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PG&E REFRIGERATOR METERING PART ONE ENERGY CONSUMPTION COMPARISON

Prepared For:
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Refrigerator Metering Analysis - Part One
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I. EXECUTIVE SUMMARY

In the residential sector, energy efficient refrigerators offer one of the most effective opportunities for reducing electricity demand and delaying the construction of new power plants and/or transmission and distribution facilities. In 1990, 1991, and 1992, Pacific Gas and Electric Company (PG&E) offered rebates for refrigerators that were more efficient than the (1990) Federal standards, as reported on the label. The amount of the rebate increased with efficiency. Refrigerators were grouped as 10-14.9% better than the Federal standards, 15-19.9% better, etc. The labeled energy consumption of refrigerators is based on a specified laboratory test procedure (ANSI/AHAM HRF-1-1988), also known as the DOE test.

In the largest in-home refrigerator study to date, two hundred and fifty-six new refrigerators were metered in three geographic areas (Central Valley - Fresno weather station, Inland - Livermore weather station, and Coastal - Fremont weather station) within PG&E's service territory for one year (August 1992 - August 1993). In Part One, (Annual Energy Consumption Comparison) the energy consumption of two groups of new refrigerators (10 to 14.9% and 30 to 34.9% better than the 1990 Federal standard) was compared to their labeled consumption. In Part Two (PG&E Costing Period Study) of this study the energy consumption and load shape for each of PG&E's costing periods were developed for two groups of refrigerators (one group that meets the 1993 Federal standard and one that is representative of typical refrigerators now in use in the PG&E service territory).

PG&E undertook Part One of this study to assess the accuracy of the engineering calculations used to estimate the savings from its refrigerator rebate programs. The primary objective was to determine whether the electricity consumption estimates shown on Federally mandated refrigerator labels[1] accurately reflect consumption of refrigerators installed in customers' homes. PG&E uses the difference between the labeled energy consumption for the rebated refrigerators and the standard as the basis for the gross impact estimate as shown in Equation 1.

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[1] These labels show an estimate of the annual electricity consumption based on a laboratory test procedure established by the Federal Department of Energy as part of its program of minimum energy efficiency standards for refrigerators.

$$\text{Energy Savings} = (\text{maximum consumption according to standard} - \text{labeled consumption of rebated refrigerator}) \quad (1)$$

In particular, PG&E wanted to know if an adjustment factor needed to be added to Equation 1 to correct the consumption estimate to actual in-situ consumption as shown in Equation 2[2].

$$\text{Energy Savings} = G * (\text{maximum consumption according to standard} - \text{labeled consumption of rebated refrigerator}) \quad (2)$$

where:

$$G = \frac{\text{Actual Annual kWh Savings}}{\text{Difference in Labeled kWh}}$$

Results

The estimated annual electricity consumption for each group and the consumption difference is reported in Table 1.

[2] This study was not intended to determine: the appropriate baseline refrigerator for the energy impact, the number of rebated refrigerators with particular labeled consumption, or net-to gross issues.

Table 1. Metered Annual Consumption vs. Laboratory Estimate			
	Group S [std.err.]	Group E [std.err.]	Difference ± 95% conf.
Model 1	784 kWh[1]	600 kWh[3]	184 kWh
Model 2	782 kWh[1] [14.5]	598 kWh[3] [11.4]	183 ±36 kWh
Model 3	787 kWh[1] [1.9]	602 kWh[3] [1.7]	184 ±4.9 kWh
Label	875 kWh[2]	695 kWh[2]	181 kWh[2]
Best Estimate			**156±28 kWh**[4]
Estimate from principles[5]			
Identical cabinets			≈162 kWh
Identical COP			≈131 kWh

1. Anti-sweat heater on 53.1%, occupancy 2.98 persons
2. Anti-sweat heater on 50%
3. Anti-sweat heater on 44.7%, occupancy 2.54 persons
4. Includes an estimated bias of 28 kWh [s.e.=13.8 kWh] due to occupancy and anti-sweat heater use differences between groups.
5. Based on food load and other occupancy effects equaling 15% of standard unit label

Conclusions

- The actual energy consumption of these new refrigerators in the PG&E service territory is 10% to 14% below that stated in the refrigerator labels. This will result in an overestimation of savings by the same percentage. The annual consumption of these refrigerators is overestimated because the labels are based on a test procedure at 90°F. When installed in kitchens in PG&E's service territory the energy consumption due to temperature differences is substantially reduced. Even with the additional energy consumption from occupant effects and accessories such as icemakers, the in-situ consumption does not increase to the level of the label.
- The estimated difference in annual consumption derived from the Federal labels for the two metered groups (181 kWh) lies within the confidence bounds of the consumption estimated through this metering study. It should be noted that a potential sampling bias exists between the groups and that by physical principles, the in-situ difference would be at least 10% less than the labeled difference (for PG&E's service territory). Part Two of this study establishes the actual difference as 13.8% less than the labeled difference based on customers most likely to participate in rebate programs for high efficiency refrigerators (Proctor et. al., 1994).

- Refrigerator consumption is increased 100 to 125 kWh by the anti-sweat heater (according to the DOE test) and 75 to 105 kWh by an automatic icemaker. The anti-sweat heater and automatic icemaker can be the target of consumer education.

Recommendations

- An adjustment factor (G in Equation 2) should be added to the calculation of gross impact. The value of G is estimated in Part 2 of this study as 0.862.
- Regression coefficients for average temperature and "cool temperature" from this study may be used to estimate energy consumption of similar refrigerators in other areas, if appropriate temperature data are substituted.
- The DOE test and label should be revised to show the effect of an automatic icemaker.

II. INTRODUCTION

In the residential sector, energy efficient refrigerators offer one of the most effective opportunities for reducing electricity demand, and putting off or delaying the construction of new power plants and/or transmission and distribution facilities. Because consumers are indifferent to the cost savings opportunities associated with purchasing energy efficient refrigerators [see, e.g. Meier and Whittier, 1983], minimum efficiency standards for refrigerators as well as other household appliances were established. California first established standards (in 1979 and 1987) which were followed by national standards in 1990 and 1993. While these standards set a minimum efficiency, they do not provide incentives for consumers to purchase even more efficient appliances. Higher levels of efficiency are often warranted in many utility service areas, depending on the demand growth rates and the ability of energy savings to avoid or delay capital outlay for construction of power plants and associated T&D networks.

In 1990, 1991, and 1992, Pacific Gas and Electric Company (PG&E) offered rebates to consumers that purchased refrigerators that were more efficient than the (1990) Federal standards. The amount of the rebate increased with efficiency, grouped as 10-14.9% better than the Federal standards, 15-19.9% better, etc. The efficiency of refrigerators, both for the Federal labels and the utility rebates, is based on a specified laboratory test procedure (ANSI/AHAM HRF-1-1988), also known as the DOE test. The result of the test, expressed as an annual consumption in kWh, is published on the “Energy guide” label on each unit sold. A compilation of all models on sale is included in directories published periodically by the Association of Home Appliance Manufacturers [e.g. AHAM, 1991]. A consumers’ guide of the most efficient models is published annually by the American Council for an Energy Efficient Economy (Washington, DC).

A question has always been posed: how closely does the labeled consumption represent energy consumption under actual use? This question becomes fundamental in utility Demand Side Management programs, such as the PG&E refrigerator rebate program, where investments in end-use energy efficiency are intended to offset supply-side investments. For an accurate comparison of investment alternatives, the costs and energy savings of DSM measures must be known.

Key features of the laboratory test procedure are a high ambient temperature (90 ± 1°F) and no door openings. In most houses, of course, the ambient temperatures are lower, and are likely to be different in warmer and colder climates. While most houses are kept warm in the winter, air conditioning use is more discretional so that larger interior temperature variations are likely during the warmer months. In any case, there will usually be significant seasonal variations in ambient temperature, which would alter energy use. In actual use there will be door openings as well as food loading. Since food is generally placed into the refrigerator at ambient or higher temperatures, it adds to the cooling load and energy consumption. Indeed, the higher ambient temperature specified in the test procedure is intended to compensate for the absence of door openings and food loading in the laboratory test. The test procedure specifies freezer temperatures, and the actual freezer temperature will depend on the user's thermostat setting. Some refrigerators are equipped with an anti-sweat heater switch, which the user may have on or off. The laboratory procedure calls for testing the unit in both switch settings and averaging the results. The lab test procedure does not specify the relative humidity of the test chamber; in actual use, ambient humidity could affect energy consumption in a number of ways. For a list of key features of the lab test procedure, see Appendix F.

This study was intended to determine whether the electricity consumption estimates shown on Federally mandated refrigerator labels accurately reflect consumption of refrigerators installed in customers' homes. PG&E uses the difference between the labeled energy consumption for the rebated refrigerators and the standard as the basis for the gross impact estimate as shown in Equation 1.

$$\text{Energy Savings} = (\text{maximum consumption according to standard} - \text{labeled consumption of rebated refrigerator}) \qquad \text{(1 repeated)}$$

In particular, PG&E wanted to know if an adjustment factor needed to be added to Equation 1 to correct the consumption estimate to actual in-situ consumption as shown in Equation 2[3].

$$\text{Energy Savings} = G * (\text{maximum consumption according to standard} - \text{labeled consumption of rebated refrigerator}) \qquad \text{(2 repeated)}$$

where:

$$G = \frac{\text{Actual Annual kWh Savings}}{\text{Difference in Labeled kWh}}$$

Several studies have compared the field performance of refrigerators with the laboratory test and/or labeled consumption. [Meier and Heinemeier, 1988; Bos, 1993; Meier et al., 1993; Parker and Stedman, 1992; etc.] Alissi, Ramadhyani, and Schoenhals [1988] have looked for effects of ambient temperature, ambient humidity, and door openings--the most significant differences between the laboratory procedure and actual operating conditions--on energy consumption.

This 1992-1993 PG&E study differs in several ways from the previous studies. It represents the largest sample size of any refrigerator monitoring program, covering 256 units in all, monitored over a year. More relevant to the evaluation of a PG&E

[3] This study was not intended to determine: the appropriate baseline refrigerator for the energy impact, the number of rebated refrigerators with particular labeled consumption, or net-to gross issues.

DSM program is that the measurements were conducted within the utility service area, representing both local climate and behavioral influences on energy use. Finally, the units tested were energy efficient units of recent vintage.

III. METHODOLOGY

The 1992-93 field monitoring study measured the actual energy consumption of two groups of refrigerators qualifying for the PG&E efficiency rebates, and compared these values with laboratory test data as reported on the refrigerator labels. The program offered rebates that varied by efficiency category, e.g. 10-14.9% more efficient than 1990 Federal standards, 15-19.9% better, etc. For this study two such efficiency groups were selected:

- Group S (the standard group) - Models that exceeded the efficiency standard by 10 to 14.9%. These refrigerators were eligible for a rebate in 1991. (This study did not attempt to determine the efficiency level of refrigerators that would have been purchased in the absence of a rebate program.)
- Group E (the efficient group) - Models that exceeded the efficiency standard by 30 to 35%. These were eligible for a rebate in 1992. These models meet the 1993 Federal standard.

Matched pairs of refrigerators were sampled from Groups S and E. An hourly recording meter was installed on each refrigerator and data were analyzed by a multivariate regression technique. These regression models were used to estimate the average difference in annual energy consumption between the two groups.

Sample Selection

One significant goal of the sample design was to make the two test groups as similar as possible. This makes the difference in rated efficiency the primary source of differences in energy consumption between the two groups. Refrigerator energy use may vary by size, freezer style (top mounted, or side- by-side), presence of energy consuming features (automatic icemakers, and anti-sweat heaters), temperature settings, kitchen temperatures, number of household occupants, clearances around the unit, and many other factors. The sample design attempted to control four important factors by matching the two groups by size, freezer style, presence of automatic icemaker, and ambient (outdoor) temperature (geographic matching).

Households who had purchased new rebated refrigerators in 1991 and 1992 were potential metering sites. In order to insure that the two groups would be comparable, the sample was confined to 17 through 21 ft^3 units with top freezer and automatic defrost. This sample selection was chosen to reflect the most common refrigerators purchased under the rebate program as illustrated by Table 2. Three geographical areas were chosen for these tests: Coastal (clustered near Hayward), Inland (clustered near Livermore), and Central Valley (clustered near Fresno).

Table 2. 1990 PG&E Refrigerator Rebates in 10 to 14.9% Group	
Size (cubic feet)	Number of Rebates
12 to 13	351
13 to 14	117
14 to 15	0
15 to 16	0
16 to 17	66
17 to 18	1,753
18 to 19	6,642
19 to 20	4,731
20 to 21	3,856
21 to 22	6,929
22 to 23	235
23 to 24	2,450
24 to 25	2,692
25 to 26	2,269
26 to 27	1,811
30 plus	55

The pool of potential metering sites was limited by the number of refrigerators in Group E. Group E refrigerators were randomly selected from a list of rebated customers that met the sample selection criteria. Each Group E refrigerator recruited was matched with a Group S refrigerator of the same volume and identically equipped with (or without) an automatic icemaker. The list of rebated refrigerators was prepared by the Electric and Gas Industries Association (EGIA), which processes the rebates for PG&E.

All potential participants were contacted by phone and offered an incentive of $100 to participate in the monitoring project.

Data Acquisition

Refrigerator energy consumption was measured using a 120-volt version of PG&E's residential time-of-use meter. This submeter stored the total kWh for hourly time increments. Each location was visited by a PG&E technician who installed a submeter, completed a short interview with the occupant, and recorded "snap shot" information on factors that might influence refrigerator energy consumption, including temperatures (fresh food compartment, freezer compartment, kitchen) and other factors (number of people in household, presence of an automatic icemaker, anti-sweat heater switch on or off, refrigerator thermostat setting, refrigerator clearances, whether the house had an air conditioner or an evaporative cooler).

Since the refrigerators in Group S were one year older than those in Group E, refrigerator coils were cleaned on all units. Meters were installed beginning August 1992 and data acquisition continued until August 1993. After data attrition, the number of metered refrigerators in Group S was 136 and the number of metered refrigerators in Group E was 120.

Data Analysis

The data analysis consisted of five steps:

- Data checking and merging
- Model development and diagnostics
- Normalization to PG&E residential customer base (climate normalization)
- Analysis of potential estimation bias

Data Checking and Merging

All of the on-site data collected by the technicians (occupancy, presence of icemaker, etc.) were checked carefully to eliminate data errors. Missing data, inconsistencies in data (i.e. icemaker on but none installed), or changes in data from visit to visit were investigated and clarified either by phone or in person at the next visit. These data were matched with other data: the laboratory estimate of average consumption, refrigerator volumes, and a geographic variable that identified the nearest weather station (Fresno, Livermore, and Fremont weather stations).

Hourly data from each metered refrigerator were summed to daily total kWh, annualized (multiplied by 365) and matched with the average daily temperatures from the closest weather station.

Model Development

The basic data analysis procedure is multivariate (multiple) regression. The measured annualized consumption is the dependent variable. The predictor variables are chosen to produce the best model (judged by statistical and practical analysis). Three models are detailed in this report:

- Model 1 - annualized consumption against daily average outside temperature and several static variables (i.e. that do not change from day to day). This model has a data point for each day each refrigerator was metered (Group S, N=35239; Group E, N=31063). Predictor variables include outside temperature, operation of an automatic icemaker, anti-sweat heater operation, number of occupants, refrigerator dial setting, and adjusted volume.
- Model 2 - similar to Model 1 except that the only predictor variable used is outside temperature.
- Model 3 - a aggregated regression of annualized consumption against daily average outside temperature. This model was limited to days when there were data for at least 75 refrigerators in the group (N=302 for Group S and 299 for Group E).

The models are summarized here and detailed in Appendix B.

These models were initially developed using an Ordinary Least Squares (OLS) analysis. For Models 1 and 2 White's method was used to estimate the appropriate standard errors (see Appendix D).

Model 1--Analysis of Consumption of Individual Refrigerators

Model 1 was the precursor of the other models. For this model the electrical consumption of the refrigerator is a linear function of a number of predictor variables:

$$\text{Ann. kWh} = A + B \mathbf{x}\, v1 + C \mathbf{x}\, v2 + \ldots \qquad (3)$$

where:
A = the intercept constant,
B = the coefficient of predictor variable 1, etc.

The electrical consumption of each group of refrigerators is modeled as a linear response (with an "elbow") to the average outside temperature and linear responses to several static variables. These variables are shown in Table 3.

Table 3. Model 1 Predictor Variables	
Variable code	Description
Avg temp	average daily outside temperature, °F nearest weather station
Icemaker	if on (=1), if not (=0)
Sweat	anti-sweat heater switch setting: on (=1), off (=0)
Occupants	number of people in household[1]
Ref set	thermostat setting, between coldest (=100) & warmest (=0)
Adjusted vol	1.63 x Frez vol + Fresh vol, cu.ft.
Cool Temp	heating degree days to the base 59°F

Of the 32 potential predictor variables, only Avg temp and Cool Temp are based on daily data corresponding to the measurement of consumption; all others are based on prior information or on "snap shot" measurements taken at instrumentation and meter readings. Table 4 shows how closely the groups were matched on the model variables.

Table 4. Summary Statistics for Model 1 Variables					
	Group S		**Group E**		**Difference**
	Mean	**Std. dev.**	**Mean**	**Std. dev.**	**Mean**
Avg temp	61.3	12.2	61.4	12.1	-0.1
Icemaker	0.243		0.281		-0.038
Sweat	0.532		0.447		0.085
Occupants	2.98	1.69	2.54	1.29	0.44
Ref set	54.2	16.9	63.8	16.4	-9.6
Adjusted vol	22.47	1.95	22.39	1.73	0.08

Groups E and S are not identical. When the variables are different and they significantly affect energy consumption, their differences must be accounted for in the final analysis. As long as the coefficients derived by Model 1 are statistically valid and physically meaningful, these differences will be corrected in the analysis.

Table 5 contains the regression coefficients for Model 1. When the grand mean values for the static variables are substituted into the model (attempting to correct sample differences to the population), the energy consumption for each group of refrigerators can be plotted against the average outdoor temperature (Figure 1).

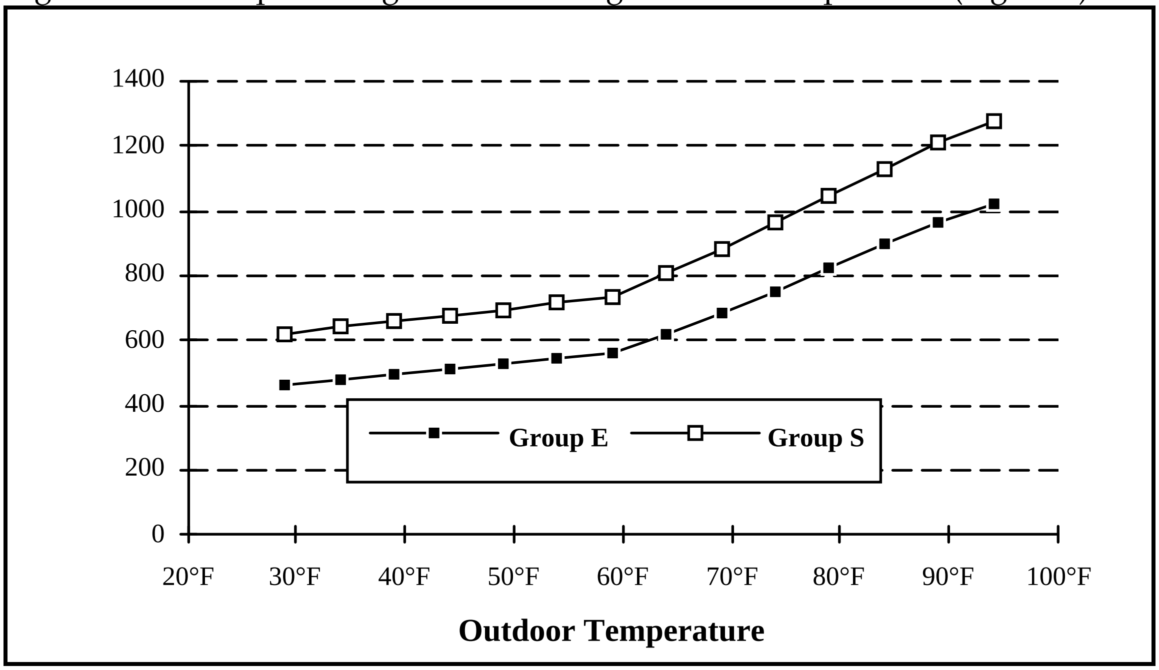

Figure 1. Annualized Consumption vs. 24 Hour Average Outdoor Temperature

Table 5. OLS Elbow Regression-- Model 1 Reference Temperature 59°F		
	Group S	Group E
Adjusted R squared	.611	.549
Standard Error of Residual	163 kWh	140 kWh
	Coefficient Value [Std. Error]	
Constant	- 1174 [13.8]	- 786 [13.9]
Avg. temp	16.3 [.13]	13.9 [.12]
Icemaker	78.2 [2.18]	99.9 [1.93]
Sweat	137 [1.77]	73.3 [1.61]
Occupants	36.0 [.55]	21.9 [0.63]
Ref set	2.43 [.05]	1.62 [.05]
Adjusted vol	27.7 [.49]	13.7 [.51]
Cool temp	12.3 [.27]	10.5 [.25]

These standard errors are computed by ordinary least squares and were used only for comparison of possible predictor variables in Model 1. These standard errors are smaller than the standard errors computed using the method described in Appendix D.

VALIDITY OF MODEL COEFFICIENTS

Model coefficients that are statistically valid and stable, physically meaningful, and internally consistent can be confidently considered valid[4].

The statistical validity of the coefficient was judged first by its t-ratio[5] and second by the effect of its inclusion on the overall R squared and standard error of the regression (when using OLS). The stability was judged by how much it changed as other explanatory variables were added or deleted. Prior knowledge, including other field and lab studies as well as engineering estimates were used to determine if the

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[4] While it can be argued that the regression coefficients do not have to be physically meaningful (because they are controlling for another factor omitted from the analysis), use of these variables as predictors is only valid if their relationship to omitted variables is the same in the population as it is in the sample. After extensive work with this data, such an assumption does not appear valid.

[5] The t-ratio is the coefficient divided by its standard error. High t-ratios imply a higher level of significance.

coefficient could be physically meaningful. For the anti-sweat heater for example, regression coefficients were compared against lab results.

The coefficients for Average temperature, Occupant effects, and Icemaker represent the response of the refrigerator to equal increases in load. To be internally consistent, coefficients of the two groups must differ no more than the percentage difference in annual consumption as judged by the label consumption (with allowances for standard errors). This is called the Ratio Test. The percentage difference in the label consumption is 20% {(875-695)/875}.

How well Model 1 coefficients meet the criteria of statistical significance, physical meaning, and internal consistency is summarized in Table 6 and detailed in Appendix B.

Table 6. Validity of Model 1 Coefficients

Coefficient	Statistical Significance and Stability	Physical Meaning	Internal Consistency (Ratio Test)
Avg temp	Yes	Yes	Yes (15%)
Icemaker	Yes	Yes	No (-28%)
Sweat	Yes	No	Not Applicable
Occupants	Yes	Yes	No (39%)
Ref set	Yes	Unknown	Not Applicable
Adjusted vol	Yes	No	No (51%)
(Avg temp - Cool temp)[1]	Yes	Yes	Yes (15%)

1. The difference between these coefficients describes the increased consumption with increased temperature in cooler days (days with an average temperature below 59°F).

ESTIMATING ANNUAL CONSUMPTION--NORMALIZATION

Since refrigerator energy use is highly dependent on temperature, it is necessary to normalize the metered results based on the climates of PG&E's residential customers. This normalization consisted of a bin analysis based on the weather conditions across PG&E's service territory. Based on the Typical Meteorological Year (TMY) associated with each of the PG&E divisions residential meter weighted temperature bins were established. These bins represent the percentage of time the outdoor ambient temperature will be in that bin based on typical meteorological data. These bins are given in Appendix C and illustrated in Figure 2. Regression coefficients for Avg.

temp and Cool temp were combined with bin temperature data to estimate annual consumption in a Typical Meteorological Year.

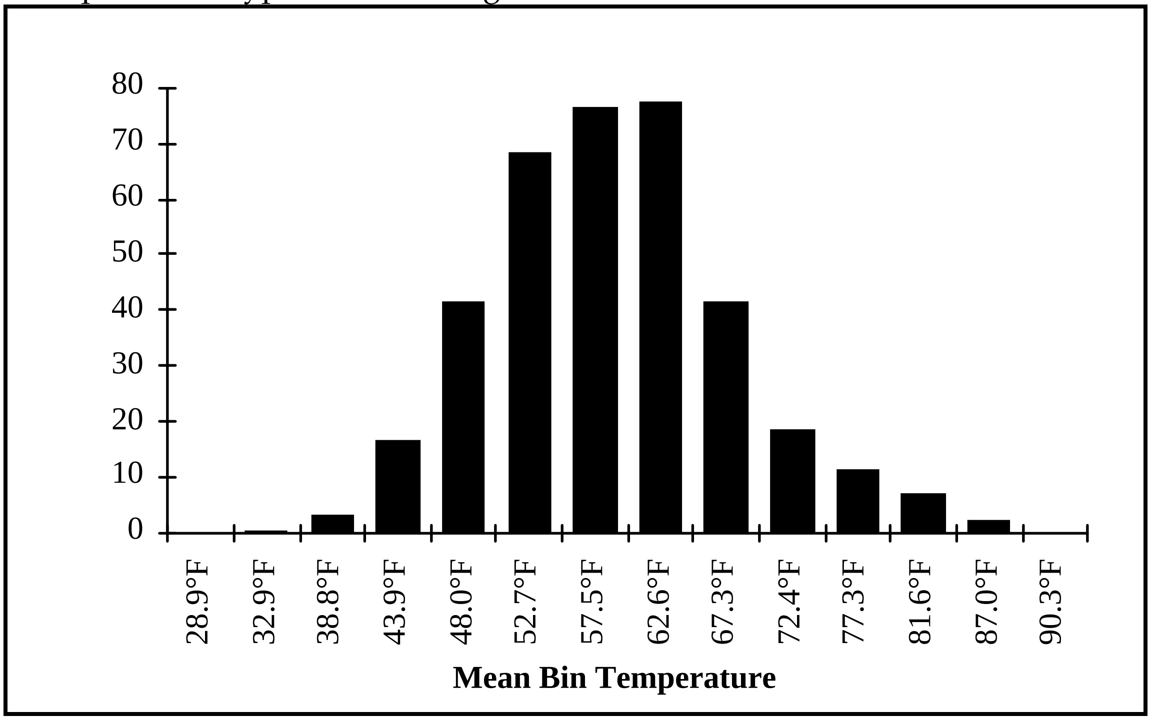

Figure 2. Bins of Daily Average Outdoor Temperature Weighted for PG&E Residential Customers

These bins were used to weight the Model 1 regression in the following manner:

- The mean temperature of each of the bins was calculated; this is not the midrange of the bin but an arithmetic mean.
- The mean bin temperature was used to calculate the refrigerator energy consumption for that bin (using the regression coefficients from Model 1)
- The annual consumption was calculated as follows:

$$\sum_{i=1}^{i=N} w_i \cdot E_i \qquad (4)$$

where:

w_i = the weight for bin i

E_i = average energy consumption for bin i.

The weather normalization procedure can be used to estimate the energy consumption of similar refrigerators in other parts of the country if the appropriate temperature bin data corresponding the geographical location are used. This normalization is appropriate as long as occupant behavior and the relationship of kitchen temperature to outside temperature can be assumed to be similar to this sample. The annual consumption would be higher at locations where the temperatures are warmer, and vice versa.

Model 1 attempts to normalize for variables other than temperature. The non-weather related regression coefficients are multiplied by the average value of the appropriate parameter in Equation (3), e.g., multiplying the coefficient of "Occupants" by the number of occupants. If the regression coefficients are valid, Model 1 coefficients could be used to adjust to local demographics.

Model 2--Analysis of Consumption Based on Temperature Only

Model 2 is Model 1 with predictor variables limited to the daily average outside temperature. This model assumes that all other variables are extraneous variables that occur randomly in the selection process. The model uses an “elbow” regression characterized by:

$$\text{Annualized consumption} = A + B \mathbf{x} (\text{Avg temp}) + C \mathbf{x} (\text{Cool temp}) \tag{5}$$

where:

A = the intercept constant

B = the coefficient of the daily average outside temperature

C = the coefficient of Cool temp.

The model coefficients for Model 2 are shown in Table 7. The change in consumption with outdoor temperature is of the same form as Figure 1.

The weather normalization procedure is the same as Model 1, and the normalized results are presented in Table 9.

Model 3--Analysis of Averaged Consumption Data

With Model 3 the varying effect of temperature from house to house, as well as the effects of other randomly distributed variables, is reduced by averaging the data. The averaged data closely corresponds to the diversified effect of these refrigerators viewed from PG&E’s perspective. For each day the consumption for all the refrigerators in each group is averaged and this consumption is the dependent variable in the regression. The model takes the form:

$$\text{Ann. kWh} = a + b \mathbf{x} \text{ Avg temp} + c \mathbf{x} \text{ Cool temp} \tag{6}$$

where:

a = the intercept coefficient,

b = the coefficient of the 24 hour average temperature that day for the nearest weather station,

c = the coefficient of Cool temp (defined in the same manner as with Model 1)

This model has a number of assumptions. First, the effect of temperature is linear in both the cool and warm temperature regions. Second, aside from efficiency range, size, and the presence of an icemaker, all other variables that influence refrigerator energy consumption are randomly distributed among all the study refrigerators and between the two groups.

The model coefficients are shown in Table 7 and the change in consumption with changes in outdoor temperature is of the same form as Figure 1.

Table 7. Elbow Regression-- Models 2 and 3 Reference Temperature 59°F

	Group S	Group E
	Coefficient Value [Std. Error]	
Model 2		
Constant	- 293 [62.8]	- 309 [46.1]
Avg. temp	17.4 [1.0]	14.6 [.75]
Cool temp	14.2 [1.4]	12.2 [1.0]
Model 3		
Constant	- 234 [20.8]	- 271 [20.1]
Avg. temp	16.6 [.31]	14.1 [.31]
Cool temp	12.3 [.56]	10.9 [.53]

The weather normalization procedure is the same as Model 1, and the normalized results are presented in Table 9.

Estimation of Consumption Difference Based on Physical Principles

As a check of the three models estimates of consumption differences between the two groups a first order analysis was performed. The difference in annual consumption between the two groups of refrigerators was estimated based on physical principles, the labels, and metered results. The measured differences in the lab test (labels) establish a relationship between the two groups of refrigerators under identical conditions. The consumption differences are only due to differences in cabinet efficiency and/or Coefficient of Performance (COP). When these refrigerators are moved into identical homes and identical food and door opening loads occur, the difference in consumption was estimated as shown in Table 8.

Table 8. Physical Principals Estimated Difference in Annual Consumption (Normalized to Group S Label)			
	Refrigerator S	Refrigerator E	Refrigerator E'
	Laboratory Test (Labels)		
Cabinet load at 90°F	100%	79%	100%
COP	1	1	1.26
Label kWh use	100% (100/1)	79% (79/1)	79% (100/1.26)
	In Identical Homes		
Cabinet load at kitchen T	75% (100x.75)	60% (79x.75)	75% (100x.75)
Food & Door Load	15%		
Total load	90% (75+15)	75% (60+15)	90% (75+15)
In-situ kWh use	90% (90/1)	75% (75/1)	71% (90/1.26)
Difference		15% (90-75)	19% (90-71)

The analysis in Table 8 illustrates:

- When the in-situ energy consumption of a standard refrigerator is 10% less than the labeled consumption, the in-situ difference between that refrigerator and one with a labeled consumption 21% less has the approximate bounds;
  - maximum 19% {.21 * (1-.10)}. when both are placed in identical homes,
  - minimum 15%, when both are placed in identical homes.

<u>Discussion of Potential Estimation Bias</u>

The sampled refrigerators were randomly selected from refrigerators that met the stratification criteria. In spite of this random selection, the two samples differed from each other on a number of significant parameters (see Table 4). Both the number of occupants and the percentage of anti-sweat heaters on were lower for Group E than they were for Group S. This would lower the metered consumption for Group E, and increase the difference between the two groups. This potential bias may be counteracted by colder refrigerator temperature dial settings for Group E, if those settings are representative of lower refrigerator and freezer temperatures.

It is likely that the differences in occupancy came from the source of the two groups of customers. Group S customers purchased refrigerators from the least efficient group of rebated refrigerators in 1991, while the Group E customers purchased refrigerators from the most efficient group of rebated refrigerators in 1992.

The difference in anti-sweat heater operation may be a result of the refrigerator design, or it may be truly random. The difference in refrigerator temperature dial setting is likely just an artifact of the design. The numbers on the dial only show relative "colder" temperatures so 63% cold on one refrigerator may represent the same temperature as 54% on another. In fact the "snapshot" temperatures measured by the technicians (not considered a reliable measurement) showed Group E fresh food compartments 1°F warmer than those in Group S.

The difference in consumption estimated based on Model 1 was considered insufficiently reliable because of the lack of internal consistency and physical meaning for some of the predictor variables. The difference in consumption, estimated using Models 2 and 3, between the two groups of refrigerators is potentially biased because of differences in the number of occupants and the proportion of units with the anti-sweat heater on. The magnitude of this bias was estimated in two parts as detailed in the Results Section.

IV. RESULTS

This study was designed to determine whether the differences in electricity consumption reported on the refrigerator label (based on laboratory measurements) are an accurate basis for estimating the differences in electricity consumption between refrigerators of different efficiencies. In addition it was able to estimate:

- The relationship between electricity consumption reported on the label and actual consumption in customers' homes.
- The range of effect on annual consumption that can be attributed to various factors including:
  - use of an anti-sweat heater
  - use of an automatic icemaker
  - occupancy effects (door openings and food loading)

<u>Annual Energy Consumption and Consumption Differences</u>

Table 9 shows estimated annual electricity consumption for each group and the consumption difference for each model. While Ordinary Least Squares (OLS) techniques were used for exploratory data analysis, the improved error estimates described in Appendix D were used for Models 2 and 3.

Table 9. Metered Annual Consumption vs. Label Estimate			
	Group S [std.err.]	Group E [std.err.]	Difference ± 95% conf.
Model 1	784 kWh[a]	600 kWh[c]	184 kWh
Model 2	782 kWh[a] [14.5]	598 kWh[c] [11.4]	183 ±36 kWh
Model 3	787 kWh[a] [1.9]	602 kWh[c] [1.7]	184 ±4.9 kWh
Label	875 kWh[b]	695 kWh[b]	181 kWh[b]
Best Estimate			**156±28 kWh**[d]
Estimate from principles[e]			
Identical cabinets			≈162 kWh
Identical COP			≈131 kWh

a. Anti-sweat heater on 53.1%, occupancy 2.98 persons
b. Anti-sweat heater on 50%
c. Anti-sweat heater on 44.7%, occupancy 2.54 persons
d. Includes an estimated bias (derived later in this section) of 28 kWh [s.e.=13.8 kWh] due to occupancy and anti-sweat heater use differences between groups.
e. Based on food load and other occupancy effects equaling 15% of standard unit label

Thus the refrigerator label data tend to over predict the actual consumption of these refrigerators in the PG&E service territory. The 95% relative confidence interval is 4.6% (28/602) of the annual consumption of the efficient group. This confidence interval is substantially more precise than that required for load impact measurement [CPUC, 1993].

The Effect of Non-Temperature Parameters on Annual Consumption

Based on this study we can estimate the range of effect in annual consumption due to the anti-sweat heater, the automatic icemaker, and occupancy effects (door openings and food loading). These are reported in Table 10.

Table 10. Estimated Range in Annual Consumption Change Due to Changes in Non-temperature Parameters		
Variable	Estimated Range (annual)	Source
Anti-sweat Heater Use	90 to 136 kWh 15% to 18%	Lab Results
Automatic IceMaker	74 to 104 kWh 12% to 13%	Model 1 Regression
Occupancy Effects (door openings and food loading)	87 to 128 kWh 14% to 17%	Hourly Load Shape Analysis [a]
Occupancy Effects (per occupant)	34 to 43 kWh 5 to 6%	Hourly Load Shape Analysis [a]

a. Hourly load shape analysis as described below as based on load shapes from Part 2 of this report.

Anti-Sweat Heater

The regression coefficients from Model 1 (Table 5) indicate that a refrigerator with this switch on consumes 137 and 73 kWh/year more, on average, than when the switch is off for Groups S and E respectively. In terms of the adjusted annual consumption, leaving the switch on adds approximately 17% to the average unit. These coefficients are well determined statistically.

The laboratory test procedure calls for testing the refrigerator with both switch settings and averaging the results. The differences in the tests average 123 kWh for Group S and 103 for Group E (AHAM, 1991 and 1992). This is good agreement between laboratory and Model 1 regression coefficient for the standard group, but significantly different for the efficient group. Additionally the estimate from the regression coefficient is 11% higher than the lab number in one case and 28% lower in the other . For these reasons we accept 90 to 136 kWh (based on the laboratory tests) as a good estimate of the anti-sweat heater effect.

The importance of the anti-sweat heater suggests that its being turned off may be a behavioral measure that could be publicized by PG&E with the rebate program. For example, “Turning on the anti-sweat heater adds about 17% to your refrigerator's energy use. If you do not need it, turn it off.”

Icemaker

According to the Model 1 regression coefficients (Table 5) the presence of an icemaker adds substantially to consumption: 78.2 (s.e. 2.2) and 99.9 (s.e. 1.9) kWh/yr. for the average refrigerator in Groups S and E respectively. The presence of an icemaker is positively correlated to refrigerator volume, which makes the coefficients less reliable. While statistically less reliable, the magnitude of these coefficients is physically reasonable: the icemaker could easily add 78 to 100 kWh to annual consumption. There are no obvious reasons why it should be higher in the more efficient units.

One study found that "icemakers can increase test estimated energy use by up to 20% when operated continuously". [BR Laboratories, 1986, as cited in Parker and Stedman, 1992] Parker and Stedman [1992, p.3.209] estimated that total icemaker average electricity use in one monitored refrigerator was 36 watt- hour per cycle; they averaged 5.7 cycles per day during a one-week spring period (in Florida), at which rate the annual consumption would be 75 kWh.

The defective operation of the icemaker, whereby it did not shut off when no longer needed, increased consumption by 357 kWh/yr. relative to the consumption with the icemaker off in one of the refrigerators studied in the 1991 PG&E field monitoring project. [Proctor and Dutt, 1992, p.12]

The energy consumption of an icemaker is not included in the laboratory test consumption figure. From PG&E's perspective, the presence of an icemaker should be assumed to add approximately 80 kWh, to the consumption of a unit of comparable volume without such a feature. This difference should be considered in an energy efficiency rebate program. It is conceivable that the addition of an automatic icemaker can offset nearly half the difference between the two groups.

As in the case of the anti-sweat heater, PG&E could make suggestions to promote energy efficient behavior, e.g. avoid buying an automatic icemaker or switch it off when not needed.

Occupancy Effects (Door Openings and Food Loading)

OCCUPANCY EFFECTS FROM MODEL 1

In the Model 1 regression, the number of occupants in the house was taken as a surrogate for door openings and food loading. Other surrogates, such as house size, showed no predictive capability.

There is significant variation in the number of occupants. Given the relatively large variation, it is expected that the regression coefficients will be statistically meaningful. Both coefficients are well determined: 36.0 (s.e. 0.5) for Group S and 21.9

(s.e. 0.6) for Group E. But the coefficients are very different for the two Groups, and this is not physically reasonable. As discussed in the Validity of Model Coefficients Section of Appendix B, the coefficient for Group E can be, at most, 20% less than that for Group S. However the reduction in coefficient is 39 % and not physically reasonable.

OCCUPANCY EFFECTS FROM HOURLY LOAD SHAPE

While the Model 1 regression did not supply coefficients for occupant effects that were physically consistent across the two groups, the hourly load shape analysis described in Part Two of this report (Proctor et. al. 1994) makes physically meaningful estimates possible. The load shape change over the day when the interior temperatures are likely to remain constant (winter days with daily average temperature below 59°F) is shown in Figure 3.

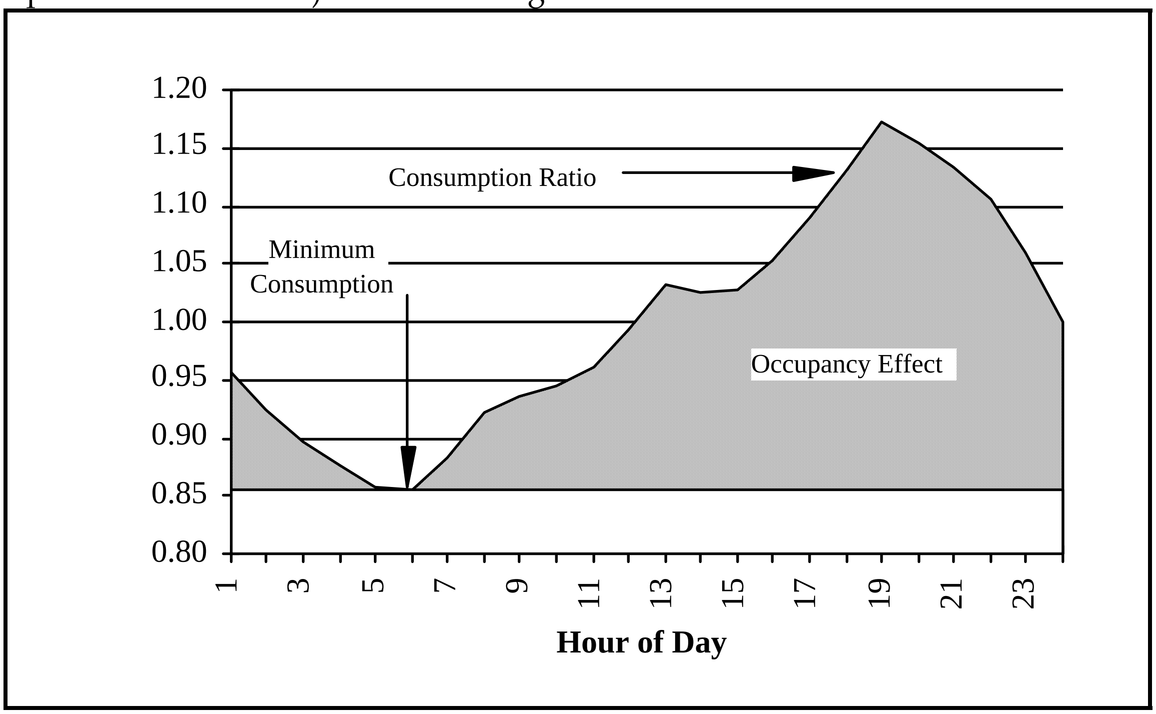

Figure 3. Hourly Load Shape Ratio in Winter (from Proctor et. al. 1994)

This load shape can produce an estimate of occupancy as follows. The minimum load is a measure of consumption without occupant effect, while the load at all other hours is increased only by occupancy effects. Based on Equation 3, page 14 in Part Two of this report, the occupancy effect is estimated as:

$$\left(\sum_{k=1}^{k=24}(R_{wk} - R_{w6})\right) \times \text{Average DailyUse}_W \qquad (7)$$

where

R_{wk} = The load ratio in the winter in hour k

R_{w6} = The load ratio in the winter in hour 6 (the hour of minimum load)

Average DailyUse_W = The annualized average daily use in the winter

An upper limit of the occupancy effect can be calculated assuming that the consumption above the 6 AM minimum is due to occupancy effects over the whole year. In reality, daytime interior temperature (and refrigerator consumption) rises both from night setback (winter) and from temperature float (mild periods and summer without air conditioning). The estimated occupancy effects from winter and whole year data are given in Table 11.

Table 11. Occupancy Effect Estimates

	Group S	Group E
Occupants	2.98	2.54
Annual Occupancy Effect Based on Winter Load Shape (average daily temperature < 59°F)	114 kWh	87 kWh
Occupancy Effect per Occupant (based on winter)	38 kWh	34 kWh
Upper Limit of Annual Occupancy Effect (based on load shapes from entire year)	128 kWh	98 kWh
Upper Limit of Occupancy Effect per Occupant (based on full year)	43 kWh	39 kWh

Adjusting for Bias from Differences in Occupancy and Anti-sweat Heater Use

The potential bias can be estimated from two sources The occupancy effect can be estimated from the load shapes as shown in the previous section and the anti-sweat heater effect can be derived from reported laboratory data.

As reported in Table 10, the upper limit of the occupancy effect was estimated to be 128 kWh/yr for Group S (with 2.98 occupants per household) and 98 kWh/yr for Group E (with 2.54 occupants per household). The upper limit of the effect per person turns out to be surprisingly similar for the two groups -- 43 kWh/yr and 39 kWh/yr, respectively. Note that the winter based estimates (34 and 38 kWh) are in close agreement with the occupancy coefficient calculated for Group S in Model 1 (36 kWh) and for Group T in Part Two of this study (33 kWh). In reality, the consumption per occupant should decrease as the number of occupants increases and these regression coefficients capture only the change in occupancy (not any intercept effect). Thus if we take an average per-occupant effect of 41 kWh/yr and adjust for the difference (0.44 occupants per household) between the two groups, we obtain an upper limit on the bias in consumption: Group S consumes at most 18 kWh/yr more than Group E, because of differences in occupancy.

Laboratory test data reported by manufacturers (AHAM, 1991 and 1992) indicate that leaving the anti-sweat heater on increases annual consumption by 123 and 103 kWh for Groups S and E respectively (113 kWh average). The heater is on in .532 of the Group S refrigerators and on in .447 of the Group E refrigerators (an average difference in heater use of .085). The average increase in Group S consumption from anti sweat heaters is {113 * .085} = 9.6 kWh relative to Group E refrigerators.

Differences in occupancy and anti-sweat heater operation between the two groups thus increase the difference in consumption by 18 + 9.6 or 27.6 kWh/yr (or slightly less). This bias is adjusted for in Tables 1 and 9.

<u>Calculation of Standard Error of the Difference in Consumption</u>

The difference in mean consumption based on measurements, and not including an adjustment for differences due to occupancy and anti-sweat heater use (from Model 3), is 184 kWh/yr

The standard error of this estimate is $\sqrt{1.9^2 + 1.7^2} = 2.55$ kWh

Adjusting for the sample bias reduces the estimated difference by 27.6 kWh/yr to 156 kWh/yr. Assuming a standard error of the sample-bias correction of 13.8 kWh, the standard error of the difference would be:

$$\sqrt{1.9^2 + 1.7^2 + 13.8^2} = 14 \text{ kWh}$$

V. CONCLUSIONS AND RECOMMENDATIONS

Based on a year of metering activity on 256 refrigerators, this study supports a number of conclusions and recommendations.

Conclusions

- The actual energy consumption of these new refrigerators in the PG&E service territory is 10% to 14% below that stated in the refrigerator labels. This will result in an overestimation of savings by the same percentage. The annual consumption of these refrigerators is overestimated because the labels are based on a test procedure at 90°F. When installed in kitchens in PG&E's service territory the energy consumption due to temperature differences is substantially reduced. Even with the additional energy consumption from occupant effects and accessories such as icemakers, the in-situ consumption does not increase to the level of the label.
- The estimated difference in annual consumption derived from the Federal labels for the two metered groups (181 kWh) lies within the confidence bounds of the consumption estimated through this metering study. It should be noted that a potential sampling bias exists between the groups and that by physical principles, the in-situ difference would be at least 10% less than the labeled difference (for PG&E's service territory). Part Two of this study establishes the actual difference as 13.8% less than the labeled difference based on customers most likely to participate in rebate programs for high efficiency refrigerators (Proctor et. al., 1994).
- Refrigerator consumption is increased 100 to 125 kWh by the anti-sweat heater (according to the DOE test) and 75 to 105 kWh by an automatic icemaker. The anti-sweat heater and automatic icemaker can be the target of consumer education.

Recommendations

- An adjustment factor (G in Equation 2) should be added to the calculation of gross impact. The value of G is estimated in Part 2 of this study as 0.862.
- Regression coefficients for average temperature and "cool temperature" from this study may be used to estimate energy consumption of similar refrigerators in other areas, if appropriate temperature data are substituted.
- The DOE test and label should be revised to show the effect of an automatic icemaker.

INTRODUCTION TO APPENDICES

Proctor Engineering Group subscribes to a set of analysis and reporting principles. These principles maintain that a quality field research/evaluation report:

1) is transparent - the analytical and measurement methods are clearly stated so other researchers can verify the adequacy of the methods used. For example, computed confidence intervals are reported with the calculation methodology and the inputs to the calculations (such as n, std.dev., etc.)
2) utilizes prior knowledge - contains discussion of prior work and how that work supports or questions the result of the present study. It discusses probable causes of the differences.
3) utilizes peer review of the results when possible in line with confidentiality.
4) provides information about potential measurement and analytical bias.
5) relies to the maximum possible extent, on measured data rather than assumed values.
5) states what assumptions are made (and implied) in the analysis.
6) states and answers the research questions addressed.
7) communicates the results.
8) states the limitations of the research (caveats).
9) states the results of any alternative models attempted and why the final model was adopted.
10) reports any attrition of data and analyses the potential effects.
11) states the context of the research/evaluation and any linkage to funding.
12) describes the technology or program being evaluated sufficiently for the reader to determine what is being evaluated. For example, "House Doctoring" is not a sufficient description (information on the actual diagnostic processes, repair processes etc. used are available to the reader).

The attached appendices are included to address these principles.

APPENDIX A REFERENCES

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APPENDIX B MODEL DEVELOPMENT

The basic data analysis procedure is multivariate (multiple) regression. The measured annualized consumption is the dependent variable. The predictor variables are chosen to produce the best model (judged by statistical and practical analysis). Three models are discussed in this report:

- Model 1 - annualized consumption against daily average outside temperature and several static variables (i.e. that do not change from day to day). This model has a data point for each day each refrigerator was metered (Group S, N=35239; Group E, N=31063).
- Model 2 - similar to Model 1 except that the only predictor variable used is outside temperature.
- Model 3 - daily averages of annualized consumption against daily average outside temperature. This model was limited to days when there was data for at least 75 refrigerators in the group (N=302 for Group S and 299 for Group E).

These models were initially developed using an Ordinary Least Squares (OLS) analysis. This was followed by a method of estimating appropriate standard errors described by White (1980). (See Appendix D.)

In order to be valid the model must meet the following criteria:

- The assumptions are not violated
- The model coefficients are physically meaningful[6]
- The model coefficients are internally consistent
- The model coefficients are stable and statistically valid

<u>Model 1</u>

Model 1 provided the base on which the other models were developed. The model was developed in five steps. First, potential predictor variables were identified and examined for interactions. Interactions between variables can cause regression coefficients to take on the effect of another variable, invalidating any assumption that the coefficient has physical meaning.

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[6] While it can be argued that the regression coefficients do not have to be physically meaningful (because they are controlling for another factor omitted from the analysis), use of these variables as predictors is only valid if their relationship to omitted variables is the same in the population as it is in the sample. After extensive work with this data, such an assumption does not appear valid.

Second, combinations of predictors were explored to find which produced a model with good fit to the data and apparently valid coefficients. In the third step, one variable (Avg. temp) was allowed to produce a different coefficient in different temperature ranges. In the fourth step, the final combination of predictor variables were selected. Fifth, the viability of the model coefficients was examined.

For this model, the electrical consumption of the refrigerator is a linear function of a number of predictor variables. The model takes the form:

$$\text{Annualized consumption} = A + B \times v_1 + C \times v_2 + \ldots \qquad \text{(3 repeated)}$$

where:

A = the intercept constant

B = the coefficient of predictor variable 1, etc.

The predictor variables include the daily average outside temperature and several static variables (i.e. that do not change from day to day).

Model Assumptions

This model assumes that the effect of each of the predictor variables is independent (which implies that the effect of the static variables is the same over the whole range of the other variables). It assumes that the effect of temperatures, thermostat setting, and volumes is linear (or with modification, linear within a temperature range).

Potential Predictor Variables

A total of 32 potential predictor variables were considered. The final variables in Model 1 are underlined in Table 12.

Table 12. Potential Predictor Variables	
Variable code	Description
Avg temp	average daily outside temperature, °F nearest weather station
Kit temp	kitchen temperature measured at technician visits, °F
Icemaker	if on (=1), if not (=0)
Sweat	anti-sweat heater switch setting: on (=1), off (=0)
Occupants	number of people in household[1]
House Size	floor area of home, sq. ft.[1]
Frez temp	freezer temperature measured at technician visits,°F
Frez set	freezer setting, between coldest (=100) & warmest (=0)
Ref temp	fresh food temperature measured at technician visits,°F
Ref set	thermostat setting, between coldest (=100) & warmest (=0)
Lab kWh	label consumption data, kWh/yr
Fresh vol	volume of fresh food space, cu.ft.
Frez vol	volume of freezer space, cu.ft.
Adjusted vol	1.63 x Frez vol + Fresh vol, cu.ft.
Coil location	location of condenser coil, back (=1), bottom (=0)
Evap cooler	does house have an evaporative cooler? yes (=1), no (=0)
Evap time	normal operation time for evaporative cooler, hour of day[1]
AC	does house have an air conditioner? yes (=1), no (=0)
AC time	normal operation time for AC, hour of day[1]
T-stat day	summer daytime house thermostat setting, °F[1]
T-stat night	summer nighttime house thermostat setting, °F[1]
Clear (1 to 6)	Six different clearances between refrigerator and walls, etc., inches
Seal	condition of door seal, good (=1), bad (=0)
LO load	frequency of leftover loading, occurrences per day[1]
LO temp	temperature of leftover loading, hot (= 1), cool (=0)[1]
Ht source	is refrigerator near a heat source? yes (=1), no (=0)[1] (also which one)
Door open	number of door openings midnight to 6 AM[1]

1 Reported by occupant.

The mean values and standard deviations of the dependent variable and potential predictor variables are shown in Table 13. Of these, only Avg temp is based on daily data corresponding to the measurement of consumption; all others are based on prior information or on "snap shot" measurements at the time the unit was instrumented or the meter downloaded. In the sample selection, refrigerators in the two groups were matched for total volume and presence of automatic icemaker. Other variables (i.e. number of occupants, etc.) were not matched and Table 13 shows differences between the group averages (weighted by occurrence in the data set) for variables tested with the entire sample set. Some variables (i.e.. freezer setting, etc.) were tested in a subset and discarded.

Table 13. Summary Statistics for Dependent Variable (Annualized kWh) and Potential Predictor Variables					
	Group S		Group E		Difference
	Mean	Std. dev.	Mean	Std. dev.	Mean
Annualized kWh	826.2	261.9	636.6	208.1	189.6
Avg temp	61.3	12.2	61.4	12.1	-0.1
Kit temp[1]	69	4.2	69	3.7	0
Icemaker	0.243	0.429	0.281	0.449	-0.038
Sweat	0.532	0.499	0.447	0.497	0.085
Occupants	2.98	1.69	2.54	1.29	0.44
House Size	1440	448	1490	542	-50
Frez temp[1]	5.3	6.3	5.5	7.2	-0.2
Ref temp[1]	37.6	3.8	39.1	3.6	-1.5
Ref set	54.2	16.9	63.8	16.4	-9.6
Lab kWh	875.4	63.3	694.6	30.9	180.8
Fresh vol	13.81	0.83	13.57	0.61	0.24
Frez vol	5.31	0.85	5.41	0.8	-0.1
Adjusted vol	22.47	1.95	22.39	1.73	0.08
Coil location	0.28	0.45	0.15	0.35	0.13
Evap cooler	0.26	0.439	0.204	0.403	0.056
AC	0.473	0.499	0.509	0.5	-0.036
T-stat day	79	3.6	79	3.1	0
T-stat night	80	2.4	79	2.7	1
Seal	0.95	0.22	1	0	-0.05
LO load	1.3	0.7	1.2	0.8	0.1
LO temp	0.05	0.21	0.08	0.28	-0.03
Ht source	0.47	0.5	0.42	0.49	0.05
Door open	0.57	1	0.55	1.1	0.02

1. “Snapshot “ reading, not necessarily a reliable estimate of long term temperatures.

As shown in Table 13, Groups E and S are not identical. When the variables are significantly different and they significantly effect the predicted energy consumption, they must be accounted for in the final analysis.

One of the strengths of models such as Model 1 is that they can make those corrections (as long as the coefficients are statistically valid and physically meaningful).

Exploring Potential Interactions Between Variables

Not all the predictor variables are independent, and this would affect the regression results. To determine the correlation of these variables, Pearson Product-Moment Correlation between the predictor variables (and the dependent variable) were computed, for each group. These are shown in Tables 13 and 14.

Table 14. Pearson Product-Moment Correlation Group S

	Ann kWh	Avg temp	Icemaker	Sweat	Occu-pants	Ref set	Label kWh	Fresh vol	Frez vol	Adj vol	Evap
Ann kWh	1.00										
Avg temp	0.56	1.00									
Icemaker	0.20	0.03	1.00								
Sweat	0.31	0.06	0.09	1.00							
Occupants	0.32	0.02	-0.10	0.05	1.00						
Ref set	0.27	0.00	-0.05	0.02	0.27	1.00					
Label kWh	0.32	-0.02	0.16	-0.03	0.21	0.13	1.00				
Fresh vol	0.16	-0.05	0.22	-0.12	0.18	0.14	0.48	1.00			
Frez vol	0.31	-0.03	0.29	-0.02	0.16	0.23	0.73	0.53	1.00		
Adjust vol	0.29	-0.04	0.30	-0.06	0.19	0.22	0.72	0.80	0.93	1.00	
Evap	0.18	0.06	-0.14	0.20	0.26	0.21	0.12	-0.06	0.16	0.09	1.00
AC	0.06	0.08	0.23	-0.08	-0.19	-0.07	-0.01	0.01	-0.03	-0.01	-0.46

Table 15. Pearson Product-Moment Correlation Group E											
	Ann kWh	Avg temp	Icemaker	Sweat	Occupants	Ref set	Label kWh	Fresh vol	Frez vol	Adj vol	Evap
Ann kWh	1.00										
Avg temp	0.58	1.00									
Icemaker	0.32	0.04	1.00								
Sweat	0.22	0.01	0.10	1.00							
Occupants	0.13	-0.06	0.02	-0.05	1.00						
Ref set	0.22	0.05	0.09	0.08	0.11	1.00					
Label kWh	0.23	-0.03	0.40	0.08	0.20	0.07	1.00				
Fresh vol	0.16	-0.01	0.30	0.15	0.17	0.06	0.76	1.00			
Frez vol	0.23	-0.04	0.37	0.05	0.18	0.06	0.97	0.58	1.00		
Adjust vol	0.23	-0.03	0.39	0.09	0.20	0.06	1.00	0.79	0.96	1.00	
Evap	0.04	0.05	0.15	0.08	-0.12	0.01	0.04	0.10	0.01	0.05	1.00
AC	0.19	0.13	0.18	0.01	-0.02	0.10	-0.08	-0.08	-0.07	-0.08	-0.21

Scanning Tables 13 and 14 for values of correlation, larger than 0.1, it is observed:

- The dependent variable (Annualized kWh) is well correlated with several of the predictor variables. The strongest correlation is with the average temperature.
- Annualized kWh is not well correlated with the presence of an evaporative cooler in Table 15 nor with the presence of an air conditioner in Table 14. This suggests that both are poor predictors.
- The average temperature is relatively independent of all the other potential predictor variables.
- The icemaker is positively correlated with refrigerator and freezer volume: larger units are more likely to have an icemaker. This fact is probably responsible for the positive correlation between the icemaker and the labeled consumption.
- The presence of an icemaker is positively correlated with whether the house has air conditioning.

- Anti-sweat heater switch positioning is nearly independent of other variables with two exceptions. For Group S the anti-sweat heater is more likely to be on if the house has an evaporative cooler. It is also correlated with fresh food volume in Group E.
- The number of occupants is correlated with a number of other predictors. The more persons in the household the larger the refrigerator is likely to be. This results in a positive correlation with the labeled consumption.
- Occupancy has a mixed correlation with both evaporative coolers and air conditioners. It also has a correlation with the refrigerator dial setting for Group S.
- Refrigerator dial setting shows many correlations in Group S, including: occupancy, volumes, and even the presence of an evaporative cooler.
- The labeled consumption is strongly correlated with refrigerator volume measurements, since the units selected are all in the same range relative to the minimum efficiency standards, which are calculated based on the refrigerator adjusted volume.
  The 1990 minimum efficiency standard specified a maximum laboratory test consumption (kWh/year) equal to 325 + 23.5 x (Adjusted vol, ft^3).
- The volume measurements are strongly correlated to each other.
- The presence of evaporative coolers is inversely correlated to that of air conditioners: a household with an air conditioner is less likely to have an evaporative cooler as well.

Given the many correlations between the predictor variables, care must be exercised. Undue weight should not be given to the regression coefficients involving these variables.

These correlations may be used as a guide in selecting predictor variables for the regression. Since Fresh vol and Frez vol are so strongly correlated with each other, Adjusted vol (as defined for the efficiency standard) was used as the single size variable. The labeled consumption is not used in the regression since it and adjusted volume are essentially the same.

Initial Model with Linear Dependence on Average Temperature

A linear multiple regression was carried out using measured annualized consumption. The corresponding regression results are shown in Table 16. The other variables in Table 11 were eliminated because they were interactive (as discussed above) or were tested in the regression and found to have little predictive value.

Table 16. Initial Regression - Model 1		
	Group S	Group E
R squared	.592	.529
Standard Error of Residual	167 kWh	143 kWh
	Coefficient Value [and Std. Error]	
Constant	-861 [12]	-537 [12.6]
Avg temp	11.5 [0.07]	9.8 [0.07]
Icemaker	72.2 [2.30]	96.1 [2.02]
Sweat	145.0 [1.82]	75.0 [1.65]
Occupants	37.8 [0.56]	21.8 [0.65]
Ref set	2.45 [0.06]	1.63 [0.05]
Adjusted vol	27.9 [0.51]	14.9 [0.53]
AC	34.3 [1.88]	33.7 [1.69]

The R-square for the OLS regression was 0.592 and 0.529. The coefficients are all highly significant (have high t values). The signs of all the coefficients (except one, presence of an air conditioner) are physically meaningful. Thus consumption goes up with increased outdoor temperature, presence of an automatic icemaker, if the anti-sweat heater is on, if there are more people in the household, if the refrigerator thermostat setting is higher (i.e. more cold), and if the adjusted volume is larger.

However, refrigerators in houses with an air conditioner use, about 34 kWh/yr more, according to the regressions. The initial analysis (Table 14 and 14) showed that the presence of an air conditioner was positively correlated with the presence of an icemaker, and that houses in hotter areas were likely to have air conditioners. The regression attempts to separate out these other dependencies by including the icemaker and average temperature as separate predictor variables. Nevertheless, the dependence on the AC variable remains anomalous, and deserves further attention.

The regression equation used to compute the coefficients in Table 16 is completely linear, i.e. the predictor variables are expected to affect refrigerator energy consumption in a linear manner. While this might be a reasonable hypothesis for most of the explanatory variables, there is one exception, average temperature.

Discussion of Outdoor Temperature, Kitchen Temperature, and Air Conditioning

Both intuitively and empirically [Meier et. al., 1993] it is known that the energy consumption of refrigerators increases with kitchen temperature. Recall that in this study, in conjunction with the large sample size, it was decided not to record the temperatures in the kitchens where the refrigerators are located. Instead, the ambient temperature variable chosen is Avg. temp, the daily average outside temperature, easily obtained from a nearby weather station. Using the average temperature makes the data from this study useful in predicting energy consumption in other climates.

The kitchen temperature is only indirectly linked to the outside temperature. A space heating or air conditioning system and an interior thermostat setting temper the relationship between the two sets of temperature.

In winter, a space heating system keeps most houses at a constant daily average temperature. Under these circumstances, the kitchen temperature would be independent of the outside temperature and refrigerator energy consumption would be nearly constant.

When it is mild outside, the heating system is turned off in most houses, and the interior temperature tends to “float”, generally a few degrees above the outside temperature. Under these conditions, refrigerator energy consumption would track outside temperature.

When it is hot outside, people respond to it in different ways. On the one extreme, they may turn on an air conditioner and maintain a constant interior temperature independent of the temperature outdoors. On the other extreme, they may not have an air conditioner (or if they have one, hardly use it), and the house continues to float close to the outside temperature. In between, people may use a limited amount of cooling, either by cooling portions of the house with room air conditioners, or using a central air conditioner sparingly. The consequence of such a diversity of resident response to hot weather is that refrigerator energy use may vary widely from house to house.

All other factors remaining unchanged, refrigerator energy consumption will increase (roughly linearly) as the interior temperature increases. The nature of the interior-exterior temperature relationship suggests that refrigerator energy consumption will be independent of outside temperature below some value of this temperature (reference temperature), while above this value, refrigerator energy consumption is likely to increase linearly with outdoor temperature.

A study of refrigerator consumption in Rochester, New York [Meier et al, 1993] produced measurements of both inside temperature and airport temperature.

Kitchen temperature measurements were collected in 21 kitchens with new refrigerators on 30 minute intervals over eight months.

The Meier temperature data were analyzed using averaged (by outdoor temperature) data in an ordinary least squares regression (Figure 4). The relationship between these temperatures has the characteristic elbow at a reference temperature of 59°F. This reference temperature was determined by iteration to produce the least square of the residuals. The regression equation is:

$$\text{Kitchen Temperature} = 43.9 + .465 \mathbf{x} \text{ Avg temp} + .338 \mathbf{x} \text{ Cool temp} \quad (8)$$

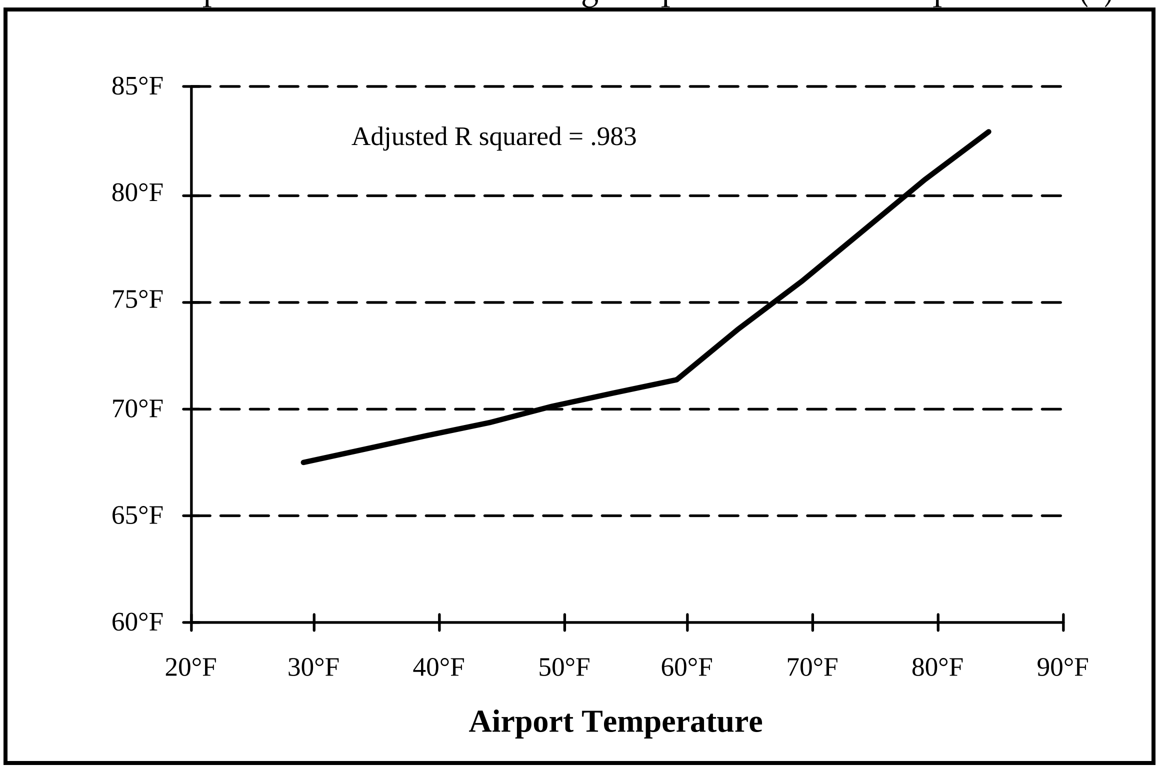

Figure 4 Relationship between Average Kitchen Temperature and Airport Temperature (Source : Meier et al., 1993)

To further explore the possible non-linear aspects of the temperature/consumption relationship, the average annualized consumption by temperature bin was plotted against average outdoor temperature for two subsets of the data. Group E (higher efficiency) refrigerators in the warmest location (Fresno) were selected and split between houses with and without an air conditioner. The results are plotted in Figure 5.

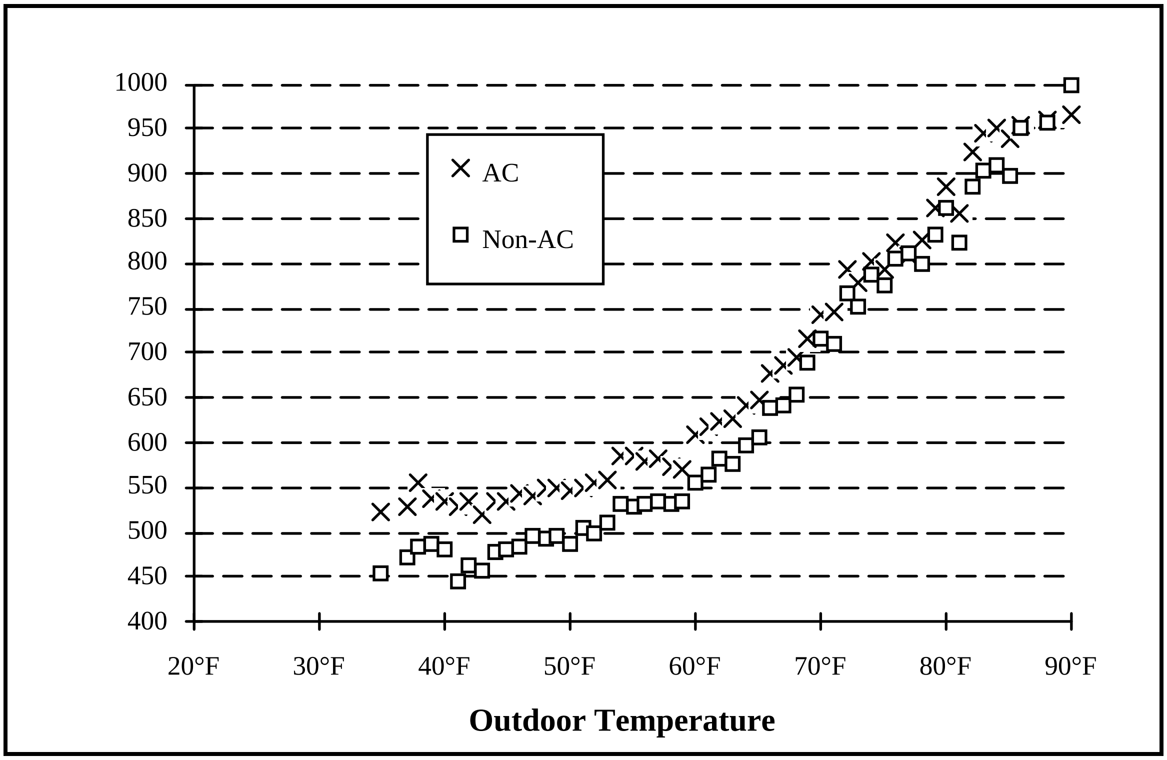

Figure 5. Effect of AC and Temperature on Refrigerator Energy Consumption

The refrigerator consumption in houses with air conditioning is higher over the entire range of outdoor temperatures (except the very highest). This is similar to the result seen in the regressions in Table 16). Since the air conditioner cannot cause the refrigerator to use more energy in the winter when it is not running, Figure 5 demonstrates that the higher consumption with AC is the consequence of an indirect relationship. For example, people with air conditioners may use their refrigerators in a different manner (including the higher likelihood of an icemaker). The data in Figure 5 is smoothed with a lowess fit to create Figure 6.

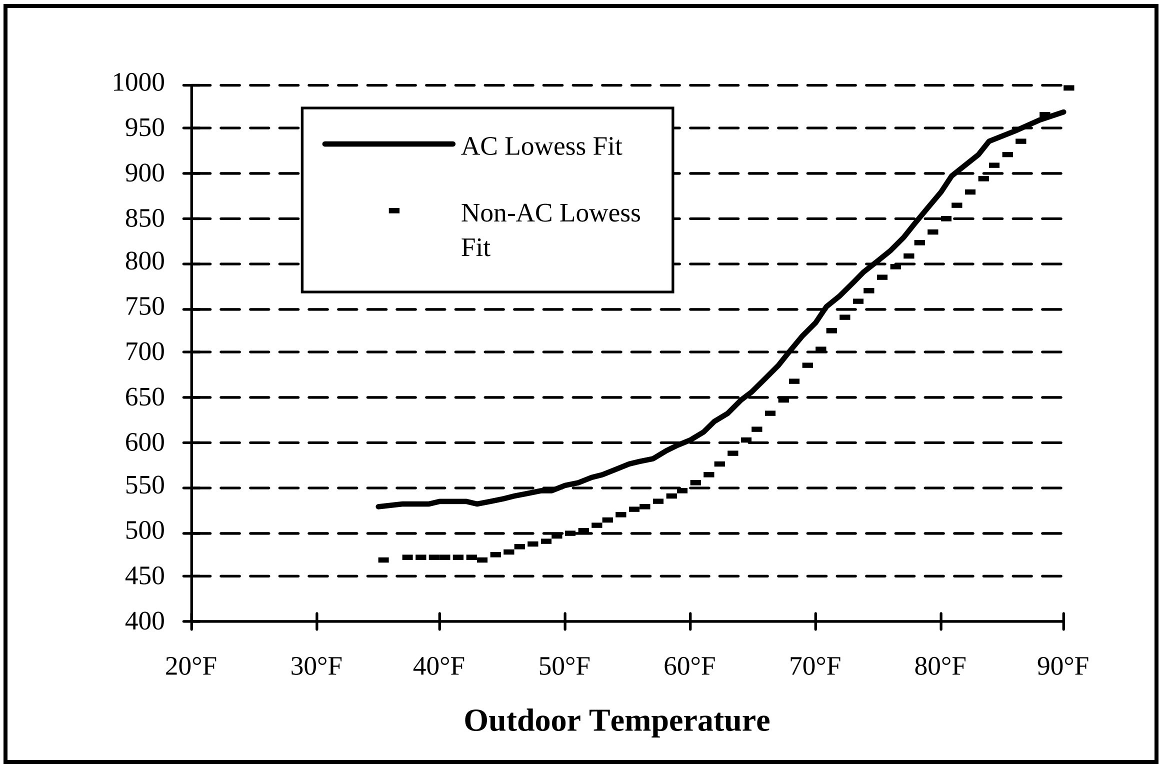

Figure 6. Smoothed Data - AC and Temperature vs. Consumption

The two curves converge at the highest temperatures, and the curve for homes with air conditioners is flatter above 83°F. This suggests that, at these temperatures, the air conditioners are likely to be operating and keep house interior at a lower temperature than their non-AC counterparts. Thus consumption does not increase as quickly with temperature as in the houses without air conditioning.

Figures 5 and 6 show the dependence of average consumption on binned outside temperature. The dependence of the standard deviation of the consumption on outside temperature, also binned, is shown in Figure 7. Recall that the data are limited to Group E refrigerators located in the Fresno area. This standard deviation about the mean is the unexplained effect once the basic dependence on outside temperature has been adjusted for.

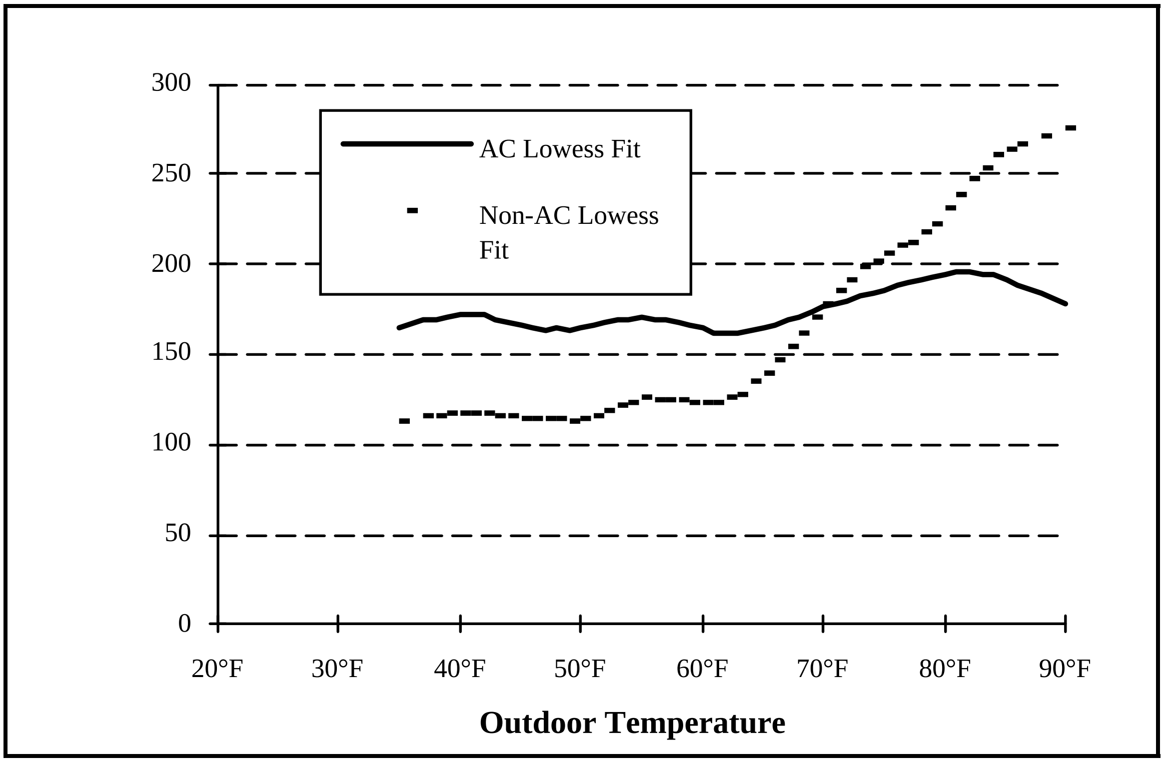

Figure 7. Standard Deviation of Consumption vs. Outdoor Temperature

For houses without air conditioners, the standard deviation increases sharply above 60°F. For houses with air conditioners, the standard deviation is roughly constant as outside temperature increases to about 60 - 65°F, increasing much less than non-AC customers at higher temperatures. This response could be the result of air conditioner operation which would reduce the effect of outside temperature on kitchen temperature, and reduce variations across data points.

Figures 5, 6, and 7 explore the relationship of energy consumption to outside temperature for the Fresno Group E data. This relationship implies a regression that will allow an “elbow” in the regression line.

Revised Model with “Elbow” Dependence on Average Outdoor Temperature

Based on the analysis of the Fresno data, the general model is revised to include an “elbow” response to outside temperature. This is accomplished by adding the variable Cool temp which is defined as (Reference temp - Avg. temp) when Avg. temp is below the reference temperature and zero elsewhere. The model takes the form of Equation 3 (see page 14, Part Two) with the variable Cool temp included with the other predictor variables: Icemaker, Sweat, etc. The results for both groups in all locations are shown in Table 17 for a reference temperature of 59°F[7]. This value of reference temperature is determined by iteration and corresponds to the value that gives the smallest sum of squares of the residual to the regression. This method of optimizing the break point of an elbow regression is familiar to users of the Princeton Scorekeeping Method (PRISM).

Table 17. Elbow Regression with AC Variable- Model 1 Reference Temperature 59°F		
	Group S	Group E
R squared	.613	.553
Standard Error of Residual	163 kWh	139 kWh
	Coefficient Value [and Std. Error]	
Constant	-1180 [13.7]	-803 [13.9]
Avg temp	16.1 [0.13]	13.7 [0.12]
Icemaker	71.6 [2.23]	93.3 [1.97]
Sweat	140 [1.78]	73.5 [1.61]
Occupants	37.1 [0.55]	21.9 [0.63]
Ref set	2.43 [0.05]	1.56 [0.05]
Adjusted vol	28.0 [0.49]	15.0 [0.51]
AC	24.3 [1.84]	26.2 [1.66]
Cool Temp	11.9 [0.27]	10.0 [0.25]

The coefficients appear to be stable and statistically valid. Yet, the coefficient for AC is not physically meaningful: all other things being equal, the refrigerator in an air conditioned house should consume less not more. We have discussed this effect earlier, and AC will be dropped as a predictor variable to eliminate this artifact.

7 "Cool temp" is then heating degree days to the base 59°F.

Revised Model without AC

Results of a regression without AC as a predictor variable and using the elbow temperature dependence are shown in Table 18

Table 18. Elbow Regression without AC Variable- Model 1 Reference Temperature 59°F		
	Group S	Group E
Adjusted R squared	.611	.549
Standard Error of Residual	163 kWh	140 kWh
	Coefficient Value [and Std. Error]	
Constant	- 1174 [13.8]	- 786 [13.9]
Avg. temp	16.3 [.13]	13.9 [.12]
Icemaker	78.2 [2.18]	99.9 [1.93]
Sweat	137 [1.77]	73.3 [1.61]
Occupants	36.0 [.55]	21.9 [0.63]
Ref set	2.43 [.05]	1.62 [.05]
Adjusted vol	27.7 [.49]	13.7 [.51]
Cool temp	12.3 [.27]	10.5 [.25]

Dropping AC results in adjustments in the other coefficients. In all cases the "with AC" coefficients plus two standard errors are within two standard errors of the "without AC" coefficients. Icemaker, which correlates with AC changes the most. The R-square and the standard error of estimates are virtually the same for this case compared to the regression that includes AC as a predictor variable (see Table 17). Thus dropping the spurious predictor AC did not appreciably hurt the data fit. This version of Model 1 was chosen as the most statistically significant and physically meaningful.

Validity of Model Coefficients

Model coefficients that are statistically valid and stable, physically meaningful, and internally consistent. can be confidently considered valid[8]. How well the model coefficients meet these criteria is summarized in Table 19.

The statistical validity of the coefficient was judged first by its t-ratio[9] and second by the effect of its inclusion on the overall R squared and standard error of the regression. The stability was judged by how much it changed as other explanatory variables were added or deleted. Prior knowledge, including other field and lab studies as well as engineering estimates were used to determine if the coefficient could be physically meaningful.

The coefficients for Average temperature, Occupant effects, and Icemaker represent the response of the refrigerator to equal increases in load. To be internally consistent, coefficients of the two groups must differ no more than the percentage difference in annual consumption as judged by the label consumption (with allowances for standard errors). This is called the Ratio Test. The percentage difference in the label consumption is 20% [(875-695)/875].

8 While it can be argued that the regression coefficients do not have to be physically meaningful (because they are controlling for another factor omitted from the analysis), use of these variables as predictors is only valid if their relationship to omitted variables is the same in the population as it is in the sample. After extensive work with this data, such an assumption does not appear valid.

9 The t-ratio is the coefficient divided by its standard error. High t-ratios imply a higher level of significance.

Table 19. Validity of Model 1 Coefficients			
Coefficient	Statistical Significance and Stability	Physical Meaning	Internal Consistency (Ratio Test)
Avg temp	Yes	Yes	Yes (15%)
Icemaker	Yes	Yes	No (-28%)
Sweat	Yes	No	Not Applicable
Occupants	Yes	Yes	No (39%)
Ref set	Yes	Unknown	Not Applicable
Adjusted vol	Yes	No	No (51%)
(Avg temp - Cool temp)[1]	Yes	Yes	Yes (15%)

1. The difference between these coefficients describes the increased consumption with increased temperature in cooler days (days with an average temperature below 59°F).

Only Average temperature and (Average temperature - Cool temperature) meet the criteria set to ensure the validity of the model. Model 2 consists only of those two predictor variables.

TEMPERATURE DEPENDENCE

The energy consumption response of these refrigerators to outside temperature is discussed in "Discussion of Outdoor Temperature, Kitchen Temperature, and Air Conditioning" earlier in this appendix. This section establishes that the coefficients of the variables Avg temp and Cool temp are in the proper range to have physical meaning.

Other studies (with smaller samples) have concentrated primarily on establishing the relationship between refrigerator energy consumption and the kitchen temperature. While the relationship to kitchen temperature is clearly more stable than the relationship to outside temperature, it is also less useful. In order to relate the results of the other studies to the present study a relationship between outdoor temperature and kitchen temperature must be used.

The Meier et al. [1993] study produced data on the relationship between kitchen temperature and outdoor temperature. That relationship was shown graphically in Figure 4 (repeated here as Figure 8 with data points shown).

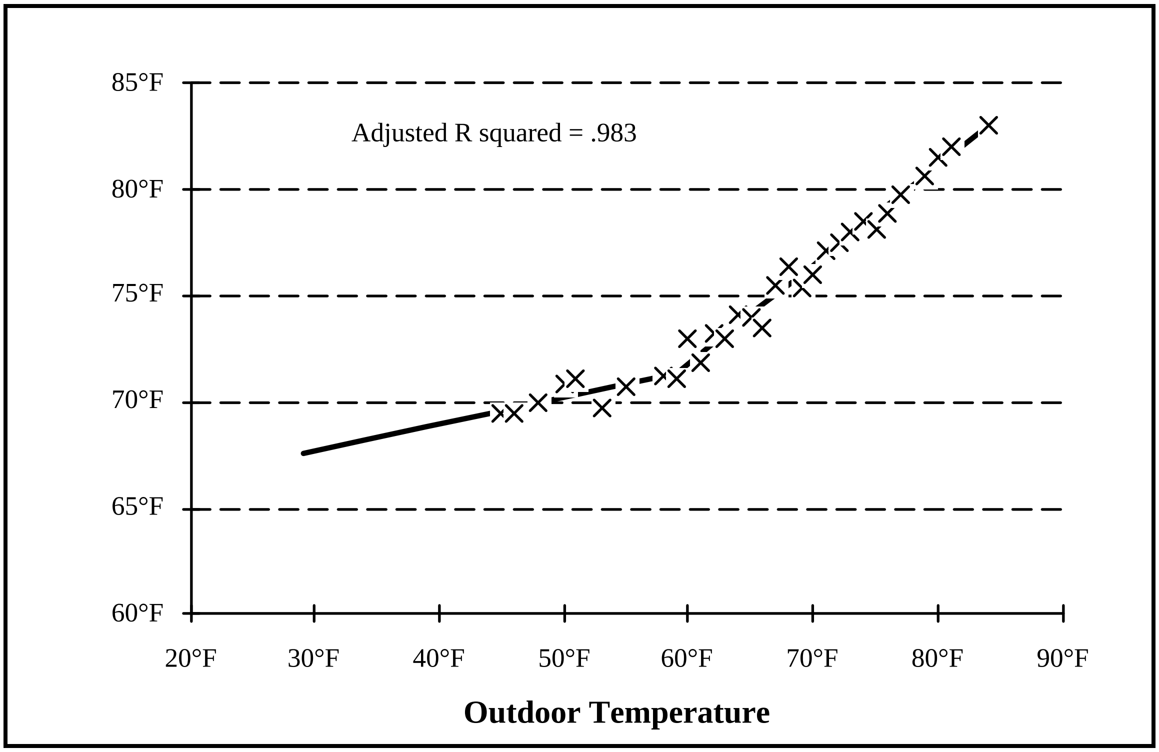

Figure 8. Relationship between Averaged Kitchen Temperature and Averaged Outdoor Temperature (Rochester, New York) from Meier et al. [1993]

From these data the relationship between kitchen temperature and outside temperature is estimated and reported in Table 20.

Table 20. Estimated Relationship between Kitchen Temperature and Outside Temperature

Daily Average Outside Temperature	$\frac{\Delta \text{ Kitchen temp}}{\Delta \text{ Outside temp}}$
Warmer than 59°F	.465
Cooler than 59°F	.128

Using these relationships our results can be compared to those of other studies . The comparisons are shown in Table 21.

Table 21. Comparison of "Avg temp" Coefficients to Similar Coefficients in Previous Studies				
Study	Refrigerator Efficiency	N	% Δ Consumption / °F Δ Outdoor Temperature	
			Warm	Cold
PG&E Gr E	highest (meets 93 Standard)	120	**2.00%**[1]	**0.49%**[1]
PG&E Gr S	high	136	**1.97%**[1]	**0.48%**[1]
Kitchen temperature data projected to outside temperature based on Table 20.				
Meier et al. [1993] # 2238	high	1	0.95%[1]	0.26%[1]
ibid. # 2209	high	1	1.94%[1]	0.53%[1]
ibid. # 1118	high	1	1.06%[1]	0.29%[1]
Parker & Stedman [1992] - Old	low	1	1.04%[2]	0.29%[2]
ibid. - New	high	1	1.87%[1]	0.51%[1]
NBS [1979]	low	unknown	0.93%[2]	0.26%[2]
Sherman et al. [1987]	low	59	0.98%[2]	0.27%[2]
ADL [1977]	low	unknown	0.93%[2]	0.26%[2]

1. percentage of labeled consumption
2. percentage of measured consumption

The PG&E results may also be compared with those of Meier et al. [1993] shown in Figure 9. There, an elbow relationship is clearly seen. The bend in the elbow was set at 50°F (the report does not make clear how this point was determined). The scatter in the data is large suggesting that the above-50°F slope of 8.4 kWh/yr/°F (or 1%/°F) is not well determined. Indeed, if an elbow point temperature of 59°F were chosen, the slope would be higher, and close to the PG&E 1992- 93 estimates. One reason for the poor determination of slope in the Meier et al. study is that at the Rochester (NY) location, there are insufficient hot days to define the temperature dependence clearly.

Figure 9. Meier Analysis - Energy Consumption vs. Airport Temperature
from Meier et al. [1993, Figure 11]. Coefficient of temperature is .023 above 50°F

For new high efficiency refrigerators the percentage change in annual consumption per change in outdoor temperature is reasonably close to the results of this study. This study also has the advantage of its varied climate and large sample size. We conclude that the slopes determined in the present study are physically meaningful.

ICEMAKER

According to the regression coefficients (Table 18), the presence of an icemaker adds substantially to consumption: 78.2 [s.e. 2.2] and 99.9 (s.e. 1.9) kWh/yr for the average refrigerator in Groups S and E respectively. The effect of an icemaker is discussed in the Icemaker section of the main report (see Page 21). The 78 to 100 kWh is judged to be physically meaningful.

ANTI-SWEAT HEATER.

The regression coefficients (Table 18) show that a refrigerator with this switch on consumes 137 (s.e. 1.8) and 73.3 (s.e. 1.6) kWh/year more, on average, than when the switch is off, for Groups S and E respectively. The effect of the anti-sweat heater is discussed in the Anti-Sweat Heater section of the main report (see Page 20). These regression coefficients are well determined statistically. However, the coefficient for

Group E is significantly lower than the lab test numbers for the same refrigerators. It is therefore concluded that the 73.3 kWh coefficient is not meaningful.

NUMBER OF OCCUPANTS

The number of occupants in the house is taken as a surrogate for door openings and food loading. The effect of the occupants is discussed in the Occupancy Effects section of the main report (see Page 22). Occupancy effects have been investigated in other studies and Table 22 compares the results with this study.

Table 22. Comparison of Occupancy Effect Coefficients to Similar Coefficients in Previous Studies

Study	Refrigerator Efficiency	N	% Consumption from Door Openings and Food Loading
PG&E Gr E	highest (meets 93 Standard)	120	**9%**[1]
PG&E Gr S	high	136	**14%**[1]
Parker & Stedman [1992] - Old	low	1	7%[1]
ibid. - New	high	1	19%[1]
NBS [1979]	low	5	13%[1]
ADL [1977]	low	unknown	14%[1]

1. percentage of measured consumption

The coefficients for occupancy are within a range that they can be physically meaningful, however the value for Group E (9%) is suspiciously low. It is expected that the percent change in consumption from occupancy effects would be higher in more efficient models. This low value for the Group E coefficient also fails the ratio test. The coefficients are judged not meaningful.

REFRIGERATOR SETTING (REF SET).

The refrigerator (thermostat) setting (Ref set), not the refrigerator interior temperature (Ref temp), appears as a significant predictor of energy consumption in the regression equations. Both variables are based on observations (Ref set) or measurements (Ref temp) at the start of the study and at every meter download. Both may have changed between readings. Physically, one would expect the refrigerator interior temperature, or the interior-exterior temperature difference, to be the most significant determinant of energy use. The refrigerator setting shows much larger standard deviation than the interior temperature readings. Another potential reason for the refrigerator setting being a better predictor is that the readings were direct and stable, whereas procedures for temperature testing may not have captured the long term interior temperature of the refrigerator.

The average refrigerator settings are very different for the two Groups, almost ten points higher for the more efficient units. The question remains whether there is anything about the Group E refrigerators that requires them to be set at a higher (cooler) level to maintain essentially the same temperature. If this is the case, adjusting annual consumption to the average setting for the entire sample (both Groups), will distort the consumption to values that are not comparable. This is a significant weakness in Model 1, in spite of its statistical validity. This is one of the reasons Model 1 was not used.

ADJUSTED VOLUME

This variable is relatively unimportant since the sample was chosen to match the volumes of refrigerators between the groups.

The consumption increases with the increasing size of the refrigerator, with the regression coefficients indicating an increase of 27.7 (s.e. 0.5) and 13.7 (s.e. 0.5) kWh/yr per cubic foot increase in adjusted volume. Since there is very little variation in adjusted volume among the units in the study (by experimental design which focused on units of roughly the same capacity) the regression coefficients are not expected to be very meaningful. The Group S coefficient is far above the 1990 standard coefficient of 23.5 (it is expected to be slightly below 23.5). The Group E coefficient is well below the 1993 standard coefficient of 16.

These coefficients may be compared with one determined by Parker and Stedman using a different approach. They statistically examined all available refrigerators in the Association of Home Appliance Manufacturers (AHAM) 1991 Directory [AHAM, 1991]. The 1541 models were classified into eight distinct types based on their configuration and features. They conducted a multiple regression using DOE test kWh as the dependent variable and a number of predictor variables and obtained the following regression equation:

$$\begin{aligned}\text{kWh} = {} & \underset{[45.05]}{27.36(\text{cubic feet})} + \underset{[25.69]}{554.3(\text{auto def.})} + \underset{[23.69]}{528.3(\text{part auto def.})} \\ & + \underset{[19.31]}{538.7(\text{man def.})} - \underset{[11.17]}{296.5(\text{single door})} + \underset{[4.32]}{79.2(\text{side-by-side})} \\ & - \underset{[9.01]}{162.8(\text{top freezer})} - \underset{[11.21]}{515.8(\text{superinsulated})} \end{aligned} \tag{8}$$

R-square = 0.929; t-values in [brackets]

The adjusted volume coefficients from Model 1 are not considered physically meaningful and they fail the ratio test.

Annual Consumption Estimated by Model 1

To estimate the annual consumption of these refrigerators for the PG&E residential population the following procedure is used. First, the effect of predictor variables other than temperature is calculated. Second, the effect of temperature (climate) is estimated using the bin analysis described in the body of the report.

The average consumption over PG&E's residential population will be dependent on the population average values of the predictor variables (Icemaker, Sweat, etc.) While the mean values for the entire service area are not known, the grand means for the entire sample can be utilized as an estimate of the service area mean. These means are shown in Table 23.

Table 23. Average Values of Predictor Variables in Entire Sample

Variable	Sample Mean
Icemaker	.26
Sweat	.49
Occupants	2.76
Ref set	59
Adjusted vol	22.43

With these means substituted into the regression equations defined in Table 18, new predictive equations with only temperature predictors is produced. Equation 3 becomes:

Group S:
Annualized consumption = -223 + 16.3 x Avg temp + 12.3 x Cool temp (9)

Group E:
Annualized consumption = -260 + 13.9 x Avg temp + 10.5 x Cool temp (10)

The equations (9) and (10) describe the dependence of annualized energy consumption of refrigerators in Group S and E, respectively, on daily average outside temperature (Avg temp). These relationships are shown graphically in Figure 10.

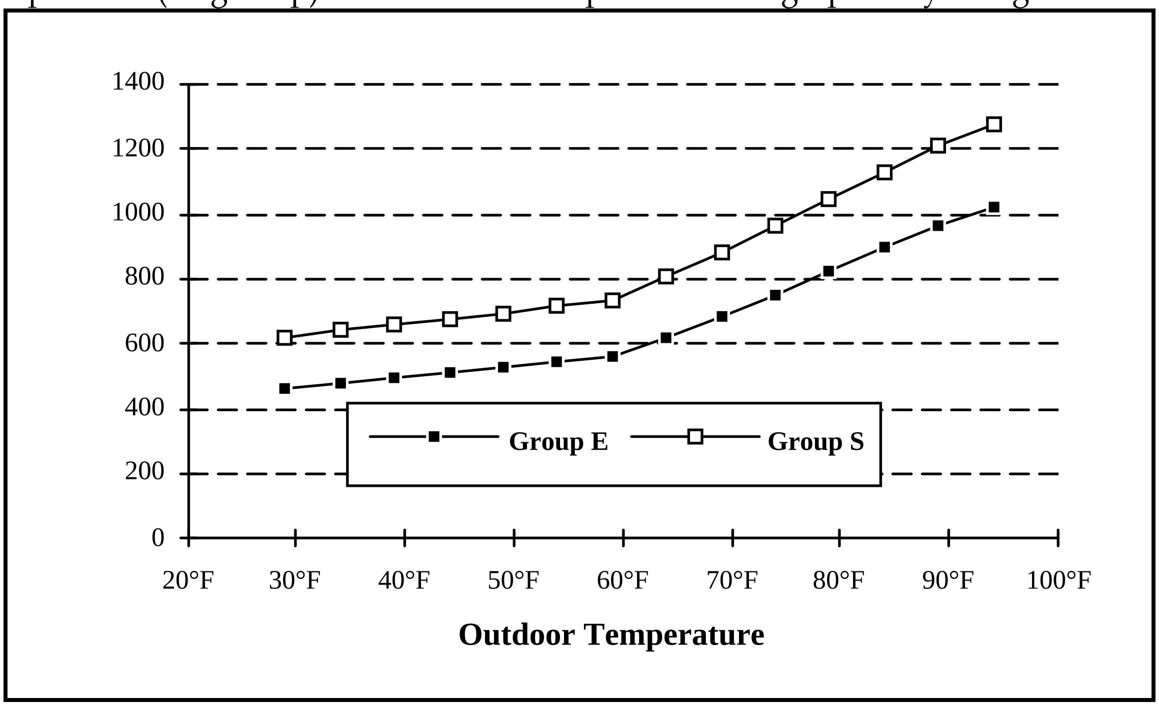

Figure 10. Model 1 - Consumption vs. Outdoor Temperature

Since refrigerator energy use is highly dependent on temperature, it is necessary to normalize the metered results based on the climate zones of PG&E's residential customers. This is accomplished by the temperature bin analysis described in the "estimating annual consumption - normalization" section in the body of the report (see Page 13). The annual consumption based on the grand means listed in Table 22 (to adjust for differences in the sample) is 784 kWh for Group S and 600 kWh for Group E.

Model 1 Summary

Review of the regression results, comparison with other studies, and physical considerations lead to the following observations. The regression is useful overall in correcting measured consumption to average conditions. A strong and well defined relationship of energy consumption to outside temperature exists, and can be used to adjust the measured values to any location, where temperature data are available. The anti-sweat heater and the icemaker were shown to add substantially to consumption. The first is reasonably included in the laboratory test procedure and label, however the second is not. The significant difference in refrigerator settings between the two groups of refrigerators raises a question about the relationship, if any, between efficiency and the setting. The regression coefficients for adjusted volume, and the number of people in the household were too different for the two groups to be reasonable. Thus, while the overall regression is useful, and some of the coefficients are meaningful, others are not. Based on this analysis Model 2 using only outside temperature variables was developed.

Model 2

Model 2 assumes that the only significant difference between the two groups is the labeled efficiency of the refrigerators and that the outdoor temperature is the only meaningful predictor available of energy consumption for each group.

Model 2 is Model 1 with all predictor variables other than outdoor temperature discarded. The model is an "elbow" regression characterized by:

Annualized consumption = A + B **x** (Avg temp) + C **x** (Cool temp) (11)

where:

A = the intercept constant

B = the coefficient of the daily average outside temperature

C = the coefficient of Cool temp.

The results of the regressions are shown in Table 24 with the corrected standard errors (see Appendix D).

Table 24. Elbow Regression - Model 2		
	Group S	Group E
	Coefficient Value [and Std. Error]	
Constant	-293 [62.8]	-309 [46.1]
Avg. temp	17.4 [1.0]	14.6 [.75]
Cool temp	14.2 [1.4]	12.2 [1.0]

The coefficients are both statistically valid and physically meaningful. The regression results are integrated with the weighted temperature bins (Figure 2) as described in Model 1. The values obtained are virtually identical to those obtained by the much more complicated Model 1 (see Table 9).

Model 2 Summary

The Model 2 regression is useful in correcting measured consumption to a wide range of temperature conditions. However, the assumption that the two groups were equal in all significant variables that affect energy is violated by the discrepancy in number of occupants and in anti-sweat heater setting.

<u>Model 3</u>

With Model 3 the varying effect of temperature from house to house, as well as the effects of other randomly distributed variables, is reduced by averaging the data. The averaged data closely corresponds to the diversified effect of these refrigerators viewed from PG&E's perspective. For each day the consumption for all the refrigerators in each group is averaged and this consumption is the dependent variable in the regression. The model takes the form:

$$\text{Ann. kWh} = a + b \times \text{Avg temp} + c \times \text{Cool temp} \tag{12}$$

where:

a = the intercept coefficient,

b = the coefficient of the 24 hour average temperature that day for the nearest weather station,

c = the coefficient of Cool temp (defined in the same manner as with Model 1)

This model has a number of assumptions. First, the effect of temperature is linear in both the cool and warm temperature regions. Second, aside from efficiency range, size, and the presence of an icemaker, all other variables that influence refrigerator energy consumption are randomly distributed among all the study refrigerators and between the two groups.

The model coefficients are shown in Table 25 and the temperature response is plotted in Figure 11.

Table 25. Elbow Regression - Model 3		
	Group S	Group E
	Coefficient Value [and Std. Error]	
Constant	-234 [20.8]	-272 [20.1]
Avg. temp	16.6 [.31]	14.1 [.31]
Cool temp	12.3 [.56]	10.9 [.53]

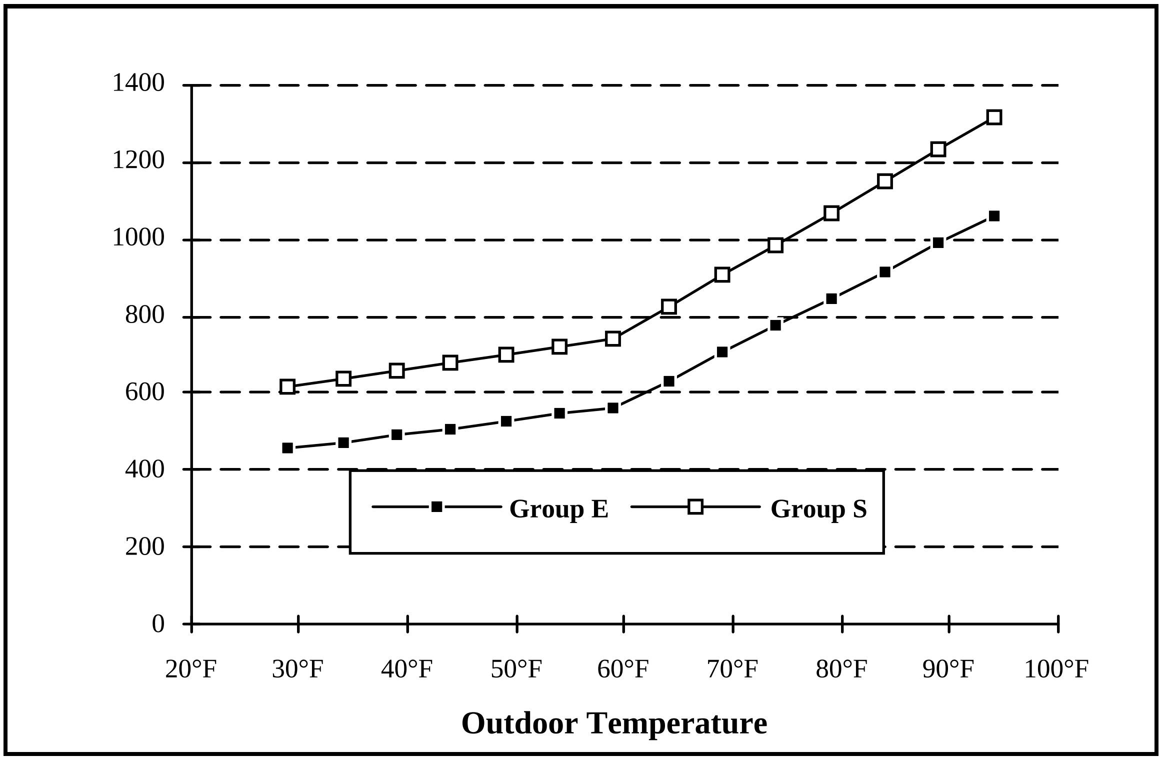

Figure 11. Model 3 - Consumption vs. Outdoor Temperature

The weather normalization procedure is the same as Model 1, and the normalized results are presented in Table 9.

Comparing Models 1, 2, and 3

Model 1 did not satisfy all the criteria set forth for model validity in the beginning of this Appendix. Although all regression coefficients were statistically significant and stable, a few were not physically meaningful while several were not internally consistent.

Models 1, 2, and 3 give virtually identical results in terms of the estimated annual consumption of the two groups of refrigerators. Thus, while some coefficients in Model 1 are not well estimated, this does not affect the overall consumption estimate. Users of PRISM are familiar with the phenomenon that the normalized annual consumption (NAC) is determined to far greater precision than are the individual coefficients α, β, and τ.

While the agreement among the three models is no doubt partly due to the large sample size of the study, the results point to the robustness of the models and the consumption estimates.

Models 2 and 3 only consider outdoor temperature as an independent variable in estimating energy consumption. Recall that Model 2 uses daily energy consumption of individual refrigerators in each group, while Model 3 considers the average consumption of all refrigerators in the group. This greatly simplifies the modeling (compared to Model 1). The regression coefficients (Table 7 for Models 2 and 3) can be used to adjust measured consumption to other locations in the US, using appropriate temperature bins in place of Figure 2.

By considering outdoor temperature to be the only predictor variable, both Models 2 and 3 neglect the effect of differences in other parameters when considering differences in consumption between groups. In this study, an adjustment for differences in occupancy and anti-sweat heater position could be made for Model 2 and 3 estimates. In extrapolating consumption to other locations, a similar adjustment could be made if survey data were available to indicate mean values of occupancy and anti-sweat heater switch position, using the adjustment factors of this study (see “Adjusting for Bias from Differences in Occupancy and Anti-sweat Heater Use”, Page 23).

APPENDIX C PG&E RESIDENTIAL CUSTOMER WEIGHTED TEMPERATURE BINS

Table 26. Service Territory Temperature Bins - PG&E Residential Customers

Bin	Days	Weighted Mean Temperature
26-30°F	.02	28.9°F
31-35°F	.36	32.9°F
36-40°F	3.03	38.8°F
41-45°F	16.59	43.9°F
46-50°F	41.46	48.0°F
51-55°F	68.42	52.7°F
56-60°F	76.61	57.5°F
61-65°F	77.42	62.6°F
66-70°F	41.77	67.3°F
71-75°F	18.68	72.4°F
76-80°F	11.45	77.3°F
81-85°F	6.91	81.6°F
86-90°F	2.19	87.0°F
91-95°F	.09	90.3°F

APPENDIX D STANDARD ERROR ESTIMATION

Consistent Standard Error Estimation Using White's Method on Grouped Data

A method described by White (1980) was used to estimate appropriate standard errors for the daily usage models and the hourly ratio estimates. When applied to "grouped" data such as in this data set, White's approach estimates standard errors which account for the within-refrigerator correlations. Essentially, the approach involves estimating the error variance-covariance matrix using the observed structure in the residuals, grouped by refrigerator (including calculating off-diagonal elements within refrigerators). The variance covariance matrix of the parameters is then calculated using this matrix in the standard equation for estimating OLS standard errors when the residual are correlated and/or heteroscedastic:

$$(X'X)^{-1}X'VX(X'X)^{-1} \tag{13}$$

where V is the estimated variance covariance matrix of the residuals

APPENDIX E PREVIOUS STUDIES

A number of previous studies have been conducted on residential refrigerators. These studies were completed by Meier et al., Parker and Stedman, Bos, RLW and Fleming, Sherman et al., and Proctor and Dutt. These studies can be characterized by their methodologies. Three studies compared the results of laboratory tests of new refrigerators: Meier et al., Parker and Stedman, and Bos. Two studies focused on the energy consumption of trade-in refrigerators[10], to evaluate the potential benefit to the utility (Bos and RLW/Fleming). Five of the studies included field metering of residential refrigerators (Meier et al., Parker and Stedman, Sherman et al., and Proctor/Dutt).

Meier et al.

In a comprehensive study in Rochester (NY), Meier et al. [1993] studied several aspects of refrigerator energy use. These aspects and the principal results are summarized below.

They compared the laboratory consumption of a group of 24 new refrigerators using the DOE test procedure with the labeled values for these models[11]. The laboratory test consumption averaged about 1% less than the manufacturers' claims. There were, however, substantial differences for different models. One model, represented by four units, consumed on average 9% more than the label. Two models consumed 11% and 7% less than their labeled values.

They compared the laboratory consumption of the same 24 refrigerators using the DOE test procedure with the value obtained by using the Japanese (JIS) procedure. The JIS procedure calls for a much lower ambient temperature, and includes door openings. All 24 refrigerators consumed less energy using the JIS procedure compared to the US/DOE procedure. The JIS test results averaged about 15% less than the DOE test value. The difference in consumption is small for refrigerators that have lower consumption (≈ 700 kWh/yr) and appears to increase with volume. Since the four largest units tested were all of the side-by-side type, and there are relatively few models tested overall, it is difficult to determine whether the difference in consumption is related to size or configuration.

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[10] A new energy efficient refrigerator saves large amounts of energy when it replaces an existing inefficient refrigerator in the household. Many electric utilities offer to collect and dispose of the existing unit, to insure that the old unit does not remain in service and that the refrigerator is properly disposed of and the refrigerant recovered.

[11] Of the total, 19 were of the top-freezer, automatic defrost type (the most popular); four were side-by-side units (the second most popular); and one unit was a manual defrost model.

Meier et al. field monitored 26 refrigerators (with an average age of 16 years) for a year. Their annual consumption averaged 2100 kWh. The refrigerators then had coil cleaning and gasket replacement. A second year's monitoring revealed that Òwhile eight refrigerators used less energy after maintenance, four units consumed more, and 14 units used about the same energy as before the maintenance." (Page ix) It is likely that the gasket replacement on some of the units resulted in more leaks and higher consumption. This effect could not be separated from the coil cleaning effect in this study.

They monitored the energy consumption of 20 new energy-efficient refrigerators for a year in houses where the older refrigerators had been monitored earlier for two years--a year before and year after maintenance and repairs. The field consumption of the new refrigerators averaged 790 kWh/yr, 60% less than the older units they replaced.

Field energy use for the new refrigerators averaged 13% less than label values. The authors suspect that much of this difference could be accounted for by the lower kitchen temperatures in the Northern New York location. The day to day variation in consumption was predominantly explained by differences in the kitchen temperature.

They found that the magnitude of electricity demand for the new refrigerators was less than half of the older units. Comparing summer and winter peak days for 1989 and 1990 for the old refrigerators (pre- and post-maintenance) with those for 1991 (new refrigerators), they measured a demand reduction of about 190 watts and 150 watts per new refrigerator on the summer and winter peak days respectively. Refrigerator maintenance (simultaneous coil cleaning and gasket replacement) had no measurable effect on peak demand.

Meier et al. conclude that Ònew and old refrigerators have similar load shapesÓ although they do not quantify this observation. The only graphical representation are the load profiles for the summer and winter peak days for the three years.

Parker and Stedman

Parker and Stedman [1992] made a careful study of two refrigerators in a Florida residence: an existing unit and a replacement energy-efficient unit.

While two refrigerators cannot be used as the basis for statistically valid conclusions, this study nevertheless leads to some interesting observations.

Parker and Stedman measured the number of refrigerator and freezer door openings and this number, together with kitchen temperature, was used as a predictor variable in regressing for energy consumption. Daily energy consumption (kWh) regressed against average daily kitchen temperature (°F) and daily door openings gave the following results.

Old refrigerator: R-sq = 0.62

$$kWh = -5.79 + 0.12\ (\text{Kitchen temp}) + 0.0095\ (\text{Door openings}) \qquad (14)$$

$$\qquad [10.92] \qquad\qquad [5.09]$$

New refrigerator: R-sq = 0.85

$$kWh = -5.05 + 0.084\ (\text{Kitchen temp}) + 0.0092\ (\text{Door openings}) \qquad (15)$$

$$\qquad [29.45] \qquad\qquad [16.17]$$

The t-values of the coefficients are shown in brackets Ò[]Ó.

On an annualized basis the older refrigerator used 1963 kWh/yr. The labeled consumption of the new refrigerator is 763 kWh/yr and the measured consumption was 833 kWh/yr, approximately 10% larger. Note that in Florida's warm climate refrigerators are expected to consume more.

The kitchen temperature dependence of the two refrigerators, on an annualized basis are 43.8 kWh/yr/°F for the old refrigerator and 30.7 for the new unit. This compares with the corresponding figures from the Meier et al, study (17.5, 21.5, and 35 kWh/year per °F, all for energy efficient units) and the NU study (69 kWh/yr/°F for trade-in frost-free refrigerators). The value for the new refrigerator is within the range of values obtained by Meier et al., and for the existing unit we find it much smaller than the NU value. The sample sizes are too small for any meaningful conclusions.

Parker and Stedman also studied the effect of door openings. Each door openings increased energy use by 9.5 watt-hour for the old refrigerator and virtually the same (9.2 Wh) for the new unit. With an average of 42 door openings per day, the openings were responsible for about 7% of the energy consumption for the old unit and 19% for the new one.

In hot climates, consumption in situ has been found to be higher than the laboratory test values. In an earlier Florida study of 25 replacement refrigerators, actual consumption was about 20% larger than DOE test estimates. [Messenger et al., 1983 cited in Parker and Stedman, p. 3.199] In the Parker and Stedman replacement, which involved a unit that was only slightly less efficient than the 1993 standard, the actual consumption was only about 10% larger than the labeled value.

Parker and Stedman estimated the new energy-efficient refrigerator would produce a 59% reduction (166 watts) in demand from 5-6 PM.

Parker and Stedman also analyzed the relationship between labeled energy use and refrigerator type for all 1541 models offered for sale in the US in 1991. They conducted a multiple regression using DOE test kWh as the dependent variable and a number of predictor variables and obtained the following regression equation:

$$\begin{aligned} kWh = \; & \underset{[45.05]}{27.36(\text{cubic feet})} + \underset{[25.69]}{554.3(\text{auto def.})} + \underset{[23.69]}{528.3(\text{part auto def.})} \\ & + \underset{[19.31]}{538.7(\text{man def.})} - \underset{[11.17]}{296.5(\text{single door})} + \underset{[4.32]}{79.2(\text{side-by-side})} \\ & - \underset{[9.01]}{162.8(\text{top freezer})} - \underset{[11.21]}{515.8(\text{superinsulated})} \end{aligned} \qquad (8 \text{ repeated})$$

R-square = 0.929; t-values in [brackets]

Of the total of 1541, majority (905) was of the top-freezer automatic defrost type.

Parker and Stedman observed that bottom-freezer models consumed more energy than top-freezer types, even when adjusted for differences in volume. This difference was also observed in the SMUD study of trade-in refrigerators.

Convenience features added to labeled energy consumption. In a matched-pair comparison of 24 models of side-by-side refrigerators which were offered both with and without through-the-door (TTD) features, these features increased consumption by about 120 kWh or about 10.3%. Although the presence of these features might reduce the number of door openings Parker and Stedman estimate that the corresponding energy savings would most likely be less than the increase in consumption associated with the TTD feature.

Northwest Utilities

In a study for Northeast Utilities (NU) prepared by RLW Analytics, Inc. and The Fleming Group a number of critical variables were measured. The annual consumption was estimated for a sample of refrigerators and freezers collected as part of an appliance pickup program. There were 25 frost-free and 22 manual-defrost refrigerators, and 11 freezers. They were tested in a warehouse for four two-week periods. The ambient temperature was not controlled but was recorded.

The frost-free units averaged 18.3 cu. ft., had a fresh food temperature of 32 °F, and were 15.6 years old. The authors estimated the annual consumption for these refrigerators as 1556 kWh ± 219 kWh[12] based on an estimated average kitchen

12 90% Confidence interval.

temperature of 68 °F. The authors point out that this estimate is highly sensitive to the actual kitchen temperature.

The NU study developed a three-variable regression equation, relating annual consumption to kitchen air temperature , amperage , and size:

The physical meaning of the coefficients they derived is not discussed in their report, nor are the standard errors of the coefficients. The overall R-square and standard errors were 0.53 and 640.8 kWh/yr respectively.

Considering that larger refrigerators are likely to be of higher amperage as well, it is expected that the size coefficient would be smaller where both size and amperage are used as explanatory variables. The size coefficient in the study appears to be too large to be reasonable, and while the kitchen temperature coefficient appears to be large, it is not unreasonably so. Since the tests were conducted with only two door openings per day, it is similar to the DOE laboratory test procedure (except for the ambient temperature control).

Sacramento Municipal Utility District

In a Sacramento Municipal Utility District (SMUD) study, authored by Bos, the energy consumption of trade-in refrigerators was determined. They selected refrigerators (79 units in total) to match the characteristics of all refrigerators traded in during a two-month period. Their test procedure was intended to be identical to the DOE test: ambient temperature of 90°F and no door openings. In effect they measured the Òlabel ratingÓ consumption of these units. For 28 traded-in units where labeled consumption data were available, the SMUD lab tested consumption were all Òsubstantially higherÓ than the labeled values. The mean labeled value was 1454 kWh and the SMUD tested mean was 2580 kWh (a 77% increase over labeled values). The authors observed, Òrefrigerators with physical and operational problems did not use significantly more energy than refrigerators with no identifiable problemsÓ. (Page 12)

The difference between labeled consumption and the SMUD lab tested consumption could be due to aging, because a particular new unit is different from the laboratory rating, or because the test procedure employed is not exactly the same as that used for the standardized label testing.

Bos found no difference between pre- and post-1982 refrigerators (there were only six refrigerators in the post-1982 group). Refrigerator aging cannot be discarded as the cause of the increased consumption of these units.

The SMUD study tested four new 1991 and five new 1992 refrigerators. While the average of the SMUD tests (811.4 kWh/yr) was 10% higher than the label average of

737.9 kWh/yr, the means were not statistically different at the 10% level of significance.

This study reports the difference between refrigerators with and without automatic icemakers. The report does not indicate that icemakers were connected to a water source, or whether they were turned on or off. They found that icemakers increased energy use by 245 kWh, but the increase was not statistically significant in a sample this size. If the icemakers were on but not connected to a water source, they use a significant amount of energy(see Proctor and Dutt, 1992).

The SMUD study also examined the effects of coil cleaning on energy consumption. Refrigerators were rated as having light, medium, or heavy dirt/dust accumulations in their condenser coils. The mean reduction in energy use from coil cleaning was 88 kWh/yr for light dirt, 136 kWh/yr for medium, and 171 kWh/yr for heavy coil dirt accumulation. These reductions are not statistically significant in a sample of this size.

<u>Sherman et al.</u>

In a 1987 study, Lawrence Berkeley Laboratory measured in situ refrigerator energy consumption of 59 refrigerators. [Sherman et al.]. These units were metered for a one week period. Twenty nine were metered in the winter and thirty were metered in the summer. The refrigerators were predominantly in Fresno, Livermore, and Sacramento, California. The average measured consumption of these units was 4.34 kWh/day (annualized to 1545 kWh). The average unit was 7.2 years old and had a volume of 20.8 cu.ft. The average conditions were 38.5°F fresh food temperature, 3.4°F freezer temperature, and 72.7°F kitchen temperature.

For 45 units that had laboratory ratings available the raw measured use was 3.99 kWh/day, a 5% reduction from an average rated use (4.21 kWh/day).

The data from this study was analyzed for aging effects and none could be determined.

<u>Pacific Gas and Electric Company</u>

In a 1992 study, Proctor and Dutt measured in situ refrigerator energy on 20 new refrigerators in Fresno, California. The study contained Refrigerators with three levels of efficiency were studied (0 to 10% better than 1990 standard, 10 to 15% better, and more than 15% better than the standard). Based on ten weeks of data spread over three seasons, the average annual consumption of the three groups was estimated to be 972 kWh, 1041 kWh, and 847 kWh. This study also determined the effect of an icemaker that was turned on but not supplied with water (use increased by the equivalent of 357 kWh/yr).

APPENDIX F FEATURES OF DOE LAB TEST PROCEDURE

(from Bos, 1993, Appendix A)

APPENDIX G DATA COLLECTION FORMS