Factors Affecting the Energy Consumption of Two Refrigerator-Freezers

James Y. Kao, P.E.
Member ASHRAE

George E. Kelly, Ph.D.
Fellow ASHRAE

ABSTRACT

Two refrigerator-freezers, one with a top-mounted freezer and one with side-by-side doors, were tested in the laboratory to determine the sensitivity of their energy consumption to various operational factors. Room temperature, room humidity, door openings, and the setting of the anti-sweat heater switch were the factors examined. The results indicated that the room temperature and door openings had a significantly greater effect on energy consumption than the other two factors. More detailed tests were then performed under different room temperature and door-opening combinations. The relationship of door openings and the equivalent test room temperature was established. Finally, the effect on energy of different temperature settings was studied. Test results are presented and discussed.

INTRODUCTION

The Association of Home Appliance Manufacturers (AHAM) has a standard (AHAM 1988) governing the thermal and energy-testing requirements of refrigerator-freezers manufactured in the U.S. by their members. The U.S. Department of Energy (DOE) has set minimum energy consumption standards (DOE 1990) for refrigerator-freezers sold in this country. The DOE energy standards require that refrigerator-freezers be tested in accordance with test procedures (DOE 1982) issued by DOE. The energy test procedures of AHAM and DOE are similar. Periodically, DOE updates the energy standards and reviews the test procedures for possible changes in new technology and materials used in the manufacture of refrigerator-freezers. The National Institute of Standards and Technology (NIST) assists DOE in maintaining and refining the test procedures.

The DOE refrigerator-freezer test procedure specifies that the appliance be installed in a test room maintained at 32.2°C (90°F) during testing. The reason for elevating the test room temperature above the temperature corresponding to normal household conditions is to compensate for not storing food in the refrigerator-freezers and for not opening the refrigerator-freezer doors during the tests. This substantially simplifies testing requirements.

In the DOE test procedure, the standard temperature for a refrigerator-freezer is specified as −15°C (5°F) in the freezer compartment. Two tests are required. The first test is performed with both compartment temperature controls set at the midpoints between the warmest and the coldest settings, and a second test is performed with both controls set at either their warmest or their coldest settings in an attempt to achieve the freezer temperatures measured during the two tests that bound the specified −15°C (5°F) freezer compartment temperature. For refrigerator-freezers having automatic defrost, the energy consumption is measured from one point during a defrost period to the same point during the next defrost period and is normalized to a 24-hour day. If the food compartment temperature is at or below 7.2°C (45°F) and the freezer temperature is at or below −15°C (5°F) in both of these tests, the final reported energy consumption is the warmest temperature-setting results. If these two conditions are not met, the per-day consumptions are adjusted for the inside temperature differences. Depending on the inside temperatures, two adjustment calculations are required using the results of the tests with the temperature controls set at the midpoint position, the warmest position, and/or the coldest position. One adjustment prorates the energy consumptions to 7.2°C (45°F) in the food compartment, and the other prorates the energy consumption to −15°C (5°F) in the freezer compartment. The final reported energy consumption is the higher value of the two adjusted levels.

Numerous studies have been conducted on the energy consumption characteristics of refrigerator-freezers (Alissi et al. 1988; Gage 1995; Grimes et al. 1977; Parker and Stedman 1992; Meier et al. 1993; Meier 1995; Proctor 1993; Wong et al. 1995). Questions have been raised as to whether raising the test room temperature to 32.2°C (90°F) is an appropriate compensation for

James Y. Kao and **George E. Kelly** are engineers in the Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Md.

not loading food in the refrigerator-freezers and for not opening doors during the tests. Questions have also been raised about whether a better way can be found to improve the method of adjusting the energy consumption caused by the compartmental temperature differences from the standard temperatures. These concerns prompted this study.

DESCRIPTION OF THE TEST REFRIGERATOR-FREEZERS

Two household refrigerator-freezers were tested in NIST laboratories. One refrigerator-freezer was a top-mounted-freezer unit with a total volume of 0.614 m^3 (21.7 ft^3) and was manufactured in 1992. The other refrigerator-freezer was a model with side-by-side doors with a total volume of approximately 0.566 m^3 (20 ft^3) and was manufactured in 1991. Both units were made by the same manufacturer and had their temperature-sensing bulbs for the compressor controls located in the food compartments. The freezer temperatures on these units were controlled by air dampers that apportion the cold air from the evaporator between the food and the freezer compartments. Automatic defrost for both units was initiated by 10-hour timers that were energized whenever the compressors were running or when the defrost cycles were operating. The electrical defrost coils were 545 W and 402 W (at 120 volts), respectively, for the top-mounted-freezer and side-by-side-door units. The top-mounted-freezer unit had a user-selectable on/off switch for a 11.5 W (at 120 volts) anti-sweat heater for the control of mullion condensation. The side-by-side-door unit had no electric anti-sweat heater.

DESCRIPTION OF THE TEST FACILITY

The refrigerator-freezers were tested in a temperature- and humidity-controlled environment room. A personal-computer-based data-acquisition and control system was used to record time, temperature, the status of compressors, and the status of defrost, and to issue door-opening commands. Watt-hour meters with digital readouts were used to record energy consumption. The refrigerator-freezer door-opening action was accomplished through pneumatic motor actuators that were controlled by the personal computer.

Thermocouples were used for measuring the test room temperature and the inside temperature of the two refrigerator-freezer compartments. They were installed in accordance with the AHAM standard. All temperature readings and the status of compressors and defrost were recorded at 90-second intervals. The recorded test room and compartment temperatures were averaged for data analysis. The compartment temperatures were averaged for the entire cycles between defrosts, except for the pull-down period immediately following completion of the first defrost. The watt-hour meters were wired in such a way that they recorded the energy consumption from the end of one defrost cycle to the end of the next defrost cycle.

EXPERIMENTAL DESIGN

A three-stage experiment was designed for this study. The first stage identified the most important operating factors that affect refrigerator-freezer energy consumption. The second stage involved additional tests to quantify the effect of the factors identified in the first stage. The advantage of this two-stage design, compared to varying each factor one at a time, was to reduce the overall number of test runs required and to concentrate more effort on tests that involved the most important factors. The last stage was to study the energy by varying the refrigerator-freezer temperature settings and the test room temperature.

First-Stage Tests—A Sensitivity Study

A two-level factorial design (Box [1978] or other books on experimental design) was employed for the sensitivity study. A commercially available statistical analysis and plotting computer program was used to generate the statistical data. The test room temperature, the test room humidity, the number of door openings, and the status of the anti-sweat heater (on the top-mounted-freezer unit only) were initially assumed to be important factors in refrigerator-freezer energy use. Food loading was not included in the study for lack of reliable user data on the type and amount of food and its storage arrangements. For a full factorial study, 16 test runs were required for the top-mounted-freezer unit and 8 runs were required for the side-by-side-door unit. Two levels of the factor values were employed. They were 21.1°C (70°F) and 32.2°C (90°F) for the room temperature, 30% and 50% relative humidity (RH) for the room humidity, 0 and 3 door openings per hour for the food compartment doors (see below for a discussion of the freezer door-opening rates), and "off" and "on" for the anti-sweat heater.

The test room temperature of 32.2°C (90°F) was used as the high value so that the DOE test condition would be included. The room relative humidity values were selected as a compromise. If humidity ratios were used as the humidity factor, test conditions would be unrealistically humid at the low temperature (95% RH at 21.1°C [70°F]) and somewhat low at the high temperature (16% RH at 32.2°C [90°F]). With the room temperatures and the relative humidities combined, the humidity ratios in the test room were 15.2 g/kg dry air (0.0152 lb/lb dry air) at 32.2°C (90°F) and 50% RH, 9.0 g/kg dry air (0.0090 lb/lb dry air) at 32.2°C (90°F) and 30% RH, 7.8 g/kg dry air (0.0078 lb/lb dry air) at 21.1°C (70°F) and 50% RH, and 4.6 g/kg dry air (0.0046 lb/lb dry air) at 21.1°C (70°F) and 30% RH.

The number of door openings during the test runs were based on a study by Chang and Grot (1979). This study of 10 townhouses in a housing development had an average of 2.03 food compartment door openings per hour, with a median of 2.25 openings per hour over 24 hours. In the same study, the ratio of the average door openings per hour of the food compartment to door openings per hour of the freezer compartment was 4.84. In this investigation, the high rate of freezer door openings that was tested along with the food compartment door opening rate of 3 openings per hour was 0.6 openings per hour (a ratio of 5). These values were arbitrarily set higher than the Chang study to exaggerate the energy effect of door openings. Both the food compartment and freezer doors were open for approximately 20 seconds each time, which is similar to Chang's average data of 21.2 seconds for the food compartment doors and 19.9 seconds for the freezer doors. Tests involving 0 door openings per hour of the food compartment also had 0 door openings per hour of the freezer compartment. All test runs in the first stage had the food compartment and the freezer temperature controls set at their midpoints.

Second-Stage Tests—Experiments Combining Temperatures and Door Openings

The first-stage sensitivity study identified the room temperature and door openings as the most important factors affecting energy consumption of the two refrigerator-freezers tested. Based on this conclusion, the second-stage testing concentrated only on the test room temperature and door openings, with tests conducted using various combinations of these two factors. First, 20 test runs were conducted with both the compartment temperature controls set at their midpoints. These tests included all combinations of five levels of room temperatures from 21.1°C (70°F) to 32.2°C (90°F) in steps of 2.8°C (5°F) and four door-opening schedules of 0, 1, 2, and 3 openings per hour for the food compartments. *In each of these tests, the opening rate of the freezer doors was set at one-fifth that of the food compartment.*

Third-Stage Tests—Varying Refrigerator-Freezer Temperature Settings

Energy consumption tests were conducted by varying the temperature control settings of the food and freezer compartments for different room temperatures. The refrigerator-freezer temperature settings included coldest/coldest (C/C),[1] coldest/warmest (C/W), warmest/warmest (W/W), and warmest/coldest (W/C). These settings were combined with five room temperatures (between approximately 21°C [70°F] and 32°C [90°F] at approximately 2.8°C [5°F] intervals) for the top-mounted-freezer unit and four room temperatures (between approximately 24°C [75°F] and 32°C [90°F] at approximately 2.8°C [5°F] intervals) for the side-by-side-door unit. All these tests were conducted with the doors closed.

DISCUSSION OF RESULTS

Results are described below for each of the three experimental stages.

First-Stage Test Results

Comparison of model and test results are shown in Table 1. A full-term factor screening analysis model for the side-by-side-door unit has the form

$$E = \mu + 1/2(\beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{123} X_1 X_2 X_3) + \varepsilon,$$

where

E = 24-hour energy consumption of the refrigerator-freezer (kWh),

μ = average 24-hour energy consumption from the test results (kWh),

β = coefficient (effect) of response terms determined by screening study (kWh),

X = sensitivity factor described below (+ for high or – for low), and

ε = error.

The $\beta_i X_i$ terms represent the effects of single sensitivity factors. The $\beta_{ij} X_i X_j$ and $\beta_{ijk} X_i X_j X_k$ terms show the effect of the interactions among two and three different factors.

In the side-by-side-door unit case, X_1 was the door opening, X_2 was the test room humidity, and X_3 was the test room temperature. The mean effects of these single factors and the interaction of two factors are shown in Figure 1. Each box in Figure 1 shows the mean effect of an individual energy-affecting factor or the interaction of these factors. The dotted line in each box is the mean energy consumption of all tests. The two heavy dots in each box represent the means of energy consumption tested at the high and low values of the energy-affecting factor. The numerical difference of these two values is shown in the box after the factor symbol. For example, the lowest box in the rightmost column is for the test room temperature (X_3). The mean energy consumption difference between 32.2°C (90°F) and 21.1°C (70°F) of all tests was 1.337 kWh/day, which is indicated after the symbol X_3. The dotted line is at 2.216 kWh/day, which is the mean energy consumption of all tests. The box above the lowest rightmost box shows the effect of the interaction between the test room humidity (X_2) and the test room temperature (X_3).

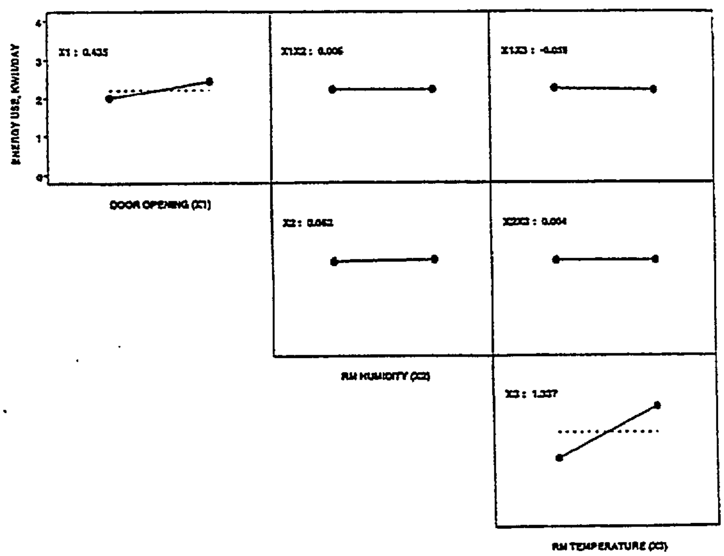

Figure 1 Energy effect of the side-by-side-door unit.

1 Throughout this paper, control settings designated "A/B" refer to an "A" temperature control setting of the food compartment and a "B" temperature control setting of the freezer compartment, where A and B can take a value of the "coldest" (C), "midpoint" (M), or "warmest" (W) setting.

The slopes of the lines in Figure 1 and the accompanying numbers in the boxes provide an easy comparison of the relative effects of all energy-affecting factors and their interactions. It can be seen from this figure that the room temperature had the greatest effect, door openings had the next greatest effect, and the room humidity and all interactions had minimal effects. The same conclusion may also be drawn from the half-normal probability plot shown in Figure 3a. Half-normal probability plots with absolute values of response effects on the y-axes were used to identify factor and interaction effects in screening processes. Any point of an effect that lies far away from a straight line formed by the majority of other points is a major effect. In Figure 3a, the test room temperature effect (X_3) and the door-opening effect (X_1) are noticeably away from the straight line formed by the bottom four points. Thus, the full screening model can be reduced to a partial model involving only the terms of test room temperature and door openings. The simplified equation is of the form:

$$E = 2.216 + 0.5(1.337X_3 + 0.435X_1)$$

with a residual standard deviation of 0.060 kWh/day. The units of the terms in this equation are the same as given previously for the full model.

A similar procedure was applied to the test data from the top-mounted-freezer unit. In this case, the number of door openings, the room humidity, the test room temperature, and the status of the anti-sweat heater were designated as X_1, X_2, X_3, and X_4, respectively. Figure 2 shows the effects of individual factors and their interactions. Figure 3b shows the half-normal probability plot of the effects. Again, room temperature had the greatest effect, followed by (in order of their effect) the door openings, the test room temperature/door-opening interaction, and the anti-sweat heater. The final partial model can be reduced to the form:

$$E = 1.876 + 0.5(1.016X_3 + 0.652X_1 + 0.278X_1X_3 + 0.239X_4)$$

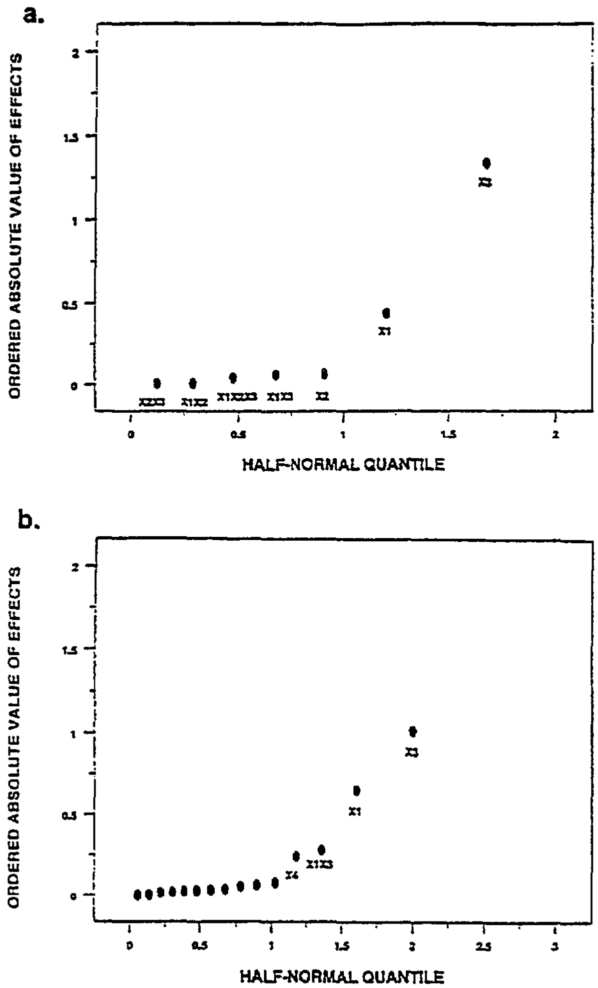

Figure 3 3a) Side-by-side door unit; 3b) half-normal probability plot.

with a residual standard deviation of 0.080 kWh/day. Again, the same units for the full model given previously also apply to this equation.

Comparisons of the test energy consumption data of these two refrigerator-freezers to those calculated from the partial models are shown in Table 1. The test energy amounts listed in the table are the means of measurements at high and low humidities.

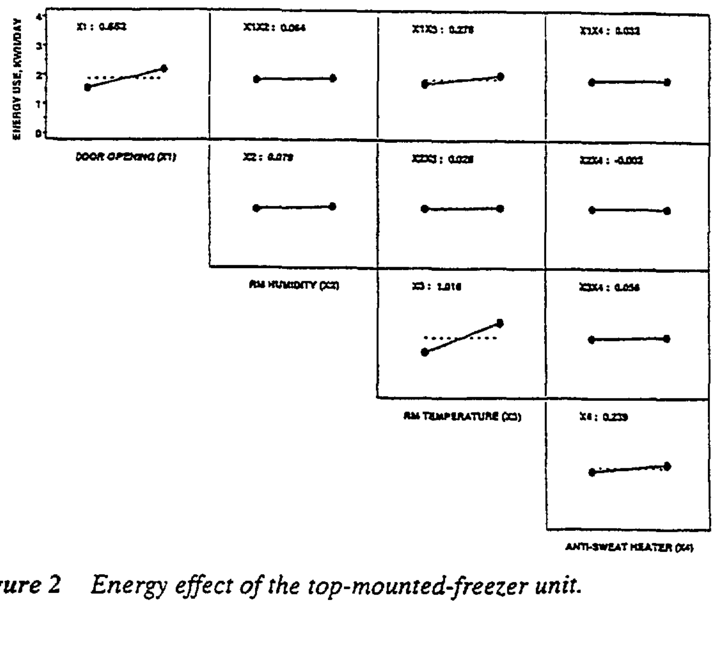

Figure 2 *Energy effect of the top-mounted-freezer unit.*

From the results indicated in Figures 2 and 3, the mean energy effects from the test room temperature for the side-by-side-door and top-mounted-freezer units were 120 and 91 Wh/day per °C (66.7 and 50.8 Wh/day per °F), respectively, which are similar to the average change of 106 Wh/day per °C reported by Meier (1995). The mean energy effects from door openings for these two units were 145 and 217 Wh/day per each food compartment door opening per hour (with a 0.2 freezer door opening per hour), respectively. These are equivalent to 5 and 7.5 Wh per individual door opening. It was not clear why the top-

TABLE 1 Energy Comparison of Model and Test Results

1a Top-Mounted-Freezer Unit								
Door Status	Open	Open	Open	Open	Closed	Closed	Closed	Closed
Room Temperature	32.2C (90 F)	32.2C (90 F)	21.1C (70 F)	21.1C (70 F)	32.2C (90 F)	32.2C (90 F)	21.1C (70 F)	21.1C (70 F)
Anti-Sweat Heater	On	Off	On	Off	On	Off	On	Off
Model, kWh/day	2.968	2.730	1.674	1.435	2.038	1.799	1.301	1.062
Measured, kWh/day	2.994	2.703	1.681	1.427	2.068	1.769	1.256	1.124
Deviation	-0.9%	1.0%	-0.4%	0.6%	-1.5%	1.7%	3.5%	-5.6%

1b Side-by-Side Door Unit				
Door Status	Open	Closed	Open	Closed
Room Temperature	32.2C (90 F)	32.2C (90 F)	21.1C (70 F)	21.1C (70 F)
Model, kWh/day	3.102	2.668	1.765	1.331
Measured, kWh/day	3.073	2.697	1.795	1.301
Deviation	0.9%	-1.1%	-1.7%	2.3%

mounted-freezer unit used much more energy during door-opening tests than the side-by-side-door unit. The anti-sweat heater's use of the top-mounted-freezer unit caused an energy use of 239 Wh/day.

The conclusion drawn from these analyses was that the test room temperatures and the door openings and their interactions (for the top-mounted-freezer unit) were the most significant energy-affecting factors. For the top-mounted-freezer unit with an anti-sweat heater, the status of the anti-sweat heater had a slightly smaller effect on refrigerator-freezer energy consumption.

Second-Stage Test Results

In planning the second-stage tests, it was decided that the tests should concentrate on the effect of the two major energy-affecting factors—room temperature and door openings. The anti-sweat heater in the top-mounted freezer was not included in the second-stage tests since it had a smaller effect than the other two effects and, more important, the heaters are often switched off during part of the year by the users. The test room humidity was allowed to float between 30% and 40% RH during the second-stage tests. In combining the five temperature levels and four door-opening schedules, 20 test runs (5 × 4) were conducted for each of the two refrigerator-freezer units. These tests were run with the compartment temperature settings fixed at the midpoint marks of the control dials.

Table 2 lists the test data for these tests. Linear regression analyses were first performed to find the relationship between energy consumption and room temperature for various door-opening rates. The regression equations are of the form.

$$E = b_0 + b_1 T_r$$

where E is the daily energy consumption (in kWh/24 hours), T_r is the room temperature (in °F), b_0 is the intercept of the regression line, and b_1 is slope of the regression line. The values of b_0 and b_1 as well as the coefficients of determination of the regressions, r^2, are shown in the following table. Note that the door openings shown are for food compartment doors.

Refrigerator	Test	b_0	b_1	r^2
Top-Mounted-Freezer	Doors closed	−0.969	0.0321	0.983
	One opening per hour	−1.093	0.0363	0.977
	Two openings per hour	−1.488	0.0435	0.947
	Three openings per hour	−2.143	0.0535	0.972
Side-By-Side Door	Doors closed	−2.037	0.0483	0.998
	One opening per hour	−2.028	0.0511	0.993
	Two openings per hour	−1.784	0.0504	0.984
	Three openings per hour	−2.363	0.0604	0.988

Using the door-closed equations, the energy consumption per day may be calculated for the DOE room condition (i.e., 32.2°C [90°F]). The values calculated were 1.919 and 2.313 kWh/day, respectively, for the top-freezer and side-by-side-door refrigerator-freezers. Substituting these values of E in the equations with various door openings, one obtains the equivalent room temperatures for different door-opening schedules that would give the same energy consumption obtained with the DOE test conditions. For the top-freezer unit, the equivalent room temperatures are 28.3°C (83.0°F), 25.8°C (78.4°F), and 24.4°C (75.9°F) for one, two, and three food compartment door openings per hour, respectively. Likewise, the side-by-side-door unit has equivalent room temperatures of 29.4°C (84.9°F), 27.4°C (81.3°F), and 25.3°C (77.5°F) for one, two, and three food compartment door openings per hour, respectively. Second-order models, then, were fitted using these room temperature and door-opening pairs. The regression equations are

$$T_r = 89.99 - 8.07(\mathrm{DO}) + 1.13(\mathrm{DO})^2$$

(coefficient of determination, $R^2 = .999$) for the top-freezer unit and

$$T_r = 89.92 - 5.09(\text{DO}) + 0.325(\text{DO})^2$$

(coefficient of determination, R^2 = .998) for the side-by-side door unit, where T_r is the test room temperature (in °F) and DO is the number of door openings per hour for the food compartment doors.

These regression equations are shown in the top figure in Figure 4. They show the relationship between the room temperature and the number of food compartment door openings for these two refrigerator-freezers that give the same energy consumption as obtained using the DOE test conditions of zero door openings and a room temperature of 32.2°C (90°F). For a given set of door openings of the freezer and food compartments (they are in the ratio of 1 to 5), one can obtain the equivalent test room temperature for these two refrigerator-freezers. For example, at a food compartment door-opening rate of one and one-half openings per hour, the equivalent test room temperatures for the top-freezer and side-by-side-door units are 26.9°C and 28.3°C (80.4°F and 83.0°F), respectively.

The same procedure can be followed using other door-opening rates and room temperatures for the energy calculations. Thus, using the two-openings-per-hour equations with an assumed yearly average kitchen temperature of 23.9°C (75°F), the energy consumptions are calculated to be 1.772 and 1.995 kWh/day for the two units. This average kitchen temperature assumes an air-conditioned and heated house and may not depart too far from the majority of houses in the northern part of the country. The room temperature and door-opening regression equations are given by

$$T_r = 85.4 - 7.53(\text{DO}) + 1.15(\text{DO})^2$$

for the top-mounted-freezer unit and

$$T_r = 83.4 - 5.16(\text{DO}) + 0.48(\text{DO})^2$$

for the side-by-side-door unit.

These relationships between room temperature and the number of food compartment door openings for the two units that give the same energy consumption as two door openings at a room temperature of 23.9°C (75°F) are shown in the lower figure in Figure 4. Assuming a 23.9°C (75°F) yearly average kitchen temperature and two door openings per hour, the closed-door condition would give equivalent test room temperatures of 29.7°C and 28.6°C (85.4°F and 83.4°F), respectively, for the top-mounted-freezer and side-by-side-door refrigerator-freezers. The average of these two temperatures is 29.1°C (84.4°F), which is 3.1°C (5.6°F) below the current DOE test room temperature.

Comparing the energy consumption results at the DOE test conditions (1.919 and 2.313 kWh/day) with the energy

TABLE 2 Room Temperature/Door-Opening Test Data

No. of Food Comp Door Openings/h	Room Temp		Top-Mounted-Freezer Unit: Food Comp. Temp.		Freezer Comp. Temp.		Energy Use kWh/day	Side-by-Side Door Unit: Food Comp. Temp.		Freezer Comp. Temp.		Energy Use kWh/day
	°C	°F	°C	°F	°C	°F		°C	°F	°C	°F	
0	21.6	70.9	3.6	38.4	−13.9	7.0	1.267	3.9	39.1	−13.3	8.0	1.389
0	23.8	74.8	3.8	38.8	−14.6	5.8	1.481	4.2	39.5	−14.2	6.5	1.596
0	26.8	80.2	4.1	39.3	−14.9	5.1	1.605	4.4	40.0	−14.9	5.1	1.819
0	29.7	85.5	4.9	40.8	−14.8	5.3	1.770	5.2	41.3	−15.3	4.4	2.086
0	31.9	89.4	5.2	41.3	−14.6	5.7	1.892	5.7	42.3	−15.5	4.1	2.299
1	21.3	70.4	3.8	38.8	−14.7	5.6	1.505	4.2	39.6	−14.2	6.4	1.602
1	23.8	74.9	4.3	39.7	−15.1	4.8	1.593	4.7	40.5	−14.9	5.2	1.769
1	26.7	80.1	4.7	40.4	−15.4	4.3	1.801	5.2	41.4	−15.7	3.8	2.067
1	29.4	85.0	5.1	41.1	−15.6	4.0	1.948	5.5	41.9	−16.2	2.9	2.281
1	32.1	89.7	5.3	41.5	−15.9	3.4	2.211	6.0	42.8	−16.5	2.3	2.590
2	21.3	70.3	4.3	39.8	−14.8	5.4	1.652	5.1	41.1	−14.7	5.5	1.819
2	23.9	75.1	4.8	40.6	−15.3	4.5	1.720	5.3	41.5	−15.6	4.0	1.929
2	26.4	79.6	5.4	41.7	−15.4	4.2	1.921	6.4	43.6	−15.3	4.4	2.215
2	29.4	84.9	5.8	42.5	−15.7	3.8	2.129	6.3	43.3	−16.7	2.0	2.483
2	32.2	89.9	5.8	42.5	−16.2	2.8	2.509	7.1	44.7	−16.6	2.1	2.775
3	21.4	70.6	4.9	40.9	−15.0	5.0	1.672	5.8	42.5	−15.3	4.6	1.884
3	24.0	75.2	5.3	41.6	−15.4	4.2	1.838	5.8	42.5	−15.9	3.3	2.156
3	26.9	80.4	5.6	42.0	−16.0	3.2	2.205	6.8	44.2	−16.3	2.6	2.575
3	29.5	85.1	6.3	43.4	−16.0	3.2	2.313	7.2	44.9	−16.7	2.0	2.730
3	32.0	89.6	6.8	44.3	−15.8	3.5	2.717	8.1	46.5	−17.2	1.0	3.041

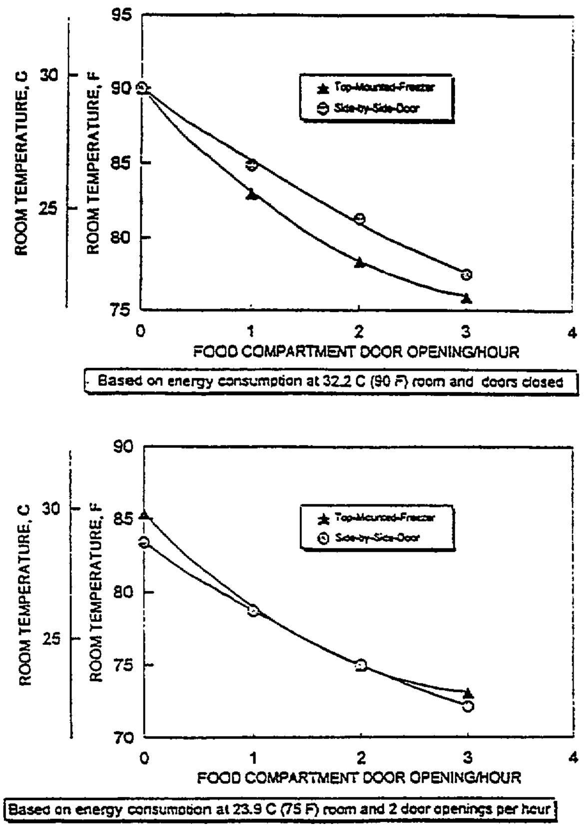

Figure 4 Room temperature vs. food compartment door openings.

consumption at the 23.9°C (75°F) room temperature/two-door-openings-per-hour conditions (1.772 and 1.995 kWh/day), the DOE tests show 8.3% and 15.9% more energy use for the two units tested, respectively. This analysis agrees with some other studies (Meier and Jansky 1993; Meier et al. 1993; Wong et al. 1995) that indicate that the DOE test procedure may result in energy consumption rates that are slightly high. However, since only two appliances were tested, the quantitative results should not be generalized. A much larger number of tests on a wide variety of refrigerator-freezers would be required to answer the question of whether or not the 32.2°C (90°F) room temperature in the DOE test procedure realistically compensates for lack of door openings in energy tests.

Third-Stage Test Results

The last stage of this project involved the investigation of refrigerator-freezer inside temperature settings on energy consumption. Tests were conducted with various food and freezer compartment temperature settings for different test room temperatures to obtain the energy consumption per day. Test data are presented in Table 3 for the two refrigerator-freezers (data for the "midpoint" settings were obtained during the second-stage tests). Regression analysis was performed to obtain an energy consumption plane for each of the refrigerator-freezers using the temperature differences between the test room and the two compartments ($T_r - T_{food}$ and $T_r - T_{free}$) as independent variables. The regression equations of the planes are

$$E = -0.801 + 0.0145\,(T_r - T_{food}) + 0.0257\,(T_r - T_{free})$$

(adjusted coefficient of determination, $R^2 = 0.850$) for the top-mounted-freezer unit and

$$E = -1.951 + 0.0172\,(T_r - T_{food}) + 0.0414\,(T_r - T_{free})$$

(adjusted coefficient of determination, $R^2 = 0.931$) for the side-by-side door unit where E is energy consumption (in kWh/24 hours) and T_r, T_{food}, and T_{free} are the room, food compartment, and freezer compartment temperatures, respectively (in °F).

Figures 5 and 6 show the two planes for the top-mounted-freezer and the side-by-side-door units, respectively. The measured data are shown in solid triangles. Solid circles are the predicted points on the energy planes. When the inside temperature of the two compartments and the room temperature are known, the energy consumption per day may be estimated using the above two equations. For example, if the units were located in a 25.6°C (78°F) room and the freezer and food compartment temperatures were measured to be −15°C and 3.3°C (5°F and 38°F), respectively, the energy consumption would be approximately 1.655 kWh per day for the top-mounted-freezer unit and 1.757 kWh per day for the side-by-side-door unit. If the temperatures in the two units were lowered 2.8°C (5°F) in both compartments, the energy consumption would be approximately 1.856 and 2.050 kWh per day for the two units, respectively. This amounts to a daily energy increase of 12.1% for the top-mounted-freezer unit and 16.7% for the side-by-side-door unit.

On the ($T_r - T_{food}$) and ($T_r - T_{free}$) coordinates, the projected data points for the five compartment temperature settings (C/C, C/W, M/M, W/C, and W/W) are scattered around the lines having the regression equations $(T_r - T_{free}) = 1.0815 \times (T_r - T_{food}) + 30.309$ for the top-mounted-freezer unit and $(T_r - T_{free}) = 1.0971 \times (T_r - T_{food}) + 31.740$ for the side-by-side-door unit. These projected data points are shown in Figures 7 and 8. Obviously, one should not estimate the energy consumption of these two refrigerator-freezers by arbitrarily selecting compartment temperatures that deviate significantly from the test data points and their regression lines.

CONCLUSIONS

A top-mounted-freezer unit and a side-by-side-door refrigerator-freezer manufactured in 1992 and 1991, respectively, were tested in the laboratory under various room conditions and operational factors. It was found that energy consumption was affected most by the test room temperature. The energy consumption was also affected, to lesser degrees, by door openings and anti-sweat heater operation. The test room humidity had the least effect on refrigerator-freezer energy consumption.

Linear regression lines were established to correlate test room temperature and the frequency of food and freezer compartment door openings. It was shown that if the number of door openings (for a food-to-freezer compartment door opening

TABLE 3 Compartment Temperature Variation Test Data

	Comp. Temp. Setting	Room Temp.		Food Comp.Temp.		Freezer Temp.		Energy Use kWh/day
		°C	°F	°C	°F	°C	°F	
Top-Mounted-Freezer Unit	C/W	21.3	70.3	−1.1	30.1	−15.7	3.7	1.695
		24.4	76.0	−1.2	29.8	−16.3	2.7	1.934
		27.1	80.7	−1.4	29.5	−16.7	1.9	2.309
		29.3	84.8	−1.4	29.5	−17.1	1.2	2.419
		31.8	89.2	−1.1	30.1	−16.8	1.8	3.147
	C/C	21.4	70.5	−0.1	31.9	−21.2	−6.2	1.488
		24.3	75.7	−0.2	31.7	−22.4	−8.4	1.744
		27.9	82.3	0.0	32.0	−23.0	−9.4	1.821
		29.7	85.4	0.1	32.1	−23.1	−9.5	2.065
		31.9	89.5	0.0	32.0	−23.3	−9.9	2.398
	M/M	21.6	70.9	3.6	38.4	−13.9	7.0	1.267
		23.8	74.8	3.8	38.8	−14.6	5.8	1.481
		26.8	80.2	4.1	39.3	−14.9	5.1	1.605
		29.7	85.5	4.9	40.8	−14.8	5.3	1.770
		31.9	89.4	5.2	41.3	−14.6	5.7	1.892
	W/W	21.2	70.1	5.0	41.0	−8.8	16.2	1.353
		23.8	74.9	5.3	41.6	−9.3	15.3	1.460
		27.9	82.2	5.6	42.1	−9.7	14.5	1.746
		29.3	84.7	5.8	42.5	−10.1	13.9	1.773
		31.9	89.4	5.9	42.7	−10.4	13.3	1.856
	W/C	21.4	70.5	5.7	42.3	−14.2	6.4	1.292
		23.9	75.0	6.3	43.4	−14.7	5.5	1.360
		26.7	80.0	6.5	43.7	−15.6	3.9	1.492
		29.4	85.0	7.1	44.8	−15.8	3.5	1.585
		31.9	89.4	7.6	45.7	−16.2	2.9	1.725
Side-by-Side Door Unit	C/W	23.4	74.2	−3.9	24.9	−21.1	−5.9	2.131
		26.4	79.6	−3.9	24.9	−21.6	−6.8	2.750
		29.2	84.5	−3.8	25.2	−22.1	−7.8	2.699
		32.0	89.6	−3.8	25.2	−22.4	−8.3	3.009
	C/C	24.0	75.2	−5.1	22.8	−27.0	−16.6	2.782
		25.9	78.7	−5.7	21.8	−27.7	−17.9	2.981
		29.5	85.1	−3.8	25.1	−26.3	−15.3	3.550*
		31.9	89.5	−1.4	29.4	−24.9	−12.8	3.607*
	M/M	21.6	70.9	3.9	39.1	−13.3	8.0	1.389
		23.8	74.8	4.2	39.5	−14.2	6.5	1.596
		26.8	80.2	4.4	40.0	−14.9	5.1	1.819
		29.7	85.5	5.2	41.3	−15.3	4.4	2.086
		31.9	89.4	5.7	42.3	−15.5	4.1	2.299
	W/W	24.2	75.6	5.4	41.7	−10.9	12.4	1.405
		27.2	81.0	5.8	42.4	−11.7	10.9	1.617
		29.4	85.0	6.0	42.8	−12.3	9.8	1.832
		32.9	91.2	6.5	43.7	−12.7	9.2	2.023
	W/C	23.7	74.6	5.2	41.4	−16.6	2.2	1.627
		26.4	79.6	5.5	41.9	−17.6	0.4	1.800
		29.2	84.5	5.6	42.1	−18.2	−0.8	2.055
		32.1	89.8	6.2	43.1	−18.7	−1.7	2.740

*Compressor did not cycle.

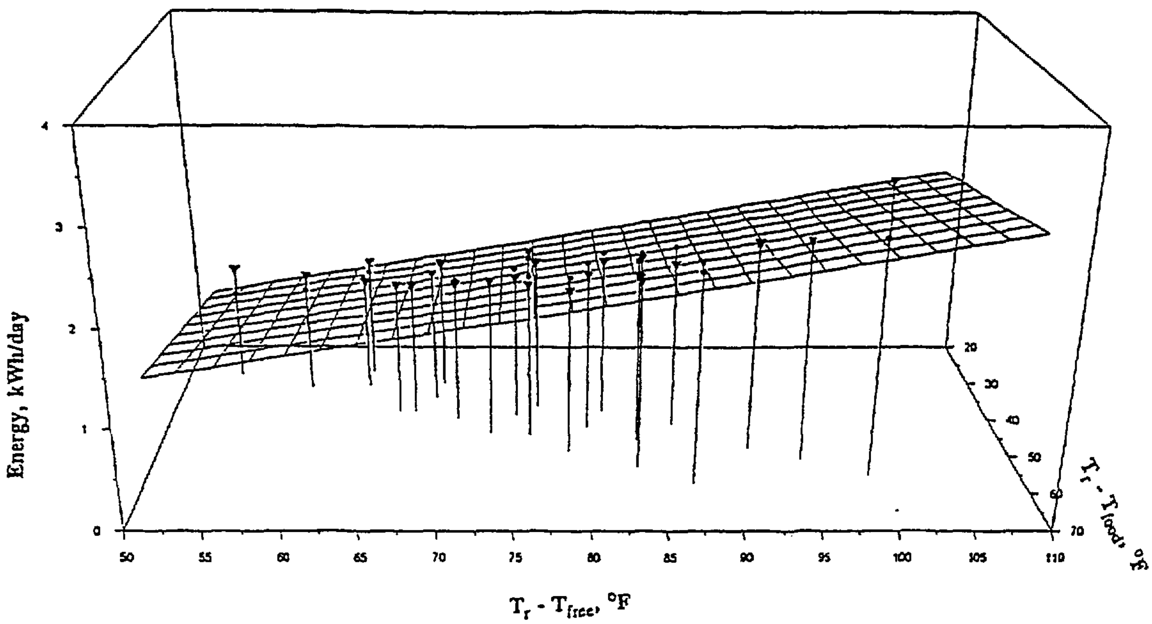

Figure 5 Energy plane for the top-mounted-freezer unit.

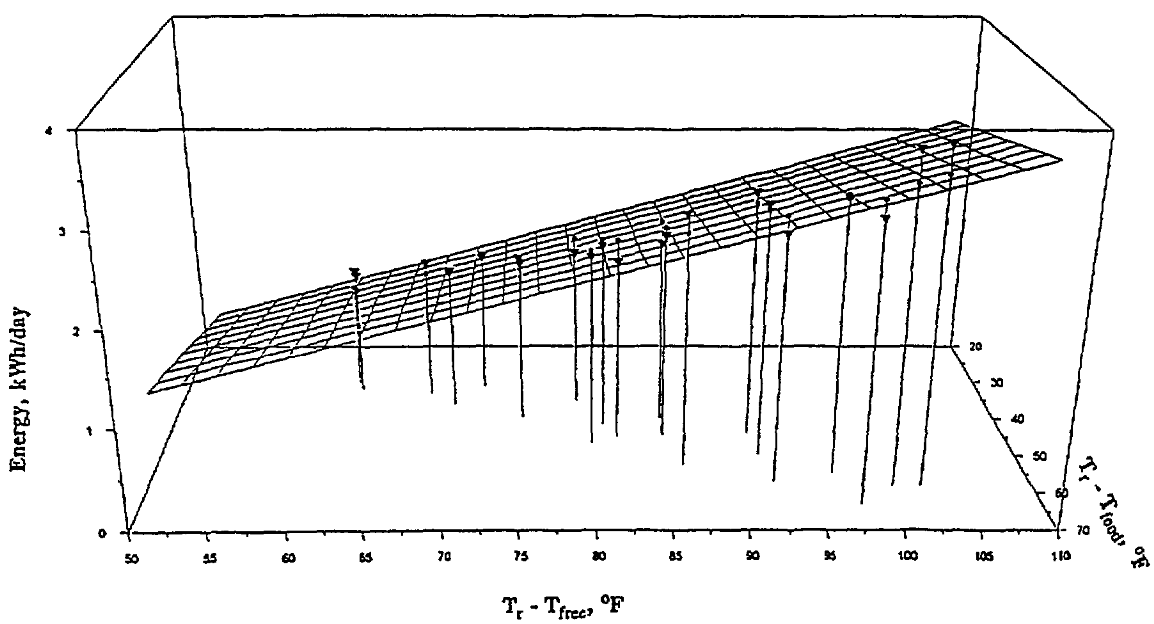

Figure 6 Energy plane for the side-by-side-door unit.

ratio of five to one) is known at a given room temperature, the equivalent room temperature and door-opening rate that result in the same energy consumption can be estimated for the two refrigerator-freezers tested. Regression lines were developed using the energy consumption at 23.9°C (75°F) and two door openings per hour as bases. For this case, it was found that the equivalent room temperature at zero door openings for the two units tested averaged 29.1°C (84.4°F). When the energy at these test conditions and those at the DOE test procedure were compared, the DOE test conditions resulted in 8.3% and 15.9% more energy use than at the lower temperature conditions for the two refrigerator-freezers. However, finding the temperature level to properly compensate for the lack of door openings for most or all refrigerator-freezers would require testing a much larger sample of refrigerator-freezers operating under "real world" conditions.

Regression planes of energy consumption of the two refrigerator-freezers were developed using the temperature differences of the test room temperature and the temperatures of the food and freezer compartments as independent variables. The regression equations are useful for estimating energy consumption at other temperature settings, provided that these temperature differences do not deviate significantly from the test data points.

Finally, it is important to note that the analyses and conclusions of this study were derived from tests on only two refrigerator-freezers. Generalization of the test results to other refrigerator-freezers may not be appropriate.

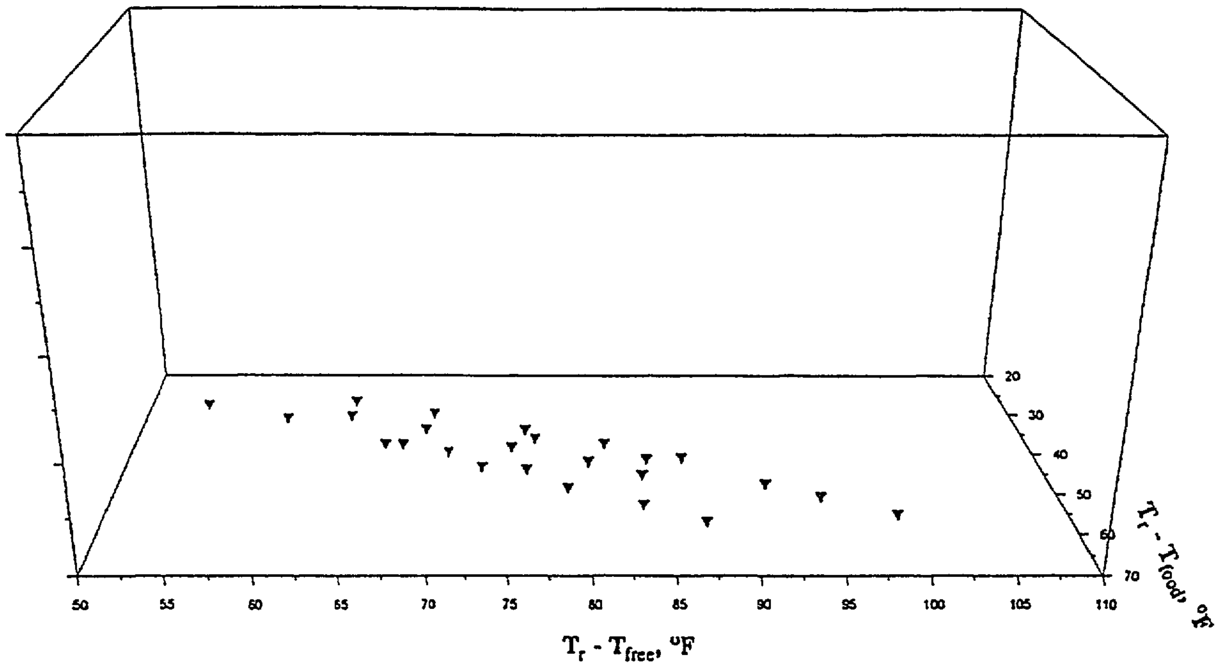

Figure 7   *Projected data points for the top-mounted-freezer unit.*

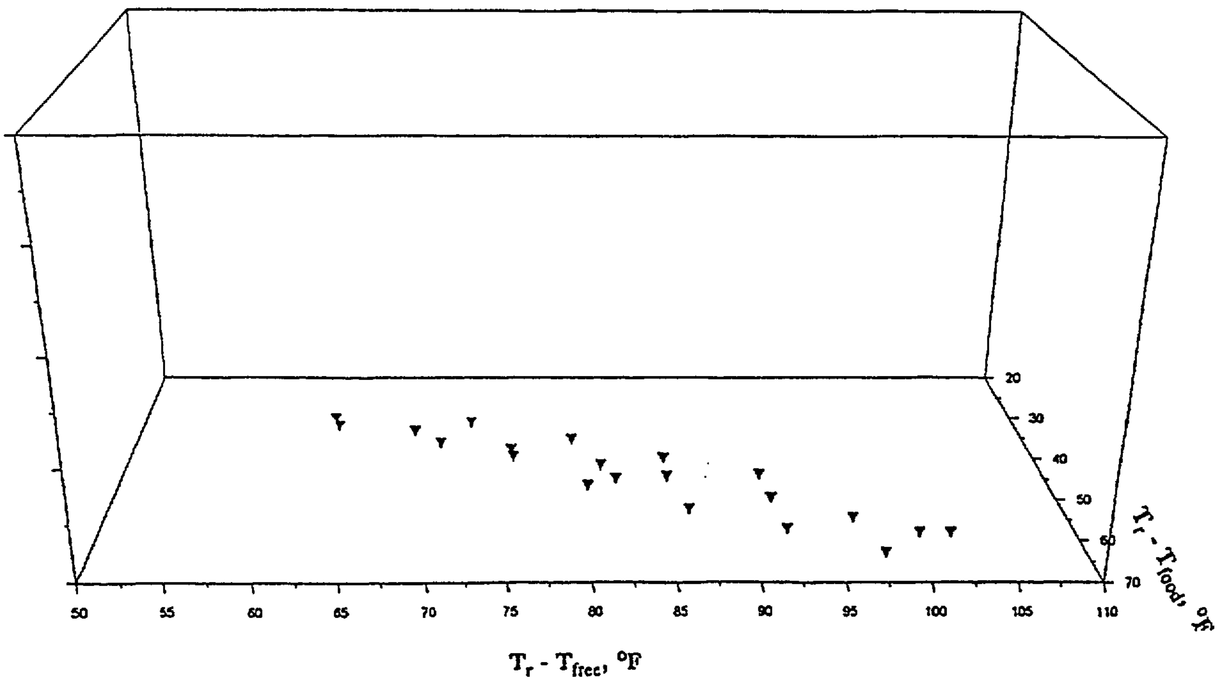

Figure 8   *Projected data points for the side-by-side-door unit.*

MEASUREMENT UNCERTAINTY

The uncertainties of the temperature and energy measurements were 0.2°C (0.4°F) and 1 watt-hour, respectively, at 95% confidence.

REFERENCES

AHAM. 1988. *ANSI/AHAM HRF-1-1988, American national standard on household refrigerators and household freezers*. Chicago: Association of Home Appliance Manufacturers.

Alissi, M.S., S. Ramadhyani, and R.J. Schoenhals. 1988. Effects of ambient temperature, ambient humidity, and door openings on energy consumption of a household refrigerator-freezer. *ASHRAE Transactions* 94(2).

Box, G.E., W.G. Hunter, and J.S. Hunter. 1978. *Statistics for experimenters: An introduction to design, data analysis, and model building*. New York: John Wiley and Sons.

Chang, Y.L., and R.A. Grot. 1979. Field performance of residential refrigerators and combination refrigerator-freezers. NBSIR 79-1781.

DOE. 1982. *Federal Register*, subpart B, part 430, vol. 47, no. 154, pp. 34517-34528, August 10. Washington, D.C.: U.S. Department of Energy.

DOE. 1990. *Federal Register* 55(206): 42845-42848, October 24. Washington, D.C.: U.S. Department of Energy.

Gage, C.L. 1995. Field usage and its impact on energy consumption of refrigerator/freezers. *ASHRAE Transactions* 101(2).

Grimes, J.W., W. Mulroy, and B.L. Shoemaker. 1977. Effect of usage conditions on household refrigerator-freezer and freezer energy consumption. *ASHRAE Transactions* 83(1).

Meier, A. 1995. Refrigerator energy use in the laboratory and in the field. *Energy and Buildings* 22.

Meier, A.K., and R. Jansky. 1993. Field performance of residential refrigerators: A comparison with the laboratory test. *ASHRAE Transactions* 99(1).

Meier, A., et al. 1993. The New York refrigerator monitoring project: Final report. Report No. LBL-33708. Berkeley, Calif.: Lawrence Berkeley Laboratory.

Parker, D.S., and T.C. Stedman. 1992. Measured electricity savings of refrigerator replacement: Case study and analysis. 1992 ACEEE Summer Study on Energy Efficiency in Building, Pacific Grove, Calif., Vol., *Commercial Performance: Analysis and Measurement*. Washington, D.C.: American Council for an Energy Efficient Economy.

Proctor, J. 1993. What's wrong with refrigerator energy rating? *Home Energy*, January/February.

Wong, M.T., W.R. Jones, B.T. Howell, and D.L. Long. 1995. Energy consumption testing of innovative refrigerator-freezer. *ASHRAE Transactions* 101(2).