were suspended when freezing became a problem within the fresh food compartment. Weather conditions also varied. The eight month period which has elapsed since installation was cooler than the average over the previous year. Therefore, to obtain comparable results, we used the average electrical use from August through November (95 W) since the average kitchen temperature over this period (82.4°F) closely matched the average annual kitchen temperature from the previous year. This equates to an annual electricity use from the new refrigerator of 833 kWh--approximately 10% greater than the DOE test value for this particular unit.

Fit of a multiple regression model to daily use data from the newer refrigerator found the same factors significant:

$$kWh = -5.05 + \underset{[29.45]}{0.084(KitchenTemp.)} + \underset{[16.17]}{0.0092(Door\ Openings)} \quad (2)$$

where:

kWh	=	daily refrigerator energy use kWh
Kitchen Temp	=	average daily kitchen temperature, °F
Door Openings	=	number of refrigerator door openings per day

$R^2 = 0.85$

The goodness-of-fit for the new refrigerator was superior, with 85% of the daily variation explained. Each degree of kitchen temperature increase was associated with an 8.4 Wh increase in refrigerator electricity use--a 31% lower value than for the original unit. The coefficient for the door openings (9.2 Wh each) was remarkably consistent with the previous value. Since average daily electricity use was 2.0 kWh with 42 average door openings, this indicates that refrigerator door openings were responsible for approximately 19% of the overall consumption in the

Table 2. Efficient Refrigerator Performance

Value	Mean	Std. Dev	Min	Max
Fresh-Food Temp (°F)	39.6	1.95	28.0	55.7
Freezer Temp (°F)	10.7	2.58	-4.1	24.8
Kitchen Temp (°F)	78.8	6.02	64.8	93.9
Daily Door Openings	41.9	26.6	0	130.0
Daily kWh	1.98	0.60	0.35	3.71
Electrical Demand (W)	82.7	42.1	12.6	93.9
4 - 5 AM (Standby Load)	71.5	34.3	28.8	230.4
8 PM (Maximum Demand)	103.8	47.8	36.0	243.0
Summer Electrical Demand (W)				
June - September	116.4	44.1	12.6	251.1
2 - 8 PM (Utility Peak Period)	125.6	4.1	55.8	247.5
5 - 6 PM (Coincident Peak)	117.4	46.1	57.6	247.5

newer unit. The remaining unexplained variation may be due to unmeasured effects such as food loading and length of door openings.

Measured Savings and Influence on Load Shape

The annual energy savings of the replacement refrigerator relative to the original unit totalled 1,130 kWh--a reduction in energy use of 57.6%.[4] Figures 5 and 6 show the comparative daily energy use of the two refrigerators as they varied with average kitchen temperature. The plot symbols are the number of times the refrigerator and freezer door were opened on each day. The regression lines from the fitted equations are shown along with the standard deviation of the prediction. The data show that the newer unit uses much less electricity on average, its demand is less sensitive to ambient temperature and its daily electricity use exhibits less variation in general than the original unit.

The seasonal nature of refrigerator electricity consumption is well established (Chang and Grot 1979; Meier and Heinemeier 1988; Nelson and Short 1990). Daily electricity use of the existing refrigerator exhibited strong seasonal variation. However, one advantage of the more efficient refrigerator was that its seasonal load varied less.

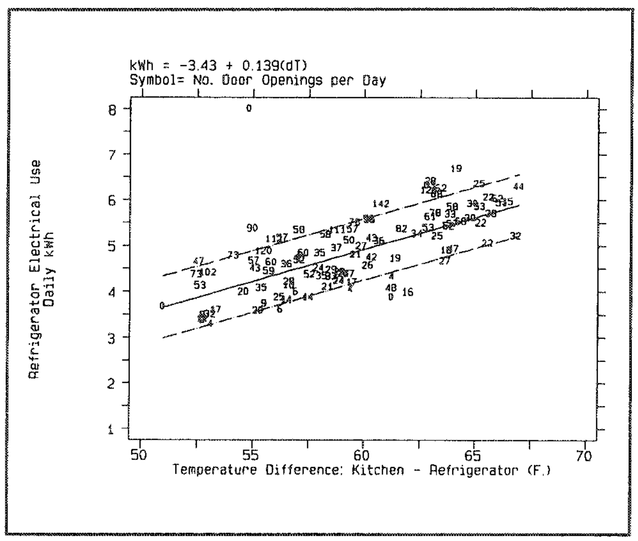

Figure 5. Variation of Existing Refrigerator Daily Energy Use with Kitchen Temperature and Door Openings

Figure 7 shows how the daily electricity use of the original refrigerator varied over the course of the year of monitoring. The lower plot of the replacement refrigerator in Figure 8, while necessarily incomplete due to the on-going status of the second year of monitoring, clearly shows much lower electricity consumption as well as less seasonal variation in use.

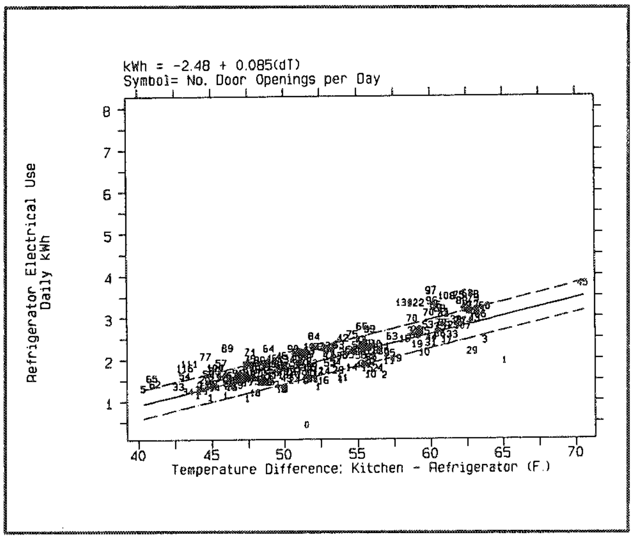

Figure 6. Variation of New Refrigerator Daily Energy Use with Kitchen Temperature and Door Openings

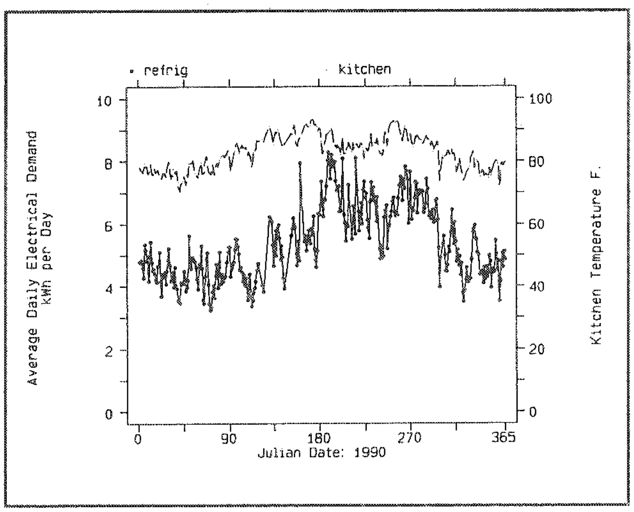

Figure 7. Seasonal Variation in Daily Electricity Use for Existing Refrigerator

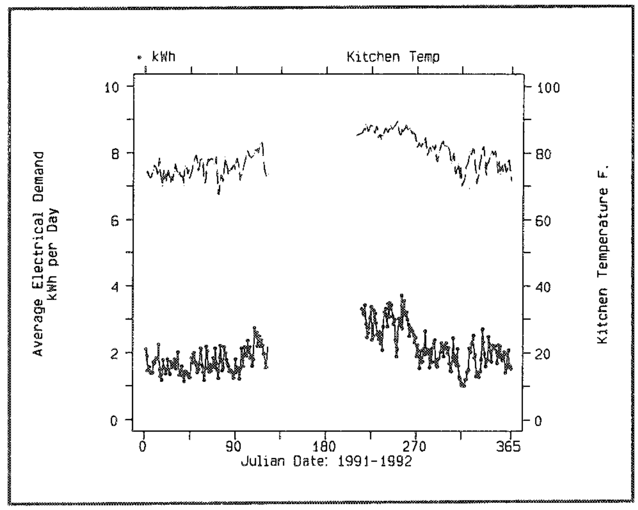

Figure 8. Seasonal Variation in Daily Electricity Use for New Refrigerator (8 months of available data)

A major objective of the study was to examine the effects of refrigerator replacement on electrical load shape. The upper two plots in Figure 9 depicts the electrical demand of the original refrigerator over the month of June, 1990. Even with the scatter, a time-of-day use pattern for the refrigerator is apparent; electrical demand is lowest in the early morning hours and highest at 8 PM after dinner preparation. The lower two graphs show the load shape for the hottest-month of August for the more efficient refrigerator. The average electrical demand is reduced by more than half (287 versus 122 Watts). Also depicted for both units are the average summer load profiles as a series of box plots. These graphs illustrate another advantage of the more efficient refrigerator: the load varies less throughout the course of the day. The average hourly load of the original refrigerator varied by almost 100 W, while the replacement unit's demand only fluctuated by 30 W throughout the daily cycle. Such characteristics may be desirable for utility planners who seek to smooth the overall daily end-use load profile.

A comparison of late-night stand-by electrical demand showed that the replacement unit used 36% of the energy consumed by the original model to maintain food storage at given temperature conditions without door openings. This likely results from a lower level of cabinet heat gain and a more efficient compressor. Reduction in utility coincident peak demand from 5-6 PM over the duration of the summer months was 59% or 166 W.

Assuming that similar reductions could be achieved for the 25% of Florida's refrigerator stock that is inefficient and awaiting replacement, the total state-wide peak demand reduction would amount to nearly 300 MW. Although this represents only a single study of refrigerator replacement efficiency potential, this goal may be attainable since utility programs which begin in the next year will enjoy the further savings brought about by the more stringent 1993 appliance standards.

Analysis of 1991 Refrigerator Energy Use Characteristics

Obviously, the above study represents an idealized case, since the existing refrigerator was replaced with a unit of an identical size and type. In a real-world setting the

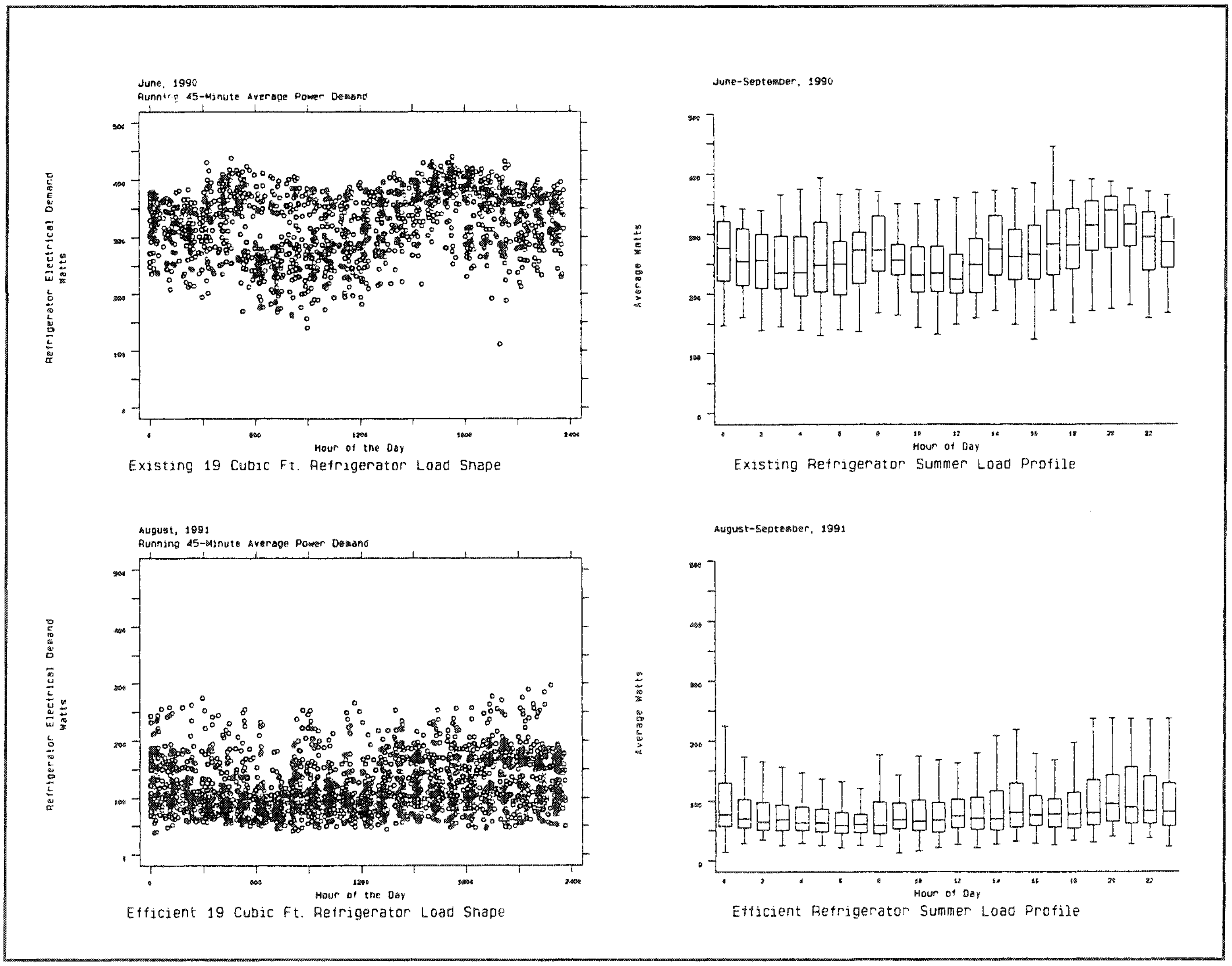

***Figure 9.** Comparison of Summer Variation in Hourly Electrical Demand for Existing Refrigerator (upper plots) and High-Efficiency Unit (lower plots)*

savings available from replacing older, less efficient refrigerators with newer models may be limited by the energy use characteristics of the new stock and how consumers select from the various options and features. Utility refrigerator programs face several potential hazards in this regard:

- Users may opt for a larger refrigerator which uses more electricity.
- Users may choose a refrigerator configuration that is less efficient.
- Users may select features that increase energy use.

A good illustration of these potential problems was evidenced in a new residential construction project which measured refrigerator energy use of "efficient" units against "base" units (Quaid et al. 1991). The study found no savings for the "efficient group" due to homeowner choice of larger refrigerators and those with more conveniences relative to the base group. We also note that many homeowners are selecting larger side-by-side units with though-the-door (TTD) ice and water dispensers. To determine the potential impact of such a tendency, we statistically examined all available refrigerators in the Association of Home Appliance Manufacturer's directory for 1991 (AHAM 1991). The 1,541 refrigerator-freezers were classified into eight distinct types based on their configuration and features (Table 3).

The data from the DOE tests are shown graphically in Figure 10. This plot displays the model type indexed against its annual estimated electrical demand and interior

Table 3. Comparison of 1,541 1991 Refrigerator Models by Type and Size

Configuration Description	No. Models	Volume cu ft	Avg. kWh	Normalized Use (kWh/cu ft)
0) Single-door, man. defrost	133	4.9	377.0	112.6
1) Single-door, auto. defrost	14	12.6	602.2	63.5
2) Side-by-side, auto. defrost	434	22.6	1251.2	55.6
3) Top freezer, partial auto. def.	36	12.3	708.2	62.1
4) Top freezer, automatic defrost	905	18.0	885.1	49.9
5) Bottom freezer, part. auto. def.	2	3.9	544.3	139.6
6) Bottom freezer, auto. defrost	14	21.1	1145.6	54.2
7) Top freezer, man. def., superins.	3	14.7	261.3	17.7
All types	1541	18.0	938.4	57.4

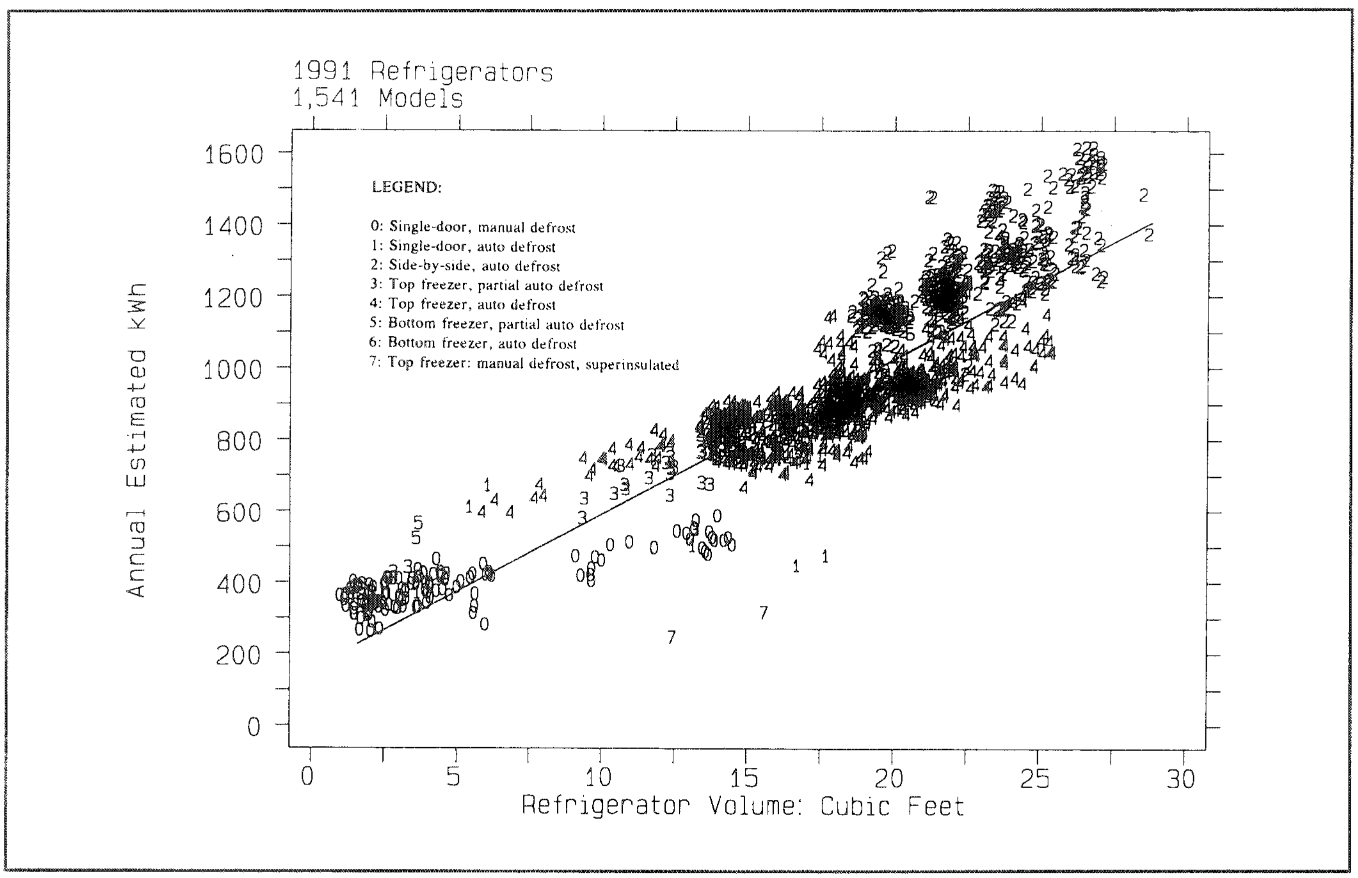

Figure 10. Comparison of the Electricity Use of All 1991 U.S. Refrigerator/Freezers by Size and Type

volume. The DOE test results have been shown to reasonably approximate real-world consumption of refrigerators, although some bias was evidenced by climate and vintage (Meier and Heinemeier 1988).[5] The scatter plot shows that consumption varies principally with the refrigerator size although substantial variation is seen by configuration type and by individual models. Two refrigerator configurations, top-freezer and side-by-side units with automatic defrost, make up 87% of the models produced--a nearly identical percentage of the total shipments that these two types comprised in 1990 (AHAM 1991b). However, the data show that the side-by-side models tend to be larger and use 11% more energy when corrected for the differences in interior volume. On average they use 41% more electricity on an absolute basis. This characterization mirrors a study of 119 sub-metered refrigerators which found that side-by-side units used 39 watts more than other refrigerator styles (131 W)--a 30% increase in electricity use (Ross 1991).

A statistical model was fit to the data to determine the magnitude and importance of the various configurations and design features. With annual DOE test kWh as the dependent variable the multiple regression model examined how refrigerator volume, defrost type and configuration influence energy use:

$$\begin{aligned} kWh = {} & \underset{[45.05]}{27.36(cubic\ feet)} + \underset{[25.69]}{554.3(auto\ def.)} \\ & + \underset{[23.78]}{528.3(part.\ auto\ defrost)} \\ & + \underset{[19.31]}{538.7(man\ def.)} - \underset{[11.17]}{296.5(single\ door)} \\ & + \underset{[4.32]}{79.2(side\text{-}by\text{-}side)} \\ & - \underset{[9.01]}{162.8\ (top\ freezer)} - \underset{[11.21]}{515.8\ (superinsulated)} \end{aligned} \tag{3}$$

$R\text{-}squared = 0.929$
$n = 1{,}541$

The fit is good, with the resulting equation predicting nearly 93% of the observed variation in the DOE test results. The major influences on refrigerator energy use are their volume, configuration type and insulation level. Each cubic foot of interior volume was estimated to increase annual electricity use by 27.4 kWh. Single door and top freezer units were most efficient. Single door units generally have a smaller door seal area (lower heat gain) and bottom mounted freezer units suffer reduced efficiency from the increased power to move cold air to the top of the fresh food compartment and the supplemental heaters in the crisper to prevent food freezing. Side-by-side units were least efficient, likely due to their greater door seal area and the proximity of the freezer floor to the hot motor compartment containing the compressor and condenser. The superinsulated, manual defrost, dual-compressor units use much less electricity than average.

Energy Use Attributable to Convenience Features

Noting the increasing popularity of side-by-side refrigerators we performed a study comparing the DOE test predicted energy use of models from individual manufacturers which have units which only differ by the presence of through-the-door (TTD) features. The DOE test is identical both types of units. A total of 24 such matched pair models were discovered by examining manufacturers' literature. A statistical comparison of the data in Table 4 and Figure 11 shows that TTD features increased DOE test estimated electricity use by an average of 10.3% (120 kWh/year).

Table 4. Comparison of 24 Side-by-Side Refrigerators: Matched Pair Annual kWh with and without TTD

Case	Avg. Ann. kWh
Without TTD Feature	1166.5
With TTD Feature	1286.5
Difference	120.0
Percent Increase	10.3%

A fundamental question, yet to be answered, is how this increase is ameliorated by the reduced opening of the freezer and main food compartment to obtain ice and chilled water. Based on our data, and from other sources, it appears that refrigerator door openings make up a relatively small fraction of overall refrigerator thermal load. One detailed study showed that reducing fresh food and freezer compartment door openings by 50% (40 fewer openings each day) lowered electrical demand by only 11% at an 85°F ambient temperature (Alissi et al. 1988). Another study showed only a 6% increase in electricity consumption associated with a reasonable schedule of door openings over closed only operation (Grimes et al. 1977).

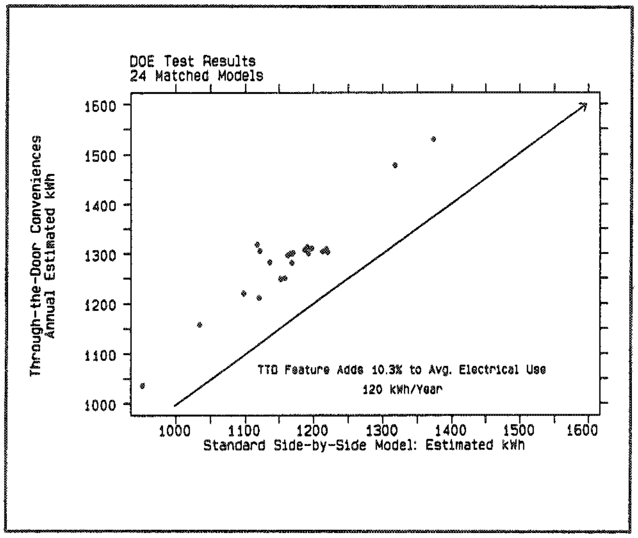

Figure 11. Matched Pair Comparison of Electricity Use of Side-by-Side Refrigerators with and without Through-the-Door Features

Since the realized reductions in door opening from TTD features is likely to be less than 50%, such conveniences may actually *increase* consumption over units without them. On the other hand, side-by-side refrigerator-freezers may be more efficient in application if the larger freezer compartment can obviate the need for a separate household food freezer.

Automatic ice makers are also becoming a highly desirable convenience for refrigerator-freezers. Ice-makers are often an add-on feature to refrigerators and the DOE test procedure does not take their use into account when estimating energy use. However, measurements made using the test procedure showed that ice-makers can increase test estimated energy use by up to 20% when operated continuously (BR Laboratories 1986).

Ice maker use in the replacement refrigerator was monitored over a period of one week. Each cycle of the ice-maker was found to produce 8 ice cubes with a weight of almost exactly 0.5 lbs. Maximum ice production was measured at 4.4 pounds per day (9 cycles). Operation over a one-week spring period averaged 5.7 cycles per day. Demand for ice in a hot climate like Florida may be greater than other regions; another study of a single refrigerator in Gaithersburg, Maryland found 2.4 ice-maker cycles per day (Wise 1983). Assuming a 70°F temperature difference between the supply tap water and the freezer interior, along with the latent heat of fusion of ice amounts to a thermal load of 31 Watt-hours (Wh) per cycle. To this must be added the energy use of the 165 W ice mold-heater, which operates for approximately 1 - 2 minutes each cycle. Total ice-maker average electricity use is approximately 36 Wh per cycle or 132 Wh per day at the compressor's coefficient of performance. With the given unit, the ice maker is probably responsible for approximately 6% of the refrigerator's electricity use. An unanswered question, however, is to what extent the availability of an ice maker and TTD features may increase the household demand for ice.

These results underscore the need for higher efficiency refrigerators which incorporate such conveniences. Projects such as the "Golden Carrot" Super-Efficient Refrigerator Program (SERP) should ensure that side-by-side models and improvements to convenience features are not overlooked in the quest for improved efficiency. To ignore consumer demand for such conveniences will miss mainstream efficiency improvement opportunities.

Conclusions

A two-year field study in Florida showed that large savings were available from replacement of a 1974-vintage 19.2 cubic foot refrigerator-freezer with the most efficient unit currently available of its size and type. Both refrigerators have a top-mounted freezer with an ice-maker and automatic defrost. The original refrigerator was monitored for a full year with data recorded at 15-minute intervals. The newer, more efficient refrigerator has been monitored for eight months.

The existing refrigerator was found to use 1,963 kWh over a year or fully 25% of the home's overall electricity use. The DOE estimated energy consumption of the new efficient model (763 kWh) is within 10% of the more stringent 1993 appliance efficiency standards for a refrigerator of its size. Likely due to Florida's warmer climate, the monitored energy use of the new refrigerator (833 kWh) was approximately 10% greater than that suggested by the DOE test label. Measured annual electricity consumption was reduced by 1,130 kWh--a reduction of 58%.

Both refrigerators exhibited seasonal variation in energy consumption as well as a changing load profile over the daily cycle. Maximum monthly energy consumption occurred in August with the maximum daily electrical demand from 7 to 8 PM. The improvement in the utility coincident peak demand at 5-6 PM from the refrigerator replacement amounted to 166 Watts, a 59% decrease. Assuming that similar reductions could be achieved for the 25% of Florida's refrigerator stock that is inefficient and awaiting replacement, the total peak demand reduction would amount to nearly 300 MW.

The savings available from replacing older, less efficient refrigerators with newer models may be limited, however, by the energy use characteristics of the new stock and how consumers select from the various features. Users may opt for larger refrigerators, less-efficient configurations or convenience features that increase energy use. A statistical analysis was performed on the characteristics of all 1,541 available refrigerators in 1991 to determine potential impacts. Our findings concluded that:

- Top-freezer and side-by-side units comprise 87% of the units produced.
- Manual and partial automatic defrost units use less electricity.
- Units with top mounted freezers are more efficient (160 kWh/yr)
- Side-by-side units tend to be larger and use 41% more electricity.
- Through-the-door features increase consumption by roughly 10%.
- Superinsulated units use half as much energy as comparable types.
- Ice-makers can increase refrigerator energy use by 6% or more.

The study concludes electrical efficiency gains from refrigerator replacement are potentially large. However, efforts to further improve refrigerator efficiency should address the increasing consumer demand for conveniences such as side-by-side units with ice makers and through-the-door features to capture mainstream efficiency opportunities.

Acknowledgments

Thanks to Sam Beach, Senior Research Engineer for the Frigidaire Company and Sharon Barata with the Florida Power and Light Company for their helpful assistance.

Endnotes

1. Other manufacturers selling the same model under different brand names includes Gibson, Tappan and White-Westinghouse.

2. Timing of the refrigerator peak electrical demand (7 - 8 PM) is similar to that measured in the NBS field study of 10 refrigerators (Chang and Grot 1979) and of sixty units sub-metered in the Pacific Northwest (Pratt et al. 1989).

3. Under procedures established by the National Appliance Energy Conservation Act (NAECA), the adjusted volume is equal to 1.63 times the freezer space plus the volume of the fresh food compartment. The maximum allowable DOE test estimated energy use (kWh) for the 1993 standard for top-mounted-freezer refrigerators with automatic defrost is equal to 355 + 16.0 (Adjusted Volume).

4. In a larger sense, the total savings attributable to the refrigerator should also include any interactions with the house space heating and cooling since all electricity use ends up as waste heat within the structure. In Florida's hot climate, reductions to appliance energy usage are a decided advantage. For the average household the air conditioning season is four months with approximately one month of overall heating in the winter. Assuming a delivered heat pump COP of 2 - 3 (including duct losses), each 1,000 kWh of appliance electrical savings could lead to a further 80 - 130 kWh decrease in the space conditioning budget.

5. The DOE test procedure measures 24-hour refrigerator electricity use in a 90°F environmental chamber. The artificially high ambient temperature is intended as a surrogate correction for the influence of door openings and food loading which are not part of the test protocol.

References

AHAM, 1991., "1991 Consumer Selection Guide for Refrigerators and Freezers," Association of Home Appliance Manufacturers, Chicago, IL.

AHAM, 1991b., "Refrigerators: Energy Efficiency and Consumption Trends," Association of Home Appliance Manufacturers, Chicago, IL.

Alissi, M.S., Ramadhyani, S., and Schoenhals, R.J., 1988. "Effects of Ambient Temperature, Ambient Humidity, and Door Openings on Energy Consumption of a Household Refrigerator-Freezer," *ASHRAE Transactions*, Vol. 88, Pt. 2, Atlanta, GA.

BR Laboratories, 1986. *Final Report on Laboratory Testing of Certified Refrigerator/Freezers*, prepared for the California Energy Commission, Agreement No. 400-84-011, Huntington Beach, CA.

Brodsky, J.B., and McNicoll, S.E., 1987. *Residential Appliance Load Study*, Pacific Gas and Electric Company, Research Section, Berkeley, CA.

Chang, Y.L., and Grot, R.A., 1979., *Field Performance of Residential Refrigerators and Combination Refrigerator Freezers*, NBSIR 79-1781, National Bureau of Standards, Washington D.C.

Grimes, J.W., Mulroy, W., and Shomaker, B.L., 1977. "Effect of Usage Conditions on Household Refrigerator-Freezer and Freezer Energy Consumption," *ASHRAE Transactions*, Vol. 83, Pt. 1, Atlanta, GA.

Meier, A.K., and Heinemeier, K.E., 1988. "Energy Use of Residential Refrigerators: A Comparison of Laboratory and Field Use," *ASHRAE Transactions*, Vol. 94, Pt.2, Atlanta, GA.

Messenger, R., Hays, S., Duyar, A., Trivoli, G., Vincent, J., Guttman, M., Robinson, J., Litschauer, B., Jarvis, J., and Pages, E., 1982. *Maximally Cost Effective Residential Retrofit Demonstration Program*, prepared for the Florida Public Service Commission, Florida Atlantic University, Boca Raton, FL.

Nelson, P., and Short, J., 1990. "Analysis of 12 Japanese Refrigerators in the Northwest," Vol. 1, *Proceedings of the 1990 Summer Study on Energy Efficiency in Buildings*, American Council for an Energy Efficient Economy, Washington D.C.

Pratt, R.G., Conner, C.C., Richman, E.E., Ritland, K.G., Sandusky, W.F., Taylor, M.E., 1989. *Description of Electric Energy Use in Single-Family Residences in the Pacific Northwest: End-Use Load and Consumer Assessment Program (ELCAP)*, Bonneville Power Administration, DOE/BP-13795-21, Portland, OR.

Ross, B.A., 1991. *End-Use Load and Consumer Assessment Program: Analysis of Residential Refrigerator/Freezer Performance*, Pacific Northwest Laboratory, PNL-7656, Richland, WA.

Turiel, I., and Heydari, A., 1988. "Analysis of Design Options to Improve the Efficiency of Refrigerator-Freezers and Freezers," *ASHRAE Transactions*, Vol. 94, Pt. 2, Atlanta, GA.

Turiel, I., Berman, D., Chan, P., Chan, T., Koomey, J., Lebot, B, Levine, M.D., McMahon, J.E., Rosenquist, G., and Stoft, S., 1990. "U.S. Residential Appliance Efficiency: Present Status and Future Directions," Vol. 1, *Proceedings of the 1990 Summer Study on Energy Efficiency in Buildings*, American Council for an Energy Efficient Economy, Washington D.C.

Quaid, M., Kunkle, R., and Lagerberg, B., 1991. *Residential Conservation Demonstration Project Cycle 2 Appliance Analysis*, Washington State Energy Office, Olympia, WA.

Spolek, G.A., 1985. *Field Performance of Refrigerators*, Bonneville Power Administration, Portland, OR.

U.S. DOE, 1989. *Technical Support Document: Energy Conservation Standards for Consumer Products: Refrigerators and Furnaces*, DE/90-003491, U.S. Department of Energy, Washington D.C.

Wise, R.A., *Field Performance Test Results on the Performance of a Refrigerator-Freezer in a Single Family Residence*, NBSIR 83-2653, National Bureau of Standards, Washington D.C.