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End-Use Load and Consumer Assessment Program:

Analysis of Residential Refrigerator/Freezer Performance

B. A. Ross

September 1991

Prepared for
the Bonneville Power Administration
under a Related Services Agreement
with the U.S. Department of Energy
Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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Richland, Washington

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The authors also extend their thanks to other PNL staff who contributed to this report's preparation: Joanne Moore for word processing and Linda Hymas for writing various parts and editing the entire report.

SUMMARY

The Bonneville Power Administration (Bonneville) is conducting a large end-use data acquisition program in an effort to understand how energy is utilized in buildings with permanent electric space heating equipment in the Pacific Northwest. The initial portion of effort, known as the End-Use Load and Consumer Assessment Program (ELCAP), was conducted for Bonneville by the Pacific Northwest Laboratory (PNL).

The collection of detailed end-use data provided an opportunity to analyze the amount of energy consumed by both refrigerators and separate freezers units located in residential buildings. By obtaining this information, the uncertainty of long-term regional end-use forecasting can be improved and potential utility marketing programs for new appliances with a reduced overall energy demand can be identified.

It was found that standby loads derived from hourly averages between 4 a.m. and 5 a.m. reflected the minimum consumption needed to maintain interior refrigerator temperatures at a steady-state condition. Next, an average 24-hour consumption that included cooling loads from door openings and cooling food items was also determined. Later, analyses were conducted to develop a model capable of predicting refrigerator standby loads and 24-hour consumption for comparison with national refrigerator label ratings.

Data for 140 residential sites with a refrigeration end use were screened to develop a sample of 119 residences with pure refrigeration for use in this analysis. To identify those refrigerators that were considered to be pure (having no other devices present on the circuit) in terms of their end-use classification, the screening procedure used a statistical clustering technique that was based on standby loads with 24-hour consumption.

The average standby load for the sample was 112 watts (W) and the 24-hour average consumption was 131 W. Of the 19 W difference between the standby and demand loads, 7 W were from a difference in room temperature (2°F) when the standby consumption was measured and compared to the 24-hour average temperature, and 12 W were attributed to occupant-related demand. Consumption changes in response to room temperature changes were typically linear and

averaged 4 W per °F. An attempt was made to develop a simple predictive model of standby consumption using physical characteristics of the refrigerators. Although the regression model did not exhibit a good fit to the data, several factors did emerge as important:

- Side-by-side units tend to use more power than top freezer units.
- Units with manual defrost use less power than ones with automatic defrost.
- Units in colder climates use less power than ones in warmer climates.

National label ratings were matched to refrigerator model numbers for 62 units. The ratios of standby loads and 24-hour consumption to these ratings averaged to be 77% and 89%, respectively. These findings indicated that the label rating test procedure, tends to overstate average consumption. A separate analysis revealed no apparent relation between refrigerator model vintage and the ratio of 24-hour consumption divided by the label rating.

Analysis of freezer energy consumption was limited; as the ELCAP sample contained only 20 residences with freezers classified as pure end use. The major finding indicated that seasonal consumption variation was greater for freezers than for refrigerators because a principal refrigerator is typically located in an air-conditioned space and freezers tend to be located in an unconditioned space (where seasonal temperature variation is greater). In addition, the demand component appears to be fractionally smaller for freezers than for refrigerators.

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FIGURES

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1.0 INTRODUCTION

The Bonneville Power Administration (Bonneville) began the End-Use Load and Consumer Assessment Program (ELCAP) in 1983. This program, conducted for Bonneville by the Pacific Northwest Laboratory[a] (PNL) involved collecting and analyzing hourly end-use data in commercial and residential buildings in the Pacific Northwest region. The results of the ELCAP analyses support Bonneville's efforts in regional load forecasting, conservation potential assessments, conservation program design, and program evaluations for both residential and commercial buildings within the agency's service territory.

Optimized refrigeration efficiency is an important part of residential conservation programs. The total percentage of residential energy consumed by refrigerators and freezers has been estimated by the Northwest Power Planning Council (the Council) to be 16.2% (NPPC 1988a). The expected savings of more efficient refrigeration equipment (the result of appliance standards) in the Pacific Northwest has been estimated to be 144 MW. These savings have been identified as the most cost-effective conservation resource available to the region (NPPC 1988b).

The purpose of our analysis was to quantify refrigerator/freezer performance in the ELCAP sample. Comparisons of performance with appliance features and label ratings were made to determine the potential of performance predictions and to investigate the variability within the sample.

Section 2 describes the special data treatment that is required to ensure that non-refrigeration loads are not accidentally included in the analyzed end-uses. The effect of indoor room temperature on refrigerator/freezer electricity consumption is discussed in Section 3. Refrigerator/freezer characteristics and their effect on consumption are discussed in Section 4. Finally, in Section 5, label ratings are compared to measured consumption, and implications of the derived ratios are discussed.

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2.0 TREATMENT OF REFRIGERATOR/FREEZER DATA

Refrigeration data have been assigned into one of three end uses for the ELCAP metering program: pure (REF), mixed refrigeration (MRF), and freezer (FZR). In principle, the REF and FZR end uses contain only pure refrigeration loads, while the MRF end use is contaminated with plug loads from kitchen appliances or other devices. The subsections that follow describe how the data from the REF and MRF end uses were analyzed to identify MRF and mixed consumption behavior. A procedure was developed to separate the pure refrigeration load from the hourly loads in the MRF end use. Defrost cycles, based on 5-min data, are described as potential tools for assessing performance degradation.

Data for a single site were referenced in terms of mean numbers in the analyses. When comparison was made across sites, however, data were usually expressed in terms of median numbers. Using median values minimized the impact of outliers or extreme values (both high and low) because one-half the values in the data set fell above the median and were greater, and one-half the values fell below the median and were lesser.

2.1 MIXED VERSUS PURE CIRCUIT MONITORING

In some residences, a circuit has been wired to a single outlet located behind the refrigerator. For these circuits, collected metered data were assigned to the REF end use because the electricity was only consumed for refrigeration. In most residences, however, the circuit that feeds the outlet behind the refrigerator was also connected to several other outlets. For these circuits, electricity was consumed by both refrigeration and miscellaneous convenience and/or lighting loads; these circuits were designated MRF.

The end-use assignments described above were made at the time metering equipment was installed. Because their assignments were made without the benefit of a detailed review of residential electrical systems, some mistakes can be expected. As a check, an examination was made of 5-min data load shapes for sites with the REF end use to see if only the expected cyclical refrigeration loads were present. Because of small, positive loads of constant magnitudes that seemed to be atypical of a refrigeration cycle, some of the end-use assignments were changed from REF to MRF. Later, these small loads were identified as low-power strip heaters used to prevent condensation (sweating) near the refrigerator door seals. Anti-sweat heaters typically consume 15 to 30 W if the *energy saver* switch is in the "off" position (or the *humid/not humid* switch is in the "humid" position).

Data was further analyzed to characterize the sites with refrigerators that had pure behavior and mixed behavior. Because the ELCAP measurement protocol does not allow for a "mixed freezer" end use, nonpure freezer circuits were assigned to the lights and convenience end-use category. This end-use category contains several circuits with a multitude of loads from various other small appliances or lighting circuits. The creation of a mixed freezer end use would have involved a time-consuming analysis of data at the channel level.

2.2 DETERMINATION OF PURE REFRIGERATION BEHAVIOR MEASUREMENTS

Five-min data, where available, are helpful in determining whether or not refrigerator consumption data are pure or mixed. The load shape for pure refrigerator consumption should indicate a fairly regular cyclical load, with zero load or a small, constant load in between. Because only a few days of 5-min data are currently available for all of the sites, the resulting load shape would not be adequate to ensure that lights or appliances are not included on the circuit. As a result, hourly data were used as the basis for this determination.

Standby consumption is the amount required to maintain the desired refrigerator temperature with the door shut, while the 24-hour consumption is simply the monthly average for all the hours of the day. A pure refrigeration load is based on both the standby loads and the average 24-hour consumption performance. Monthly standby loads and a 24-hour consumption performance were calculated for each site from monthly profile data. Nighttime data (from 12 midnight to 6 a.m.) was compared to daytime data for 30 sites and, as expected, was found to be significantly different because little demand-related load occurs at night. The average consumption for the hours from

12 midnight to 5 a.m. were essentially the same, while the consumption from 5 a.m. to 6 a.m. was slightly higher. To minimize computation requirements and the possibility of including the additional load from evening meal left-overs being placed in the refrigerator, we chose a single nighttime hour (4 a.m. to 5 a.m.) to represent the standby load. The ratios between the standby loads and 24-hour consumption were also calculated.

In an effort to obtain a large sample for analysis, refrigeration consumption data for 140 sites were determined and separated into groups:

- Group 1 - sites that have always been assigned to the REF end use and have not been questioned
- Group 2 - sites with changed or questioned end-use assignments
- Group 3 - sites that have always been assigned to the MRF end use. These sites have not been questioned and are in the lowest quartile in terms of 24-hour consumption for sites.

The selection of the Group-3 sites was a compromise between a bias toward low-consumption refrigerators and small, non-pure loads. Pure refrigeration loads existed in Groups 1 and 2, while mixed refrigeration end-use definitions with pure refrigeration loads existed in Groups 2 and 3.

A hierarchical clustering technique, that operates on a distance matrix of all pair-wise distances between objects (Becker and Chambers 1984), was used to separate the sites into *clusters* based on their consumption characteristics. The differences between clusters are illustrated in the vertical scale of the cluster plot as the height of the branch that separates the clusters (see Figure 2.1). This technique was first applied to the standby loads and the ratio of standby to 24-hour consumption of the sites in Group 1. The graphical output of this technique indicated two distinct clusters: one with pure behavior (n = 33) and one without (n = 9) (see Figure 2.1). The cluster without the pure behavior was found to have 50% to 150% higher consumption than the larger cluster and was re-assigned to a category of sites having mixed behavior.

As a seeding technique, nine of the 33 sites with pure behavior were added to the Group-2 sites (end use changed or questioned) and the hierarchical clustering technique was repeated. The results in Figure 2.2 present two

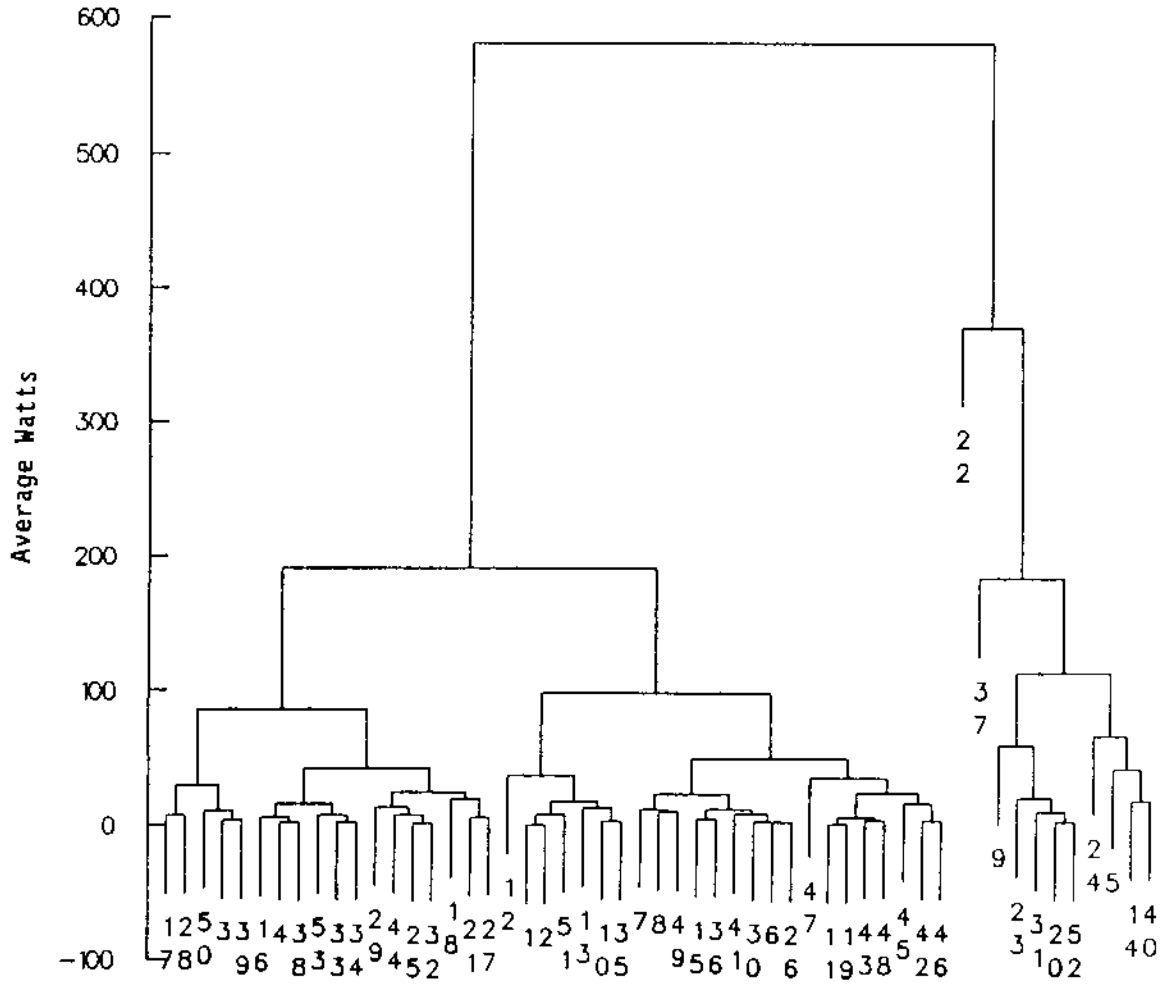

FIGURE 2.1. Cluster Plot for Pure Installation Group. Sites are identified by site numbers reading from top to bottom.

very distinct clusters, as indicated by the elevated cluster branch appearing between clusters. The nine pure sites are spread throughout the large cluster to the left, while the cluster to the right appears to have nonpure behavior.

The clustering technique was then applied a third time, by adding the same nine pure sites from Group 1 to Group 3 (mixed end use with relatively low consumption), as illustrated in Figure 2.3. This plot does not illustrate any distinct (high-level branches) groups, and the pure seeds are spread throughout the plot, indicating that all the Group-3 sites exhibit pure behavior.

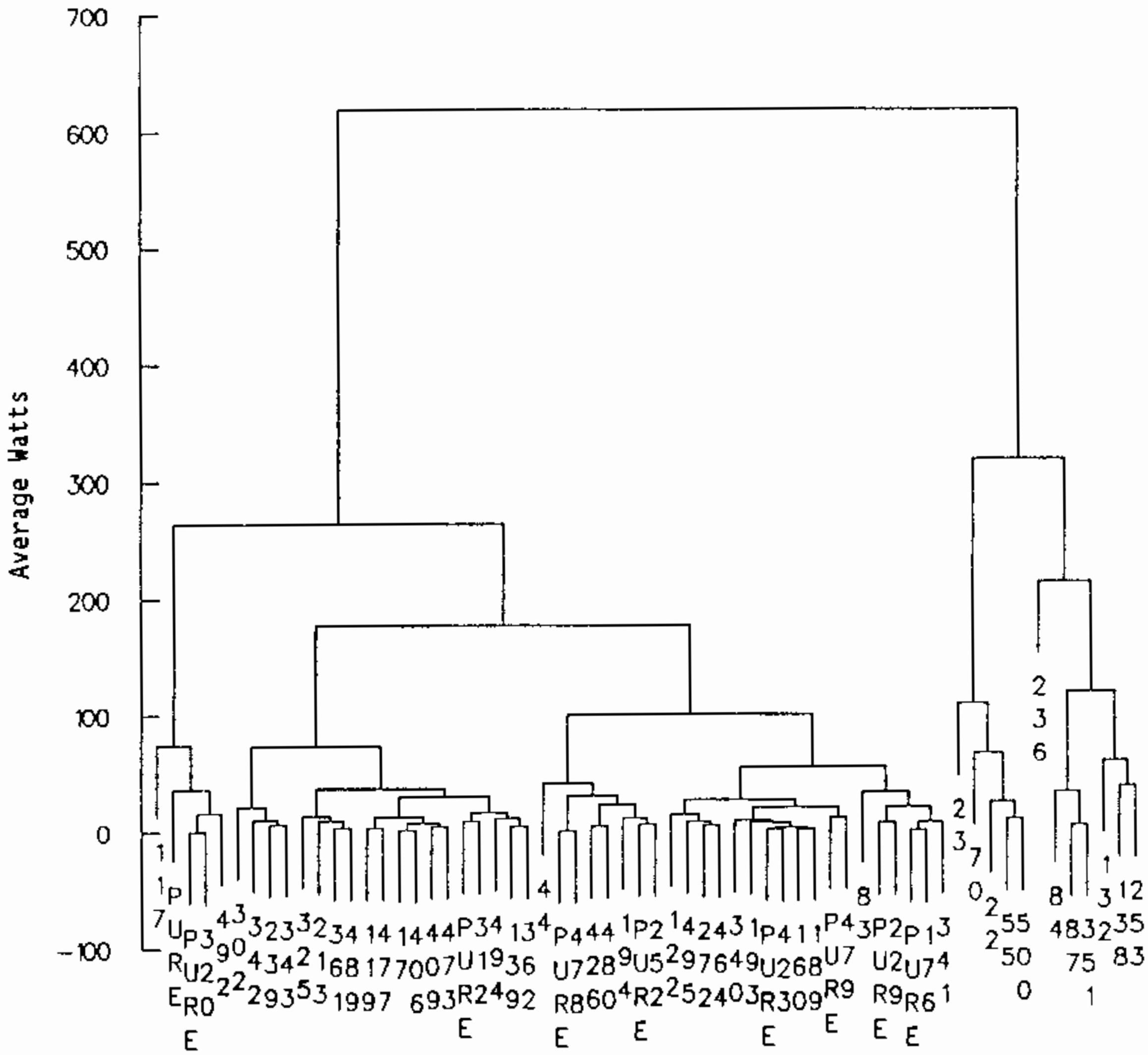

FIGURE 2.2. Cluster Plot for Changed/Questioned Installation Group. Sites are identified by site numbers reading from top to bottom.

The result of the above analysis has now separated the sites into two groups that appear to have the refrigeration end use mixed with another end use (n = 21) and three groups of sites having pure refrigeration behavior (n = 119). The performances of the latter three groups were compared with one another to confirm that the consumption characteristics for the groups are similar. The distribution of ratios for standby loads divided by 24-hour consumption for the three groups with pure behavior sites is illustrated in

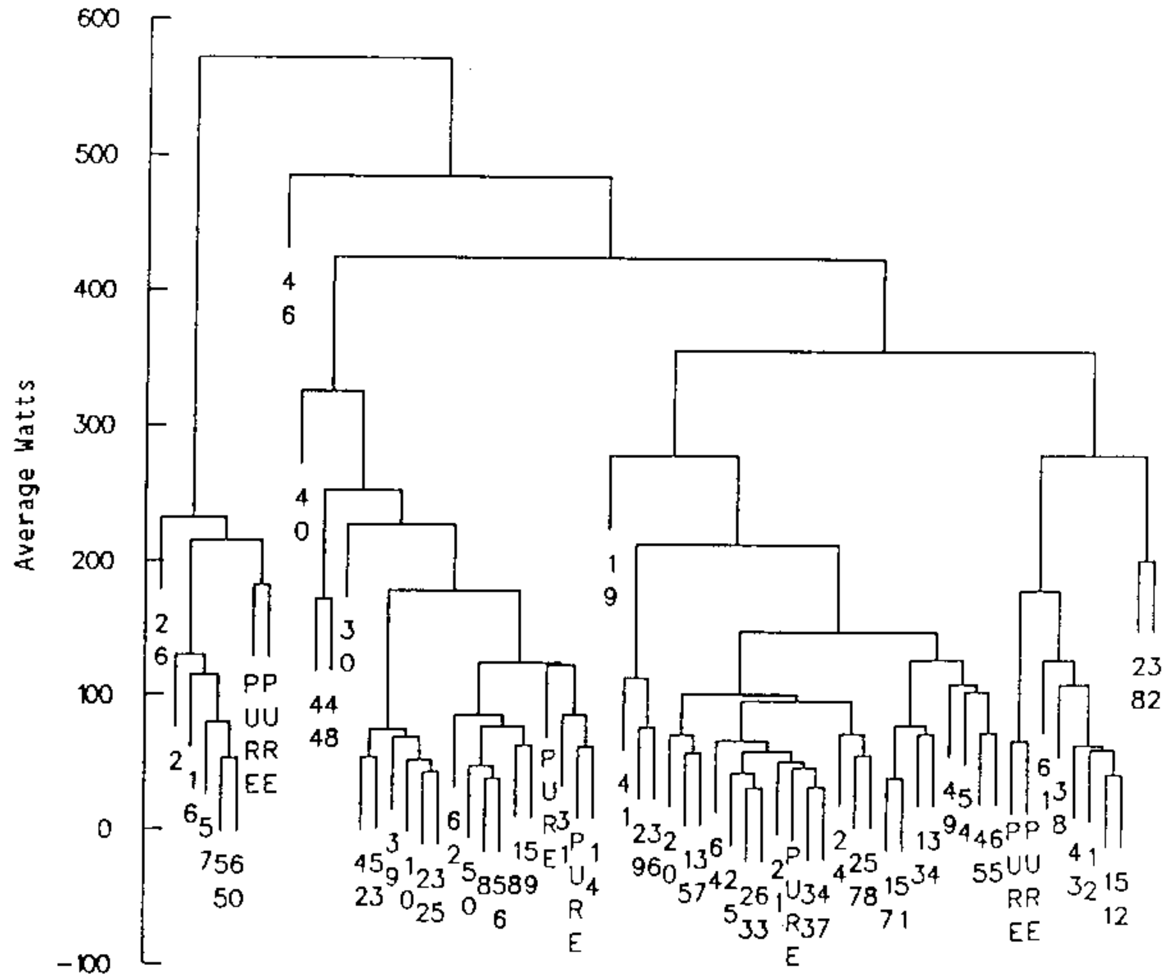

FIGURE 2.3. Cluster Plot for Mixed Installation Group. Sites are identified by site numbers reading from top to bottom.

Figure 2.4. Note that the medians (the dotted horizontal lines) are similar in magnitude, while the spread of the middle quartiles (the box heights) vary slightly. The distribution of the standby loads for the same three groups is illustrated in Figure 2.5. Note that the median of the questioned/changed group is slightly higher than the median of other groups. This is because, in most cases, the refrigerators in the questioned group were questioned or changed from the use of strip heaters near the door seals. This practice increases both the standby loads and the 24-hour consumption, but not the ratio.

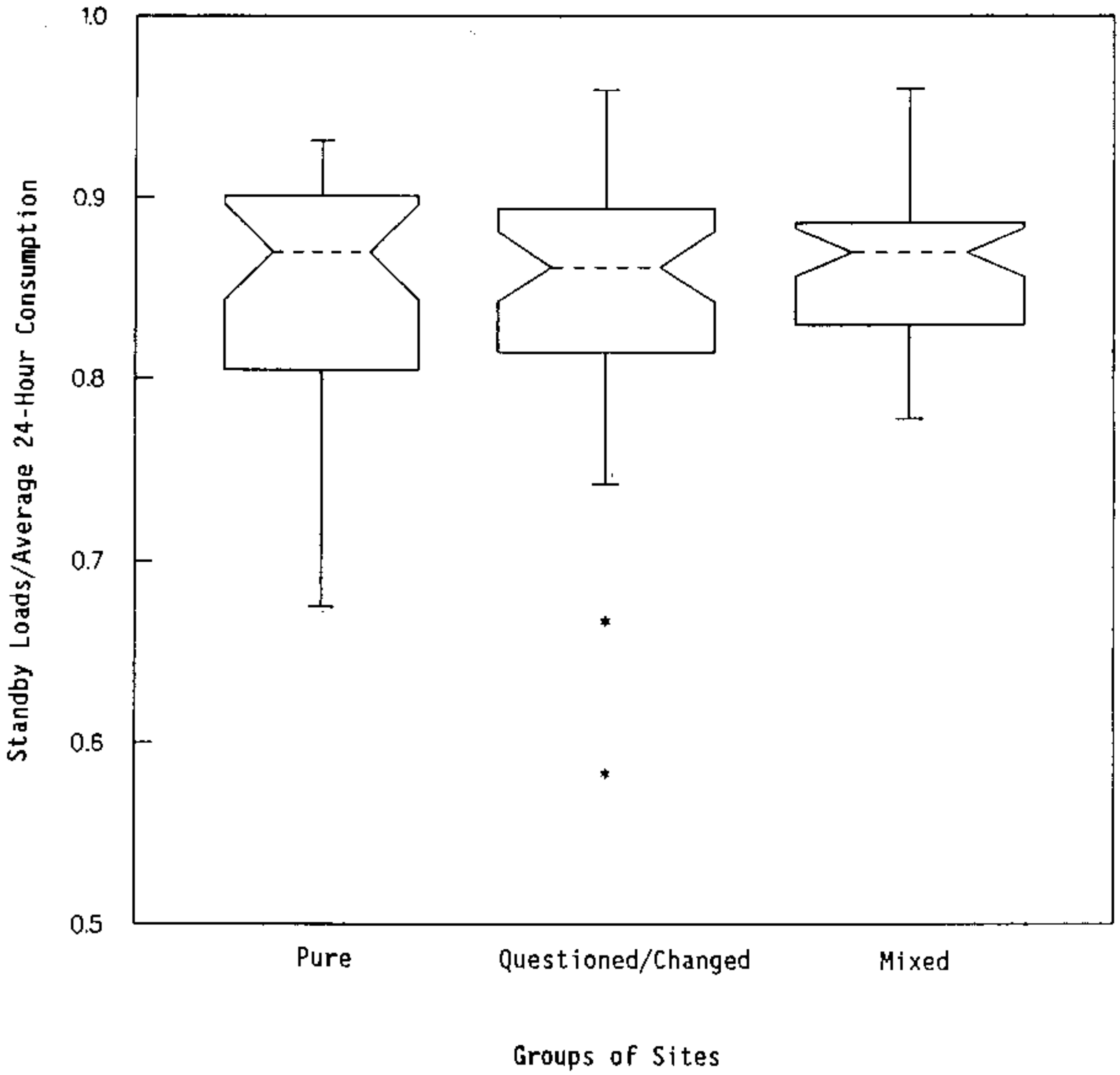

FIGURE 2.4. Standby Load/24-hour Consumption Comparison for Pure Sites Taken from Three Installation Groups

2.3 TYPICAL DEFROST AND COOLDOWN LOAD SHAPES

Although the 5-min data are not useful for determining whether or not the site has a pure (REF) or mixed (MRF) end use, an attempt was made to understand defrost and cooldown cycles through data examinations. We looked at windows of load shapes from two different sites that include a defrost cycle are illustrated in Figures 2.6 and 2.7. Figure 2.6 illustrates four cooldown cycles with a defrost cycle in the middle. The defrost cycle contains three

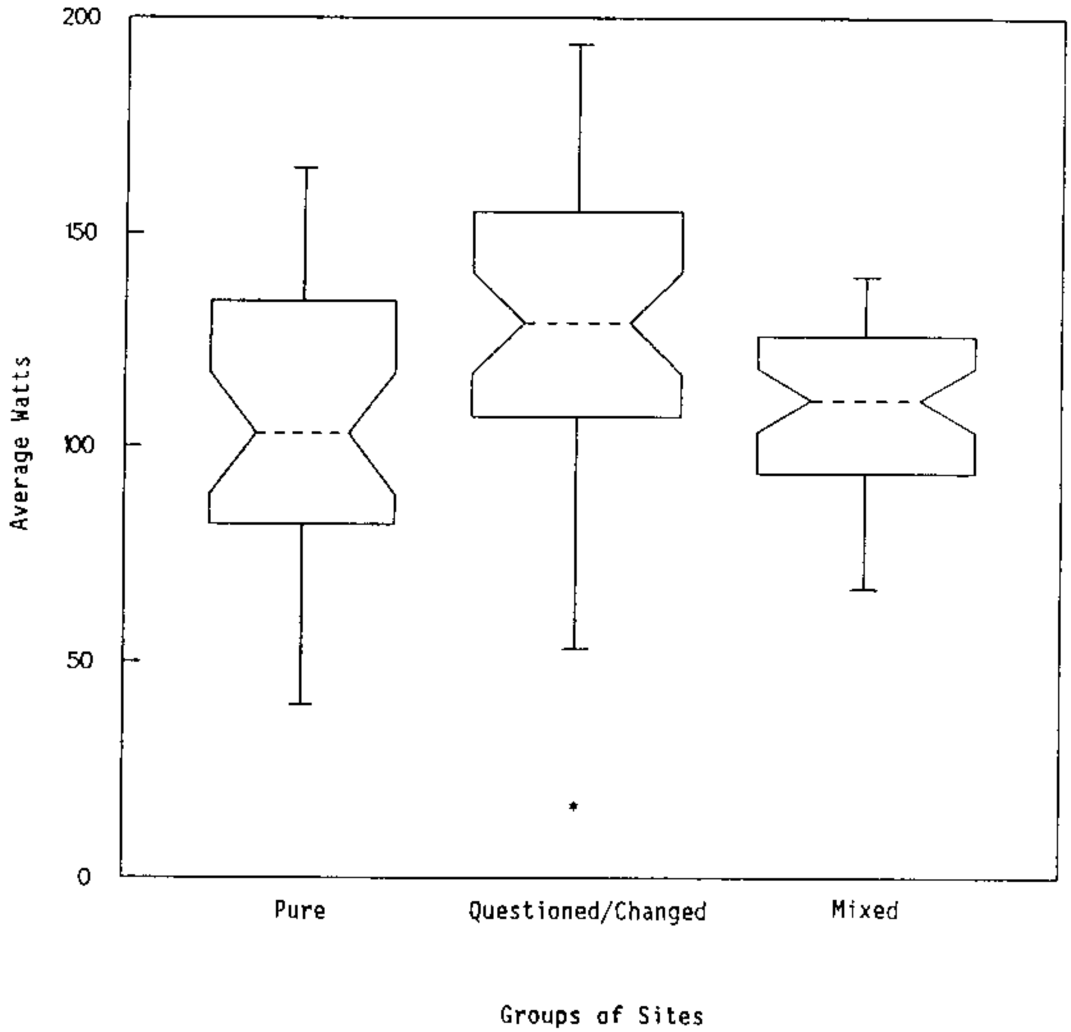

FIGURE 2.5. Standby Loads Comparison for Pure Sites from Three Installation Groups

steps: 1) heating occurs to melt the ice (the energy used in a 5-min period peaks), 2) there is a standby period with low consumption, and 3) a cooldown cycle occurs that requires more than the usual amount of energy consumption. The four cooldown load shapes look different, but represent the same amount of energy as areas under the load shape are essentially equal. Because the cooldown energies are similar, and because the data are from the 2 a.m. to 6 a.m. period, it is believed that Figure 2.6 illustrates defrost/standby behavior unaffected by consumer demand.

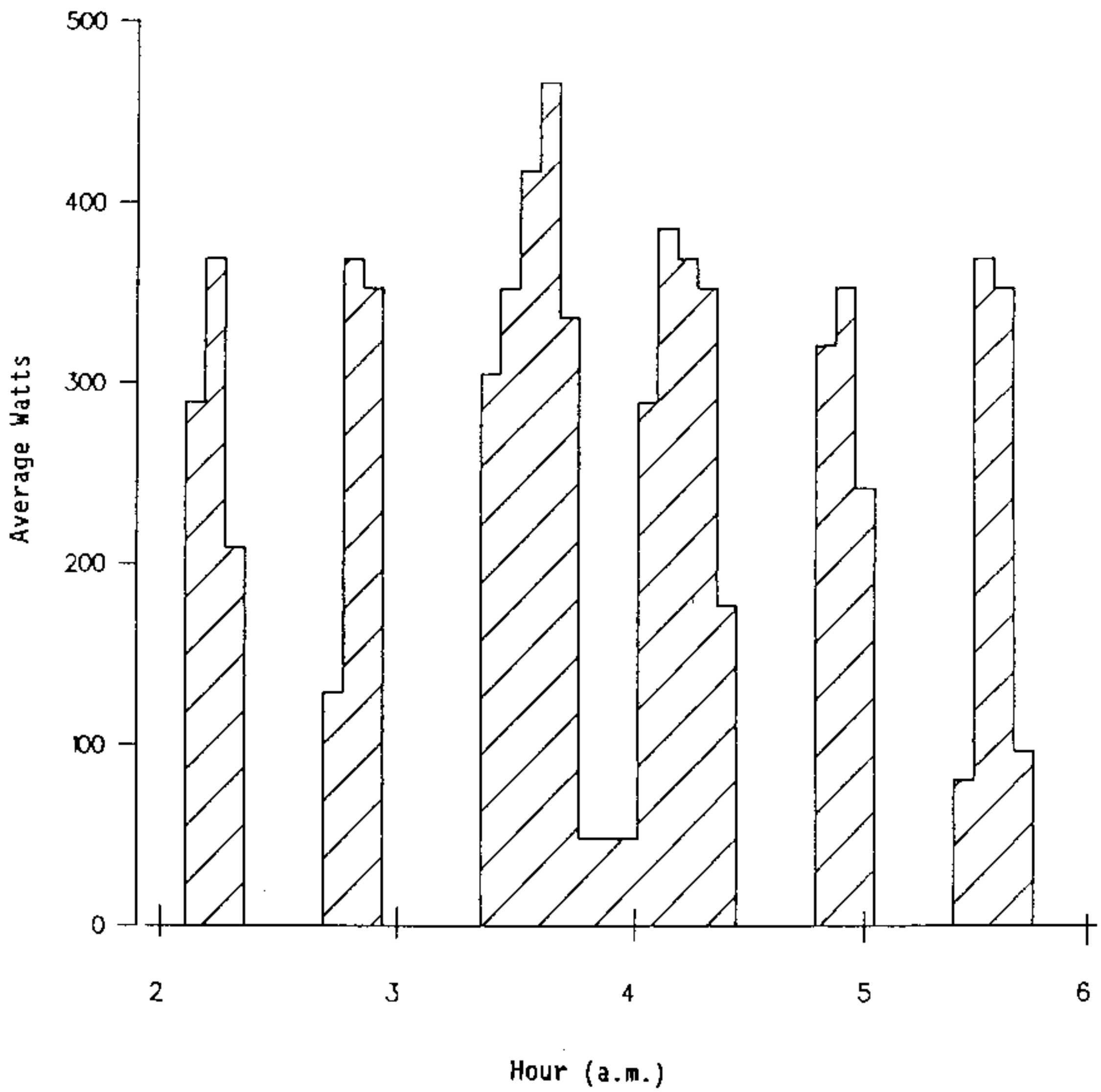

FIGURE 2.6. Standby/Defrost Load Shapes for Site 356

Figure 2.7 illustrates essentially the same type of behavior, with the exception that cool down occurs more frequently, and requires less energy per cool down. The first step of the defrost cycle uses over 50% more energy in a 5-min period than a typical cooldown cycle does. The standby period of the defrost cycle uses no energy, and the cooldown part of the defrost cycle appears to be combined with a typical cooldown cycle that follows less than 5-min later.

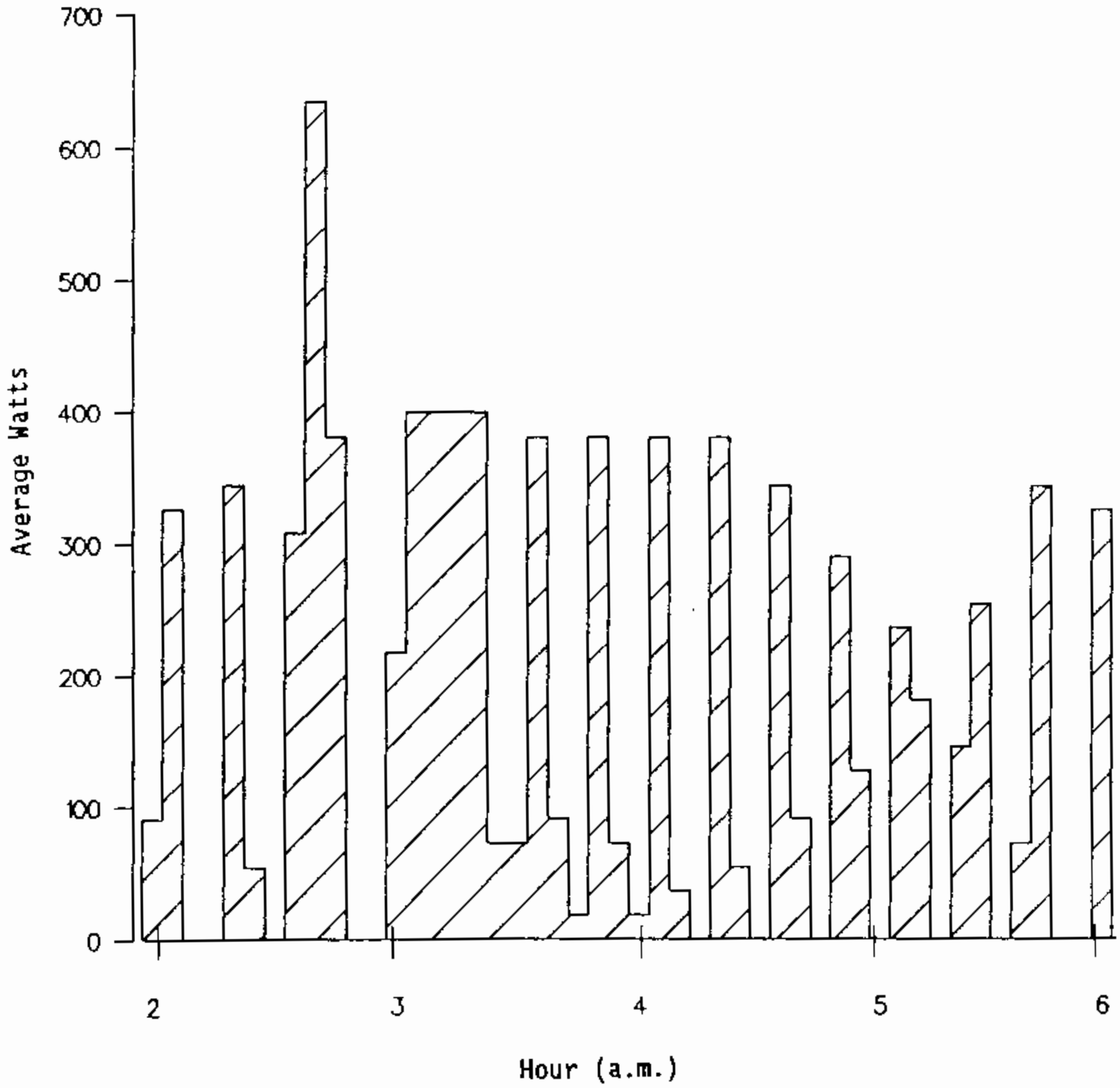

FIGURE 2.7. Standby/Defrost Load Shapes for Site 113

In an attempt to determine defrost frequency from 5-min data, we tested the peak consumption associated with the first step of the defrost cycle. Of the 11 sites tested, one had an exact 8-hour defrost interval, one had too much missing data, and three sites did not have discernable defrost peaks. The distribution of the defrost intervals for the other six sites is presented in Figure 2.8. For the middle two sites (one is the freezer), the distributions vary widely, suggesting that defrost control is by sensor. For the other four sites, the apparent defrost frequency suggests that defrost frequency is controlled by a timer.

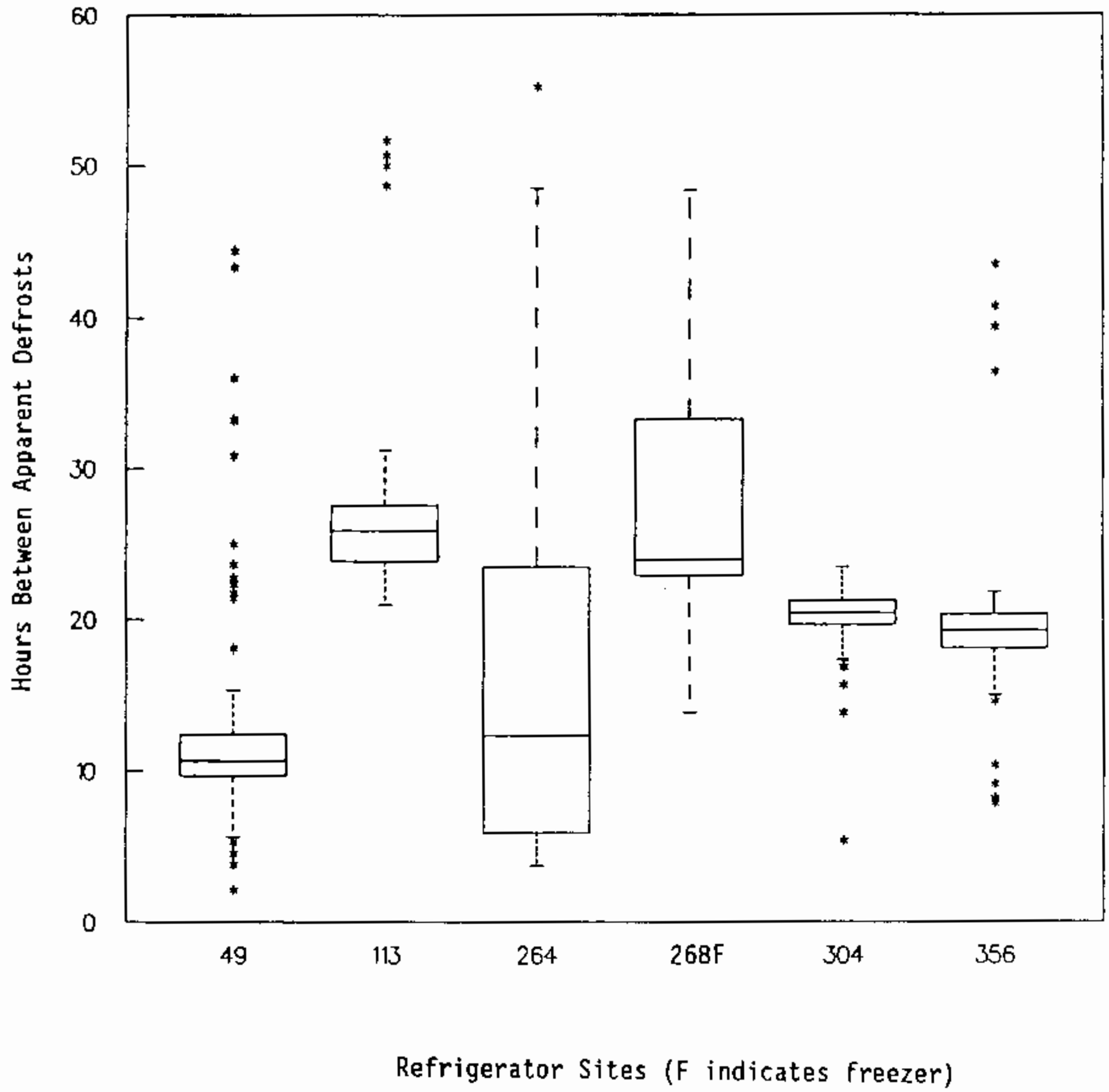

FIGURE 2.8. Defrost Cycle Intervals for Refrigerators and a Freezer

Using defrost frequency information and load shapes of individual defrost frequency is controlled by a timer.

Using defrost frequency information and load shapes of individual defrost events, it may be possible to characterize refrigerator performance--including air infiltration rates and compressor performance degradation with time. This information could be used to alert consumers when refrigerator/freezer maintenance is necessary.

3.0 INDOOR ROOM TEMPERATURE CORRECTION

The relation between indoor room temperature and consumption was examined and computed, and the characteristic coefficients that describe this relation were reviewed. The temperature of the air around a refrigerator and a freezer was expected to have a strong effect on the standby load. As the indoor room temperature increases, the heat loss from the unit increases and the refrigeration cycle efficiency decreases. This increases the standby load.

3.1 TYPICAL CORRELATION SHAPES

Scatter plots were produced by considering 200 days of daily refrigeration consumption and indoor room temperature per site. The 24-hour consumption, in watts, was compared to the difference between the indoor room temperature and 40°F. While 40°F is a typical operating temperature for the cool part of a refrigerator, a freezer typically operates at 0°F. Because the ratios of refrigerator/freezer compartment volumes are not known for all of the sites, and may vary, an arbitrary value of 40°F for the temperature difference offset was chosen.

A fair amount of scatter can be expected for this correlation for several reasons. The indoor air temperature data are taken from one or more sensors mounted near the main living areas of the house and may record temperatures significantly different than those around the refrigerator. The differences can be attributed to non-uniform ventilation patterns, differences in solar gain, outside wall characteristics, and heat generated by kitchen appliances, including the refrigerator itself. In addition, the consumption varies with occupant behavior-related demand, that may or may not be influenced by room temperature.

The correlation between daily consumption and the daily indoor room temperature for site 179 (See Figure 3.1) is typical for most sites. The curve drawn is a LOWESS statistically-smoothed curve (Becker and Chambers 1984). The results of a second-order regression are illustrated in the top left corner of the graph. The correlation between results is expected to be second order, because, as the indoor room temperature increases, the thermal

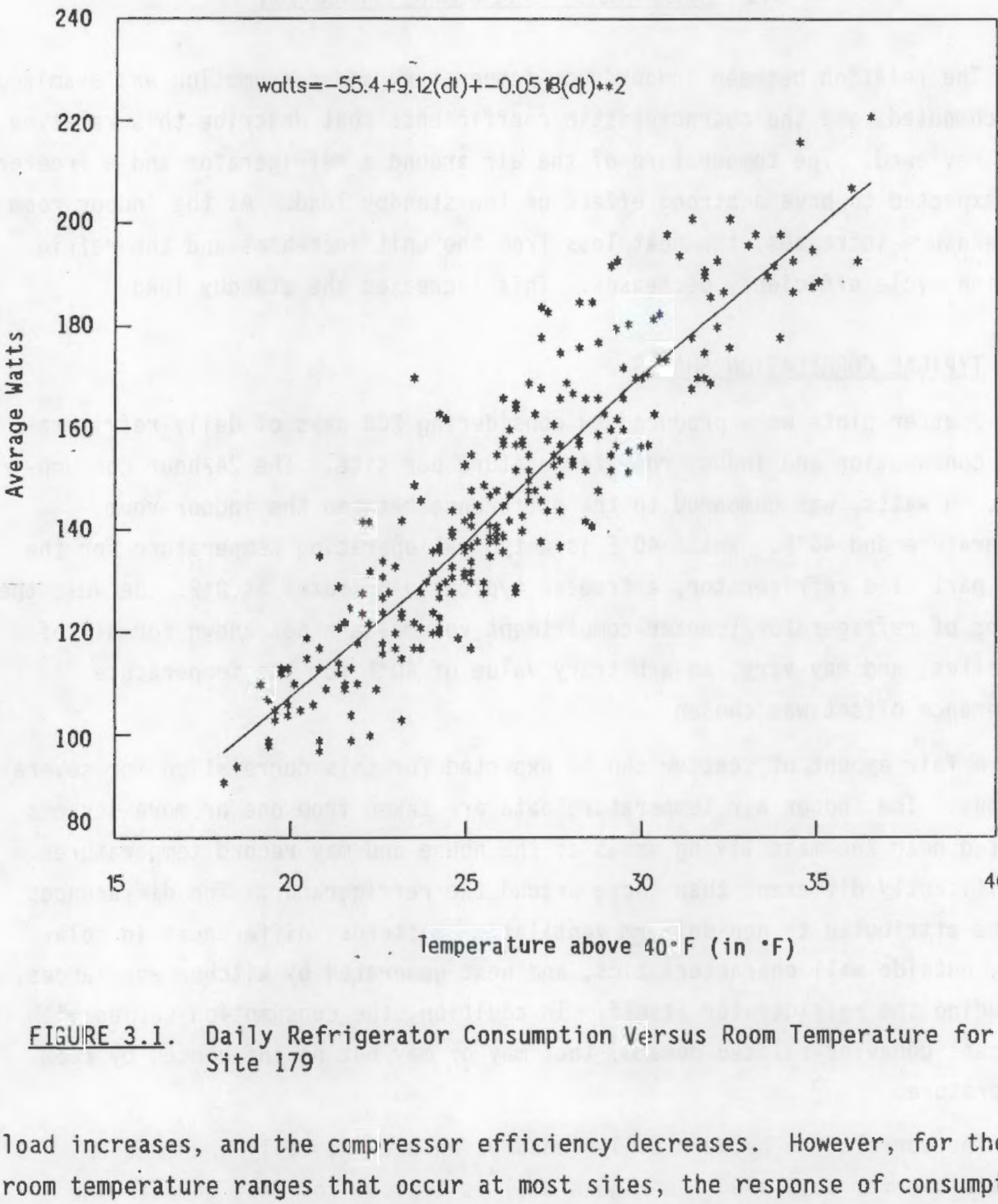

FIGURE 3.1. Daily Refrigerator Consumption Versus Room Temperature for Site 179

load increases, and the compressor efficiency decreases. However, for the room temperature ranges that occur at most sites, the response of consumption to room temperature is linear. Based on the first-order coefficient, consumption tends to decrease 9 W with each incremental decrease of 1°F in room temperature.

About 20% of the sites had a noticeable second-order response, such as the response in site 35 which is illustrated in Figure 3.2. One reason that this response was more evident than that found in Figure 3.1 was because of the cooler indoor room temperatures where the compressors were more efficient. The inflection point between the linear sections of the curve was

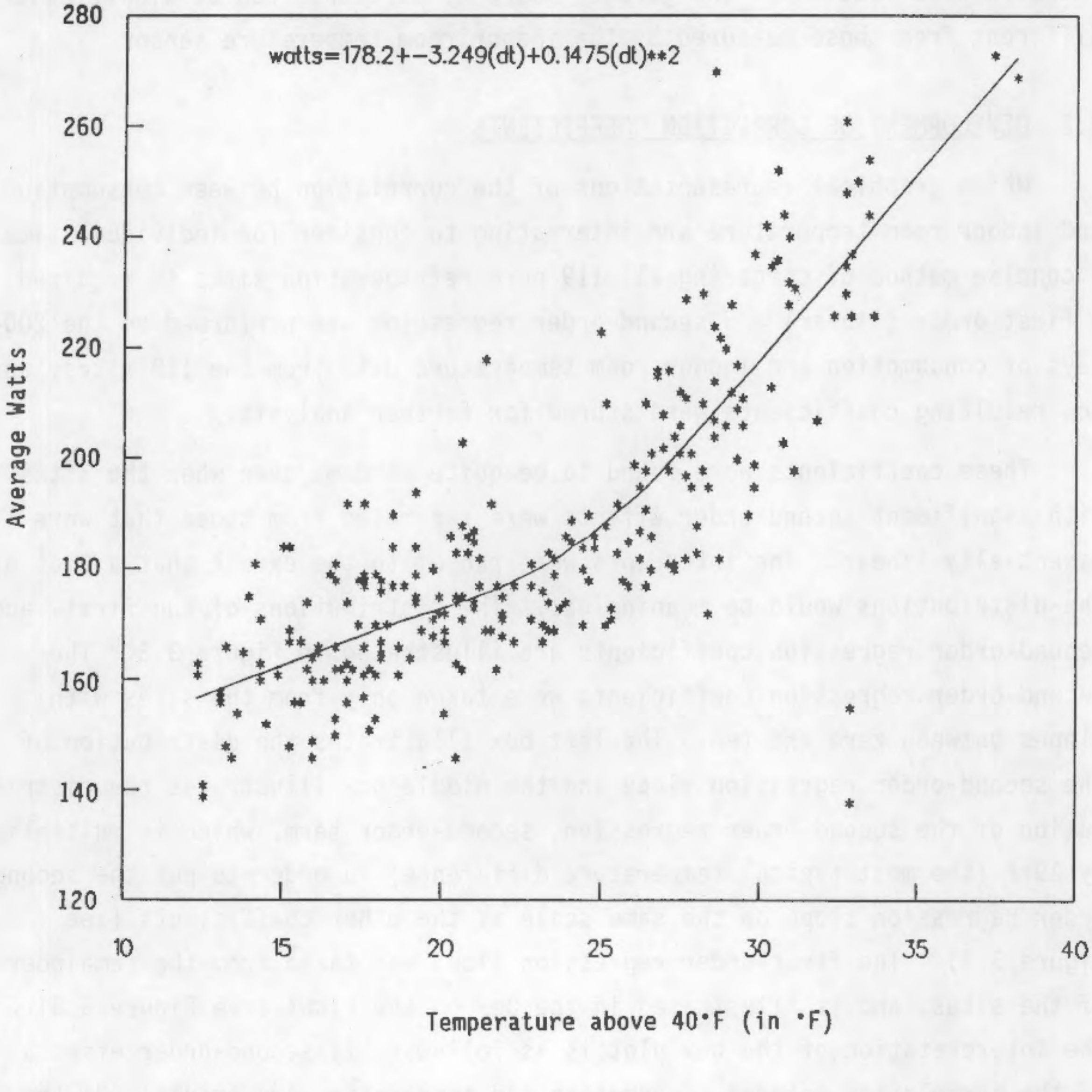

FIGURE 3.2. Daily Refrigerator Consumption Versus Room Temperature for Site 35

approximately 65°F, which is fairly low for the temperatures illustrated in Figure 3.1. The conclusion drawn from Figures 3.1 and 3.2 indicates that second-order effects are apparent, only if consumers operate their houses at relatively low temperatures. Therefore, the consumption response should be considered linear for adjustments between 65°F and 75°F.

Freezers were not considered to be part of this analysis because most freezers were located in the garage, where temperatures can be significantly different from those measured by the indoor room temperature sensor.

3.2 DEVELOPMENT OF CORRECTION COEFFICIENTS

While graphical representations of the correlation between consumption and indoor room temperature are interesting to consider for individual sites, a concise method of comparing all 119 pure refrigeration sites is required. A first-order (linear) and second-order regression was performed on the 200 days of consumption and indoor room temperature data from the 119 sites, and the resulting coefficients were stored for further analysis.

These coefficients were found to be quite random, even when the sites with significant second-order effects were separated from those that were essentially linear. The intercepts were random to the extent that a plot of the distributions would be meaningless. The distributions of the first- and second-order regression coefficients are illustrated in Figure 3.3. The second-order regression coefficients were taken only from the sites with slopes between zero and ten. The left box illustrates the distribution of the second-order regression slope and the middle box illustrates the distribution of the second-order regression, second-order term, which is multiplied by 29°F (the most typical temperature difference) in order to put the second-order regression slope on the same scale as the other coefficients (see Figure 3.3). The first-order regression slope was taken from the remainder of the sites, and is illustrated in the box on the right (see Figure 3.3). The interpretation of the box plot is as follows: 1) second-order effects of the correlation between consumption and temperature are trivial, 2) the

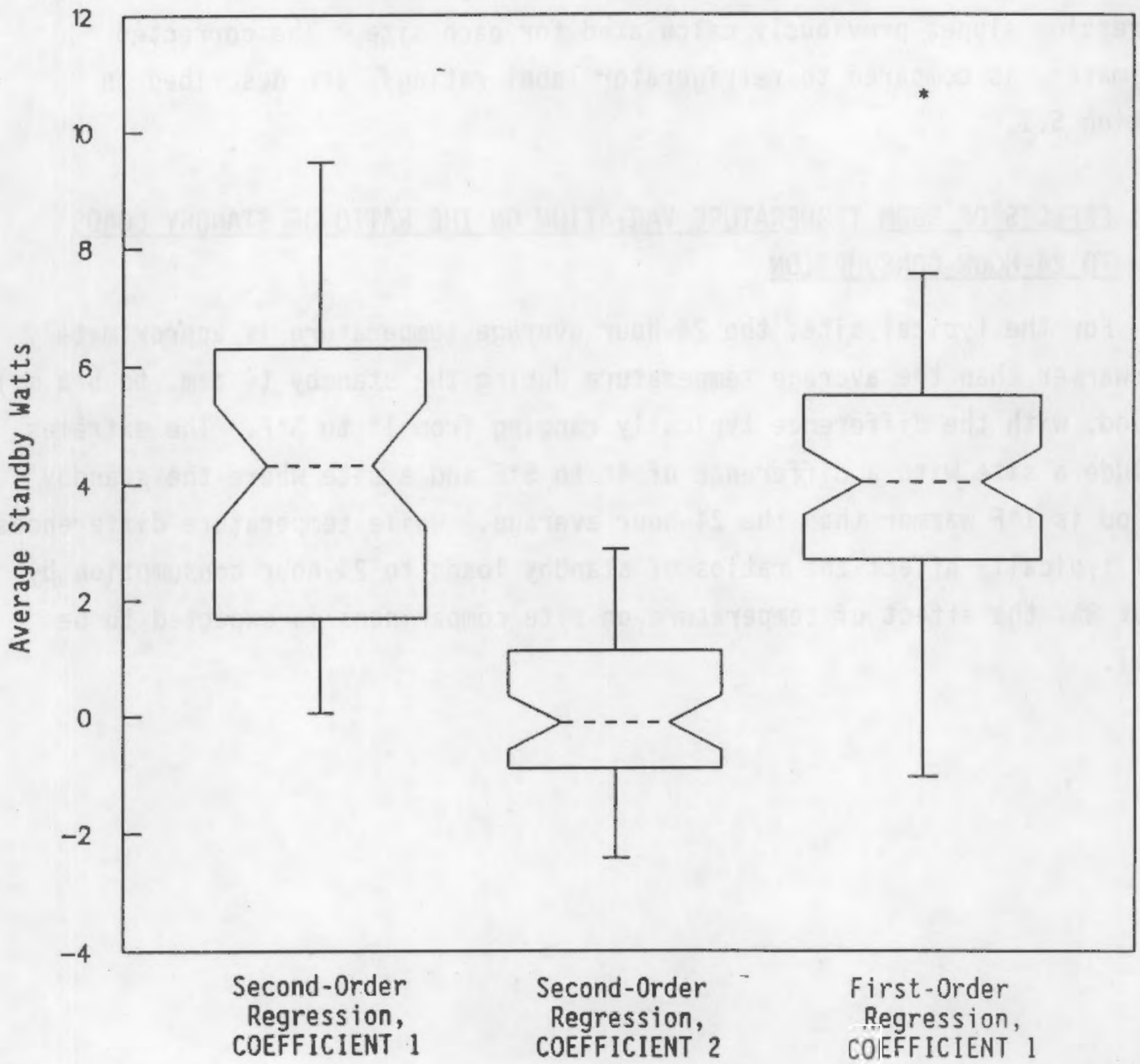

FIGURE 3.3. Consumption Versus Temperature Coefficients for First- and Second-Order Regressions

correlation varies widely between refrigerators, and 3) the average response to indoor room temperature change is about 4 W per °F for both the first- and second-order models.

The median indoor temperature for all sites during the 4 a.m. to 5 a.m. period used for standby load estimates was 69°F. The standby loads for the sites were corrected to this temperature through the use of the first-order regression slopes previously calculated for each site. The corrected sites were corrected to this temperature through the use of the first-order regression slopes previously calculated for each site. The corrected estimates, as compared to refrigerator label ratings, are described in Section 5.1.

3.3 EFFECTS OF ROOM TEMPERATURE VARIATION ON THE RATIO OF STANDBY LOADS TO 24-HOUR CONSUMPTION

For the typical site, the 24-hour average temperature is approximately 2°F warmer than the average temperature during the standby (4 a.m. to 5 a.m.) period, with the difference typically ranging from 1° to 3°F. The extremes include a site with a difference of 4° to 5°F and a site where the standby period is 1°F warmer than the 24-hour average. While temperature differences will typically affect the ratios of standby loads to 24-hour consumption by about 8%, the effect of temperature on site comparisons is expected to be small.

4.0 REFRIGERATOR/FREEZER CHARACTERISTICS VERSUS RESULTS

Characteristics data of refrigerators and freezers were collected as part of the occupancy survey and inspection activities. The consumption data from the pure refrigerators were compared to the characteristics data to determine whether they can be used to predict consumption.

4.1 CHARACTERISTICS TRENDS

The distribution of characteristics for the refrigerators with pure behavior is illustrated in Table 4.1. Most refrigerators have a compartment on the bottom and top, an automatic defrost system, and do not have automatic ice makers. All except two of the refrigerators were located in conditioned space. Most of the refrigerator end-use data used in our analysis is from sites located in Climate Zone I. An equal number of pure refrigeration sites is in the ELCAP Base and ELCAP Residential Standards Demonstration Program (RSDP) study.

The distribution of characteristics for freezers is illustrated in Table 4.2. Most freezers are upright, have both manual and automatic defrost systems, and do not have automatic ice makers. Most freezers are located in unconditioned spaces and are part of the Residential Base Sample.

4.2 AVERAGE MONTHLY CONSUMPTION RESULTS

The monthly average standby loads and 24-hour consumption are illustrated for pure refrigerators and freezers in Figures 4.1 and 4.2. The seasonal variation of refrigerator consumption, mostly the result of indoor room temperature swings, is small because the refrigerators are in conditioned spaces (see Figure 4.1).

The seasonal variation of freezers is much larger because many freezers are not in air-conditioned spaces (see Figure 4.2). The ratios between the standby loads and 24-hour consumption are fairly constant, except for the month of December. This increase in mean demand for December is probably the

TABLE 4.1. Characteristics Distribution for Refrigerators with Pure Behavior (N = 119)

Category	Characteristic	Frequency
Type	No freezer	2.5%
	Side-by-side	11.8%
	Top freezer	79.0%
	Bottom freezer	4.2%
	Inside freezer	2.5%
Defrost	Automatic	84.0%
	Manual	12.6%
	Unknown	3.4%
Ice-maker	None	63.0%
	Conventional	29.4%
	Inside door	7.6%
Volume	Mean	17.4 ft^3
	Median	17.6 ft^3
	Standard deviation	3.2 ft^3
Location	Conditioned space	98.4%
	Unconditioned space	0.8%
	Unknown	0.8%
Sample	Residential base	49.2%
	RSDP	50.8%
Climate Zone[a]	I	55.5%
	II	31.1%
	III	13.4%

(a) Climate Zone I includes regions that experience between 4000 and 6000 heating degree days and consists primarily of the western region of Washington and Oregon. Climate Zone II includes regions that experience between 6000 and 8000 heating degree days and primarily includes the inland region of Washington and Oregon. Climate Zone III includes regions that experience more than 8000 heating degree days and primarily includes Idaho and western Montana.

result of holiday and vacation activities. The ratio between standby loads and 24-hour consumption approaches 1 for freezer because the demand is very low.

TABLE 4.2. Characteristics Distribution for Pure Freezers (N = 20)

Category	Characteristic	Frequency
Type	Upright	75.0%
	Chest	25.0%
Defrost	Automatic	15.0%
	Manual	75.0%
	Unknown	10.0%
Ice-maker	None	100.0%
Volume	Mean	18.7 ft^3
	Median	19.5 ft^3
	Standard deviation	6.4 ft^3
Location	Conditioned space	40.0%
	Unconditioned space	60.0%
Sample	Residential base	80.0%
	RSDP	20.0%
Climate Zone	I	65.0%
	II	35.0%
	III	0.0%

4.3 REFRIGERATOR CONSUMPTION RESULTS

The Council estimate for refrigerator consumption, based on a relatively new 17 ft^3 model, is 1100 kWh per yr that corresponds to an average load of 126 W. The consumption averages for the pure refrigerator consumption measurements from the ELCAP sample are presented in Table 4.3. The table indicates that approximately one-third of the difference between standby loads and the 24-hour consumption, for all hours, is attributed to temperature difference. The remainder of the difference is because of occupant demand.

4.4 COMPARISONS BY CHARACTERISTICS

Comparisons by characteristics, one at a time, can be misleading when interactions dominate refrigerator consumption results. For instance, larger-volume refrigerators should require more energy, but the effect may be hidden

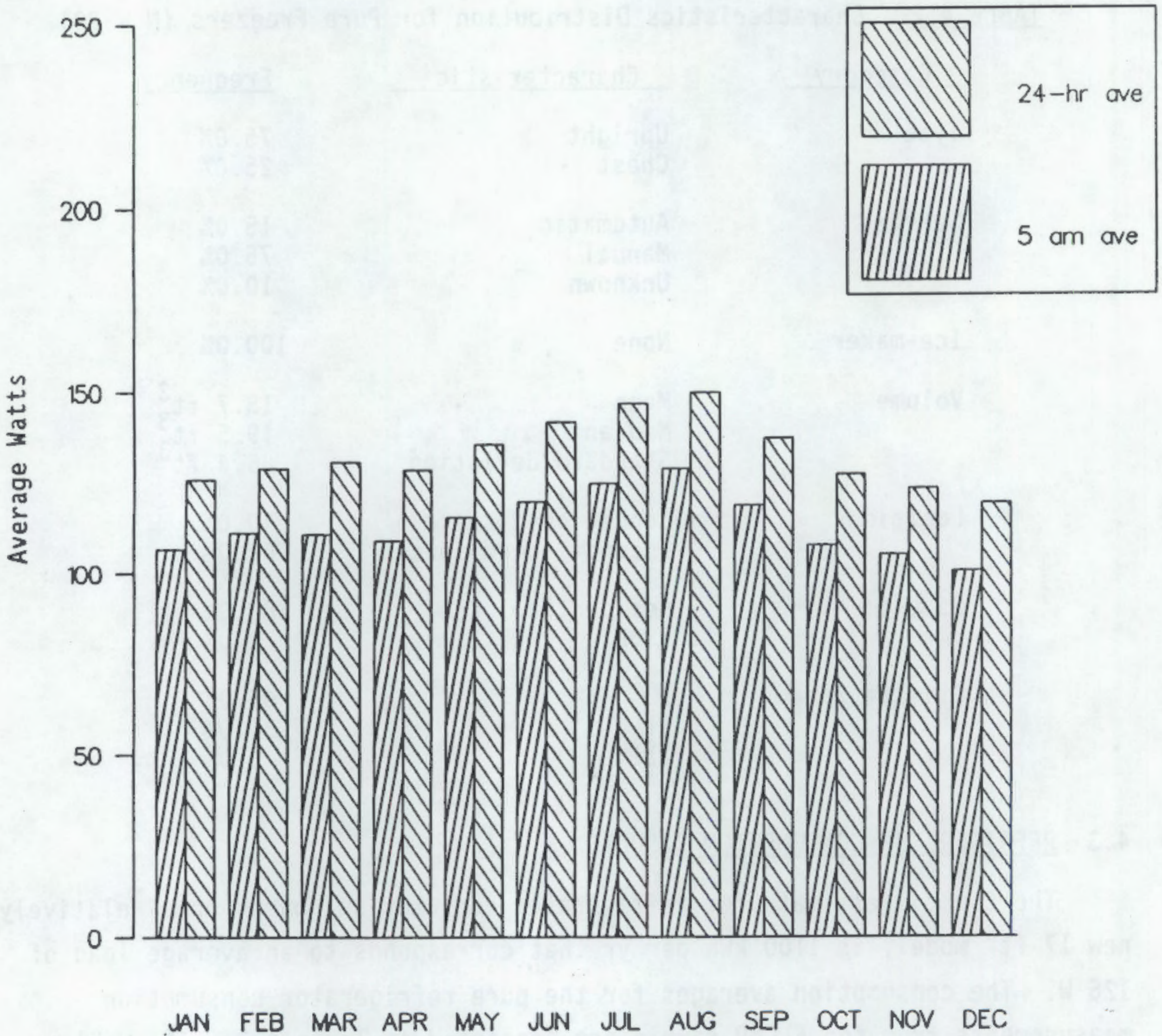

FIGURE 4.1. Monthly Refrigerator Energy Consumption

if newer, more efficient refrigerators tend to be larger. In most cases, however, comparisons by characteristics do provide some insight.

Manual-defrost refrigerators are perceived to use less electricity than automatic-defrost refrigerators. In the sample, the majority of refrigerators have an automatic defrost feature. Figure 4.3 indicates that the units with automatic defrost use more electricity, but in most cases the difference is insignificant.

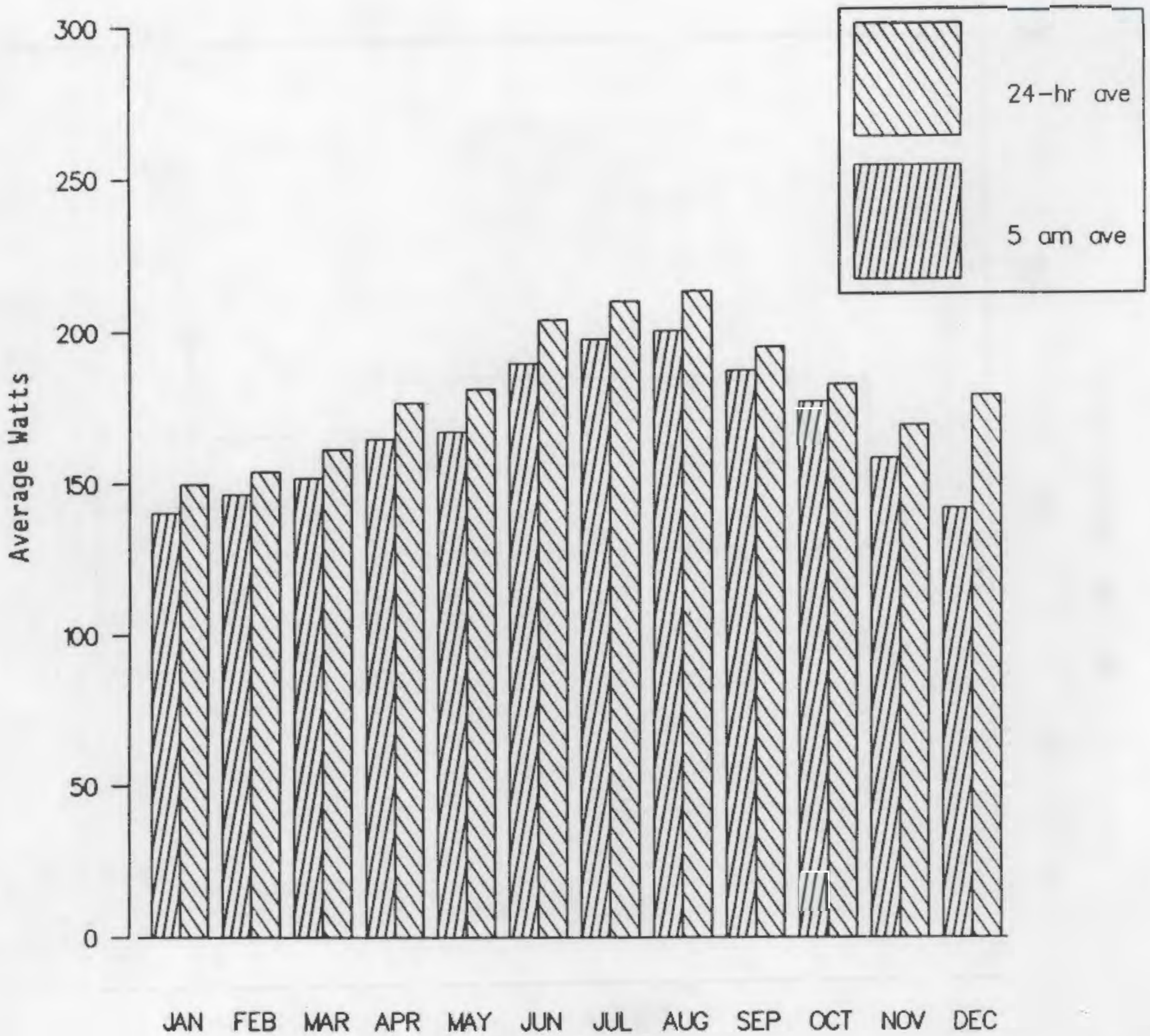

FIGURE 4.2. Monthly Freezer Energy Consumption

TABLE 4.3. Average Refrigerator Consumption Data (N = 114)

Category	Value
24-hour refrigerator consumption	131 W
Average indoor room temperature	70.5°F
Standby load	112 W
Average standby indoor room temperature	68.7°F
Temperature-corrected standby load	119 W
Temperature-corrected standby fraction	91%

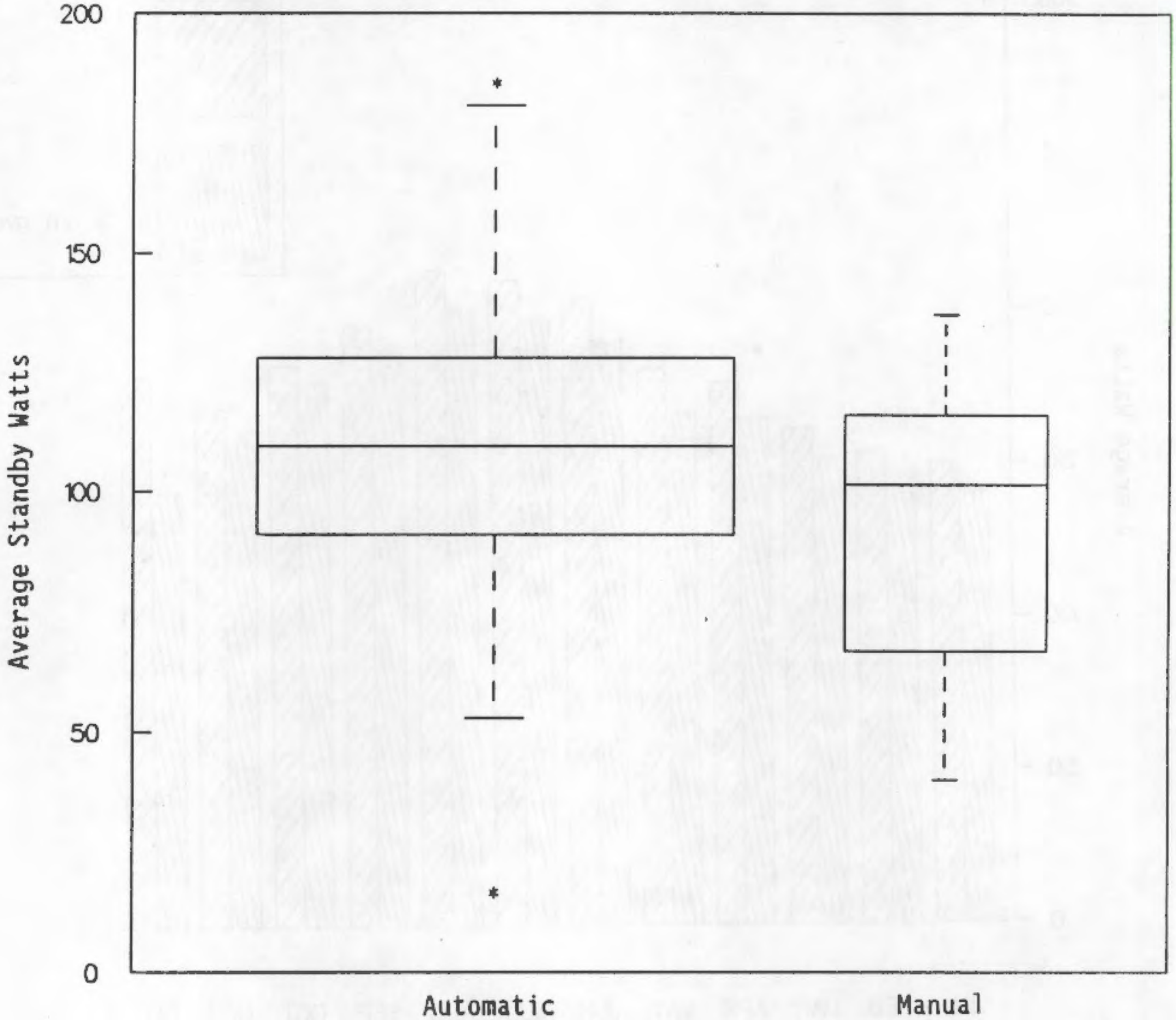

FIGURE 4.3. Standby Load Comparison Between Automatic and Manual Defrost Styles

The effect of refrigerator consumption on stove or oven proximity was also examined. Although a greater heat load is present when a stove or oven is being used, its effect on a 24-hour consumption period was not found to be significant.

Because the homes in the RSDP are newer and have been built to more efficient standards, the sample is biased towards greater energy efficiency. Figure 4.4 indicates that the refrigerators in the RSDP sample use less electricity than the refrigerators from the more normally distributed

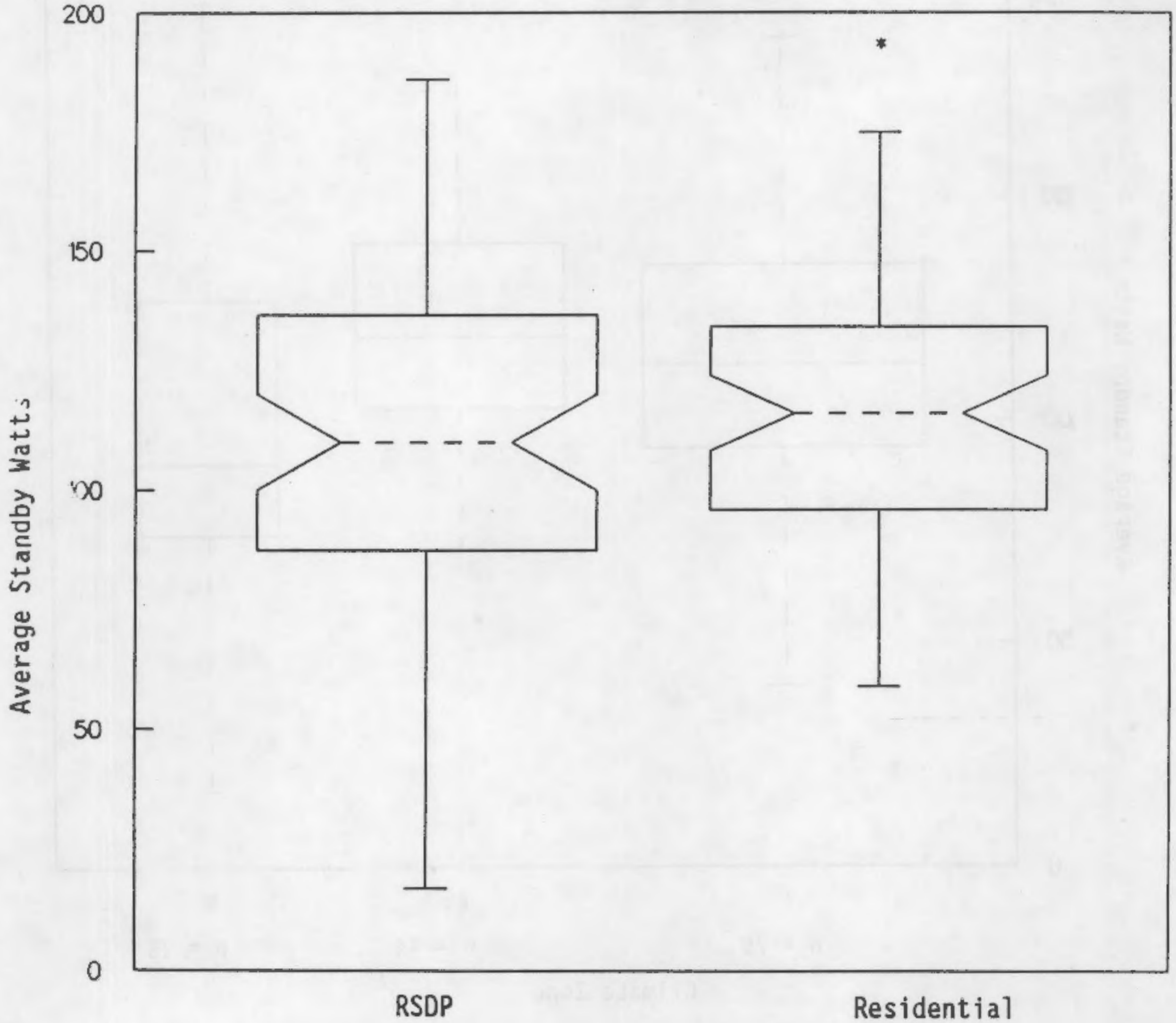

FIGURE 4.4. Standby Load Comparison Between RSDP and Residential Base Study Groups

Residential Base sample, but the difference is not large. Also, the variance in the RSDP sample is higher than the residential base sample.

There appears to be significant differences between the averages of climate zones, as indicated in Figure 4.5. Refrigerators and freezers in Climate Zone I use slightly less electricity than those in Climate Zone II, while refrigerators and freezers in Climate Zone III use much less electricity than the other two zones. This is partly because the average inside room temperature of Climate Zone III is approximately 1.5°F cooler than the other

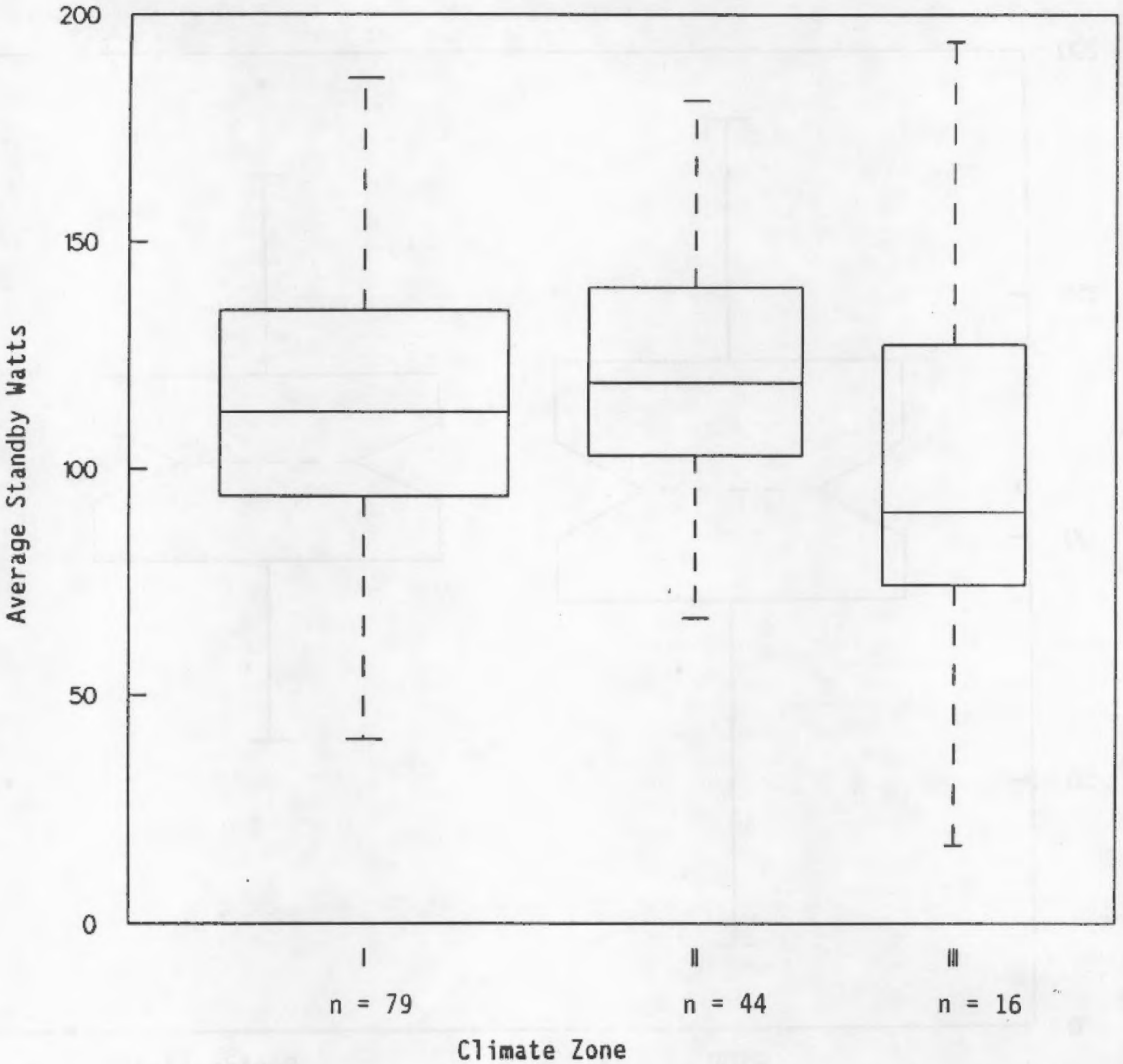

FIGURE 4.5. Standby Load Comparison Between Climate Zones

regions. However, the electricity consumption difference is primarily because of interactions with other characteristics, as described in Section 4.5, *Characteristics Versus Consumption Regression*.

4.5 CHARACTERISTICS VERSUS CONSUMPTION REGRESSION

A regression of standby loads compared to the refrigerator characteristics listed in Table 4.1 was performed. Because the R-squared value is only 0.28, the characteristics cannot be used alone to accurately predict consumption. However, the effects of some of the characteristics are statistically significant. Table 4.4 lists some of the numerical output of the regression. For each characteristic, the most common choice is assigned to be the default (left column). The coefficients column reflects the change in consumption because of the choice. For example, the regression indicates that side-by-side refrigerators consume 39 W more than other refrigerators styles.

For 110 degrees of freedom, T-Values are above 2.0 if the characteristic is significant. Side-by-side refrigerators use significantly more power than top freezers, and refrigerators with manual defrost use significantly less power than refrigerators with automatic defrost. Climate Zone II uses significantly more power than Climate Zone I.

TABLE 4.4. Refrigerator Characteristics Regression Results

Default	Choice	Coefficient, Watts	T-Value
Top freezer	Side-by-side	38.8	4.1
Top freezer	Other types	13.1	1.4
Automatic defrost	Manual defrost	-34.0	-3.7
No ice-maker	Ice-maker	1.6	0.3
RSDP study	RES study	-2.7	-0.5
Climate Zone I	Climate Zone II	12.5	2.1
Climate Zone I	Climate Zone III	-13.2	-1.7
Volume, ft^3	Continuous variable	-2.1	-1.9

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Climate Zone I	Climate Zone III	13.2	1.1
Volume, ft^3	Continuous variable	2.1	1.9

5.0 FEDERAL TRADE COMMISSION ANNUAL CONSUMPTION LABEL RATINGS VERSUS RESULTS

Refrigerator and freezer performance ratings are compiled by the Association of Home Appliance Manufacturers (AHAM 1975). These ratings are presented in units of kilowatt-hours/month or dollars/year (at a certain rate), but have been converted for this analysis to units of average watts. ELCAP consumption data have been compared to the ratings, where possible, but only 62 of the 199 units could be matched. Typically, the units that were not matched were found outside the window of label rating data, or the model numbers were incorrect or incomplete. The implications of this comparison are explained in this section.

5.1 RATIOS OF LABEL RATINGS TO TEMPERATURE-CORRECTED CONSUMPTION

Label ratings are determined from standby load testing done in warmer-than-normal rooms to approximate increased consumption due to demand. It was expected that standby loads would be less than the energy indicated on the label ratings, however, in some cases the actual consumption could be high because of poor maintenance.

The comparison of temperature-corrected standby loads to label rating wattage is indicated in Figure 5.1. This comparison is interesting because the label ratings are based on standby test conditions where the room temperature is increased to 90°F to account for demand. The heat gain at the typical ELCAP indoor room temperature of 69°F is less than 60% of what it would be at 90°F, and the cycle efficiency is much greater at the typical ELCAP indoor room temperature. For the 62 ELCAP sites displayed in Figure 5.1, the standby loads averaged up to 77% of the consumption predicted by the label ratings. This higher fraction of the label rating load indicates that test performance is better than typical performance of the sample for the same room temperature. The inferior performance of the sample can be expected, since the overall performance will decrease as the compressor parts experience wear and tear, heat exchangers become clogged, and the refrigerant inventory decreases.

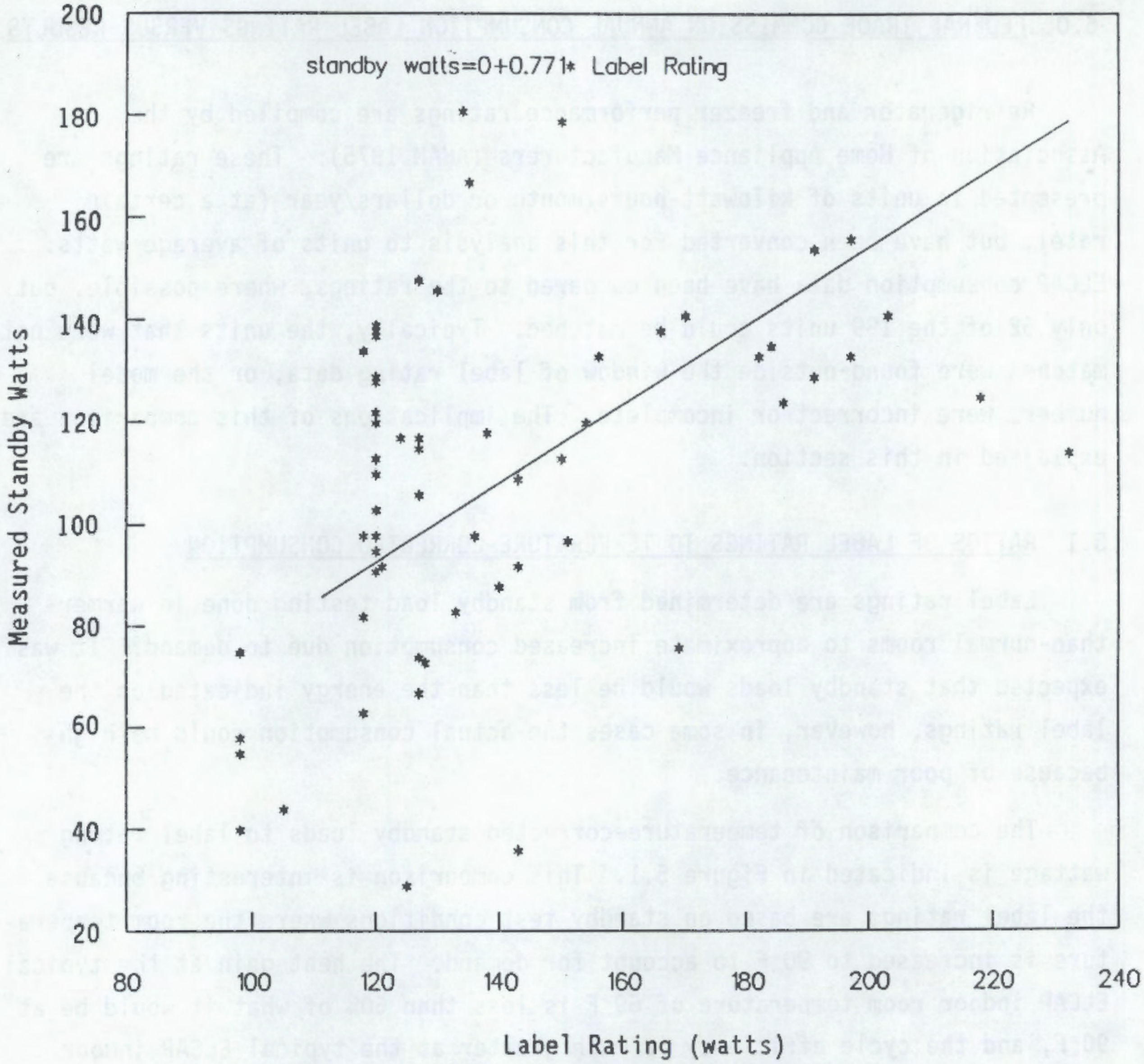

FIGURE 5.1. Standby Loads Versus National Label Ratings (n = 62)

If a fraction of the label ratings can be used as a predictor of standby loads for refrigerators with a typical amount of maintenance, then most of the points should border the regressed line, while some points should lie above or below the line because of uncommonly poor or good maintenance. This appears to be the case for Figure 5.1. The first-order regression indicated on the figure is forced to have a zero intercept and seems to follow the slope of most of the points.

The largest clump of points that are not close to the line have a label rating of about 120 W and consume a higher than expected amount of energy. It may be that these points reflect refrigerators with exceptionally dirty condenser coils or other maintenance problems. Another reason for the clump of points appearing significantly above the regressed line is that the end use may not really be acting pure (as originally thought). The group assignments of the sites with the higher ratios were checked. It was found that most of the higher ratios were from the group with the questioned or changed end-use assignments and none were from the group with the highest confidence. As a result, the five sites with the highest ratios have been removed from the list of sites that act pure, to reduce the final list of pure behavior sites to 114 (see Appendix C).

The comparison of label ratings to 24-hour consumption is illustrated in Figure 5.2. The 24-hour consumption is higher than standby loads and, as a result, the slope of the linear fit increases to 0.89. This means that the label ratings tend to overpredict the 24-hour consumption, that includes both standby and demand, by about 10%.

The effect of refrigerator age on refrigerator performance, as compared to label ratings, was investigated. The refrigerator vintage can be estimated from the label ratings, although the ratings cover only the years 1975 through 1977 and 1981 through 1987. A plot composed of the ratio of consumption to the label rating, as compared to the refrigerator, vintage was found to be random. The random plot indicates that vintage is not important for the limited sample available. Considering the long lifetime of refrigerators now in use, it is reasonable to assume that operating characteristics do not change significantly during the first 10 years of operation.

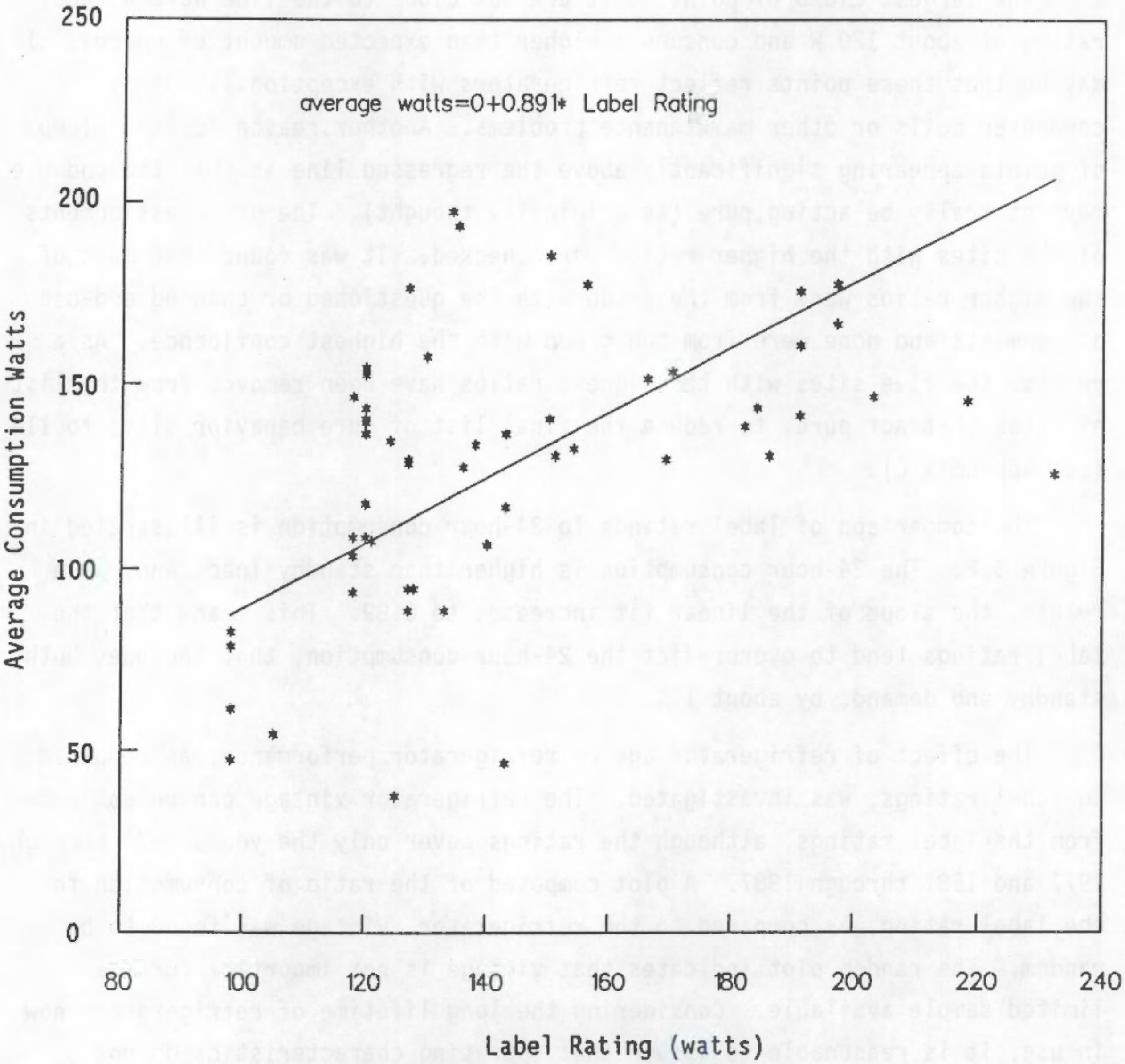

FIGURE 5.2. Twenty-Four-Hour Consumption Versus National Label Ratings (n=62)

6.0 SUMMARY

Analysis of refrigerator and freezer data taken from the ELCAP sample has yielded the following information.

- Pure measurements of refrigerator consumption can be identified using statistical clustering techniques based on standby loads and the ratio of standby to 24-hour consumption. This identification is the basis for this analysis.
- Five-minute data are useful for investigations of defrost-cycle behavior, because the event lasts less than one hour.
- The response of refrigerator consumption to changes of indoor room temperature varies between sites; on the average, an additional 4 W are consumed for each degree Fahrenheit increase in indoor room temperature. Response is typically linear, but second-order effects are evident at lower indoor room temperatures.
- Standby loads cannot be accurately predicted from refrigerator characteristics.
- Side-by-side refrigerators use more power than other types of refrigerators. The automatic defrost feature uses more power than manual defrost, and refrigerators located in Climate Zone II seem to require less energy than those located in the other climate zones.
- Standby loads average 77% of the total energy use predicted by the label rates. Based on test procedures used in developing the ratings, the standby loads are higher than expected. The 24-hour consumption, which includes stand-by and demand averages 89% of the label ratings. This indicates that although the standby loads are higher than expected, the method used in developing the ratings over emphasizes a demand load that does not occur. Or, opening refrigerator doors and placing warm food in a refrigerator has little impact on overall energy consumption.

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- Pure measurements of refrigerator consumption can be identified using statistical clustering techniques based on standby loads and the ratio of standby to 24-hour consumption. This identification is the basis for this analysis.
- Five-minute data are useful for investigations of defrost-cycle behavior, because the event lasts less than one hour.
- The response of refrigerator consumption to changes of indoor room temperature varies between sites, but the average is an additional 4.4 W consumed for each degree Fahrenheit increase in indoor room temperature. Response is typically linear, but second-order effects are present at lower indoor room temperatures.
- Standby loads cannot be accurately predicted from refrigerator characteristics.
- Side-by-side refrigerators use more power than other types of refrigerators. The automatic defrost feature uses more power than manual defrost, and refrigerators located in Climate Zone 1 seem to require less energy than those located in the other climate zones.
- Standby loads average 77% of the total energy use predicted by the label ratings. Based on test procedures used in developing the ratings, the standby loads are higher than expected. The 24-hour consumption, which includes stand-by and demand, averages 89% of the label ratings. This indicates that although the standby loads are higher than expected, the method used in developing the ratings over emphasizes a demand load that does not occur. Or, opening refrigerator doors and placing warm food in a refrigerator has little impact on overall energy consumption.

7.0 REFERENCES

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APPENDIX A

LOAD SHAPES BASED ON FIVE-MINUTE DATA

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LOAD SHAPES BASED ON FIVE-MINUTE DATA

Load shapes were plotted for several sites. Figures 2.6 and 2.7 in the text illustrate load shapes for site 356 and 113. Figure A.1 is a continuation of Figure 2.7. The cooldown energies are constant for most of the window, but the influence of demand is apparent between 8:30 a.m. and 9:00 a.m.

Figure A.2 illustrates a defrost cycle for site 351. The peak power level extends over two 5-min readings. Figure A.3 illustrates shows a defrost cycle for site 304. The normal cool down period lasts relatively long, but the time between cooldown cycles is also long. Because the cool down occurs over a 20-min period, an increase of consumption with time is indicated.

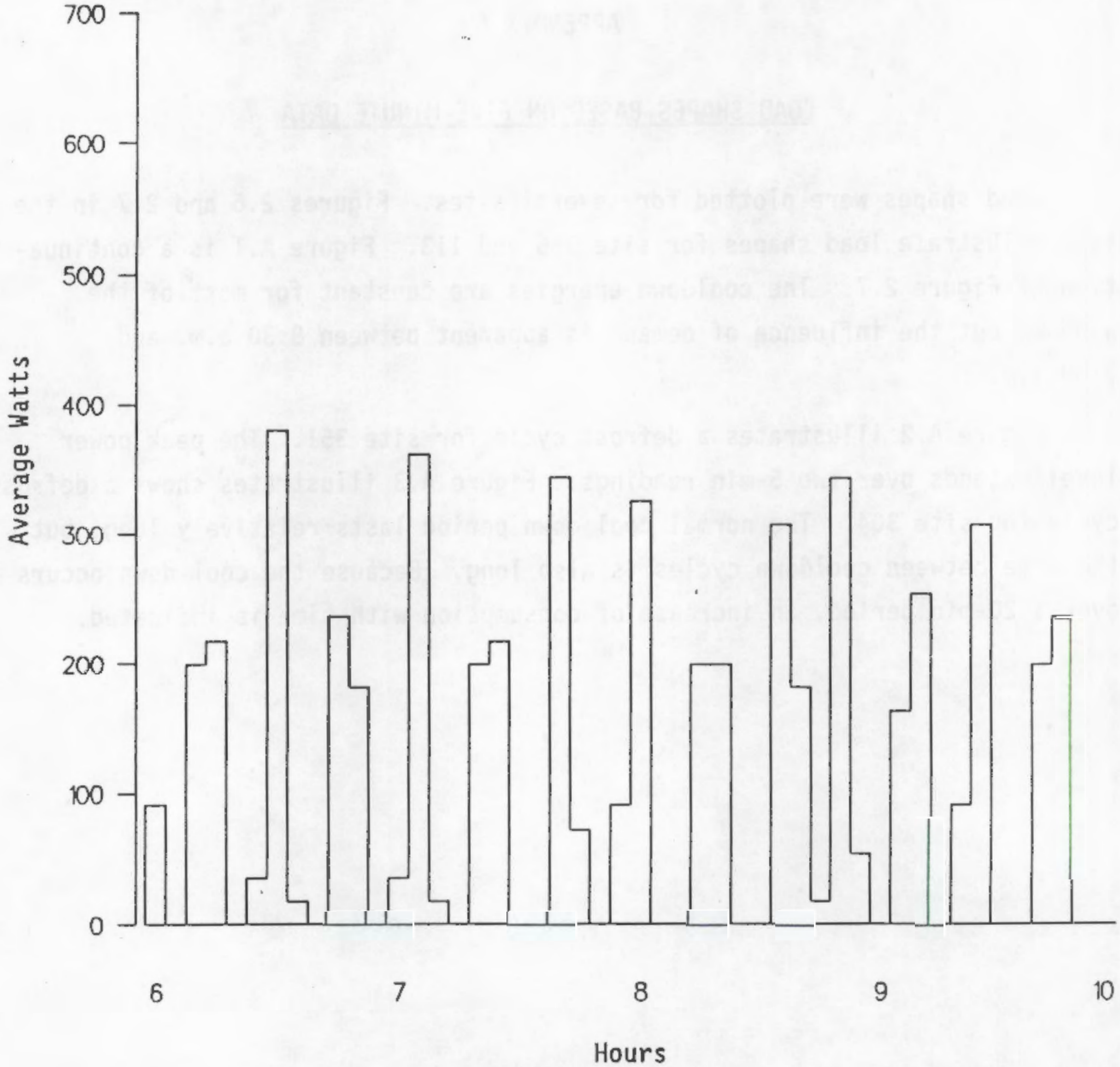

FIGURE A.1. Defrost Cycle Consumption for Site 113, Five-minute Sample Frequency

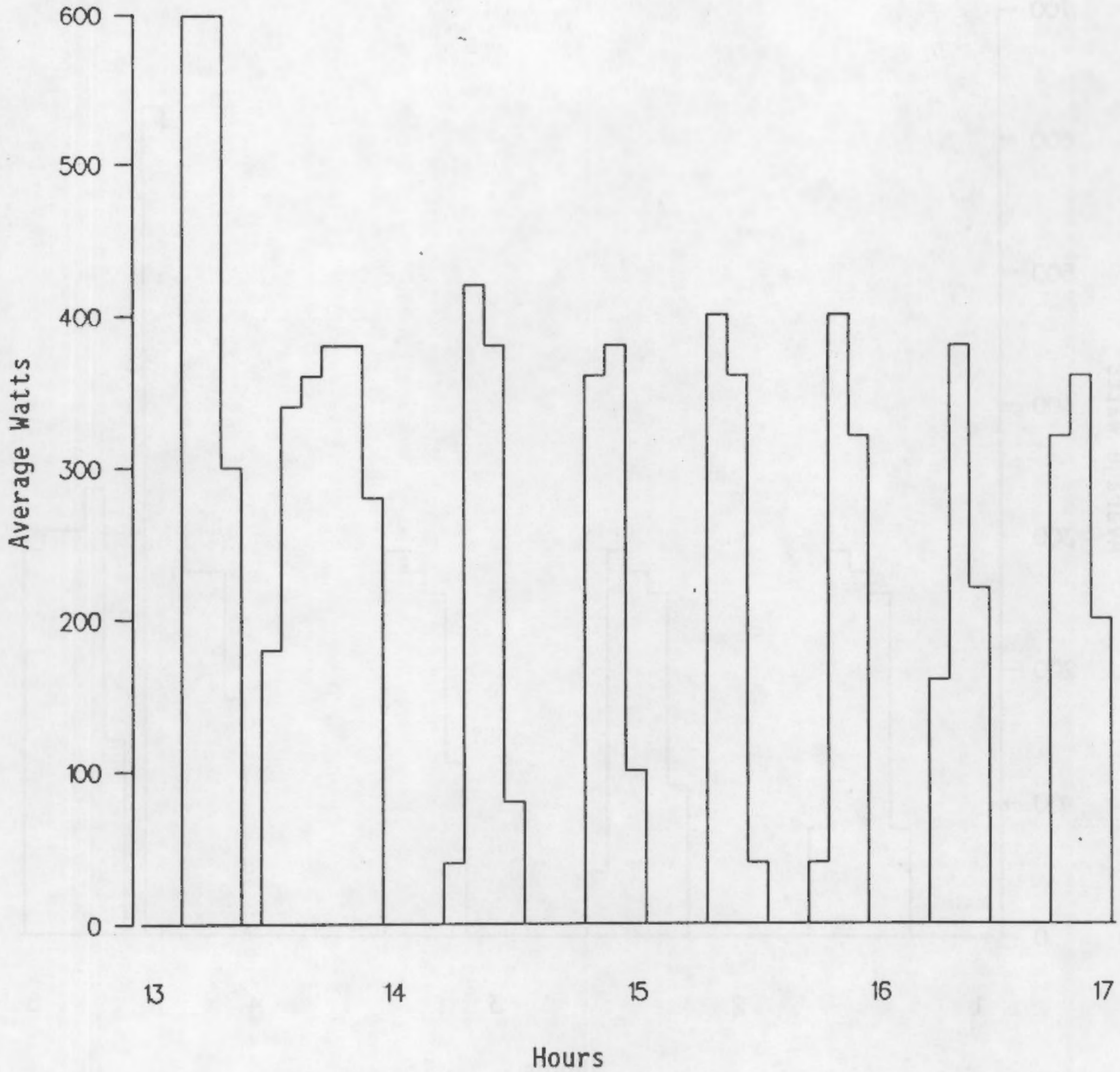

FIGURE A.2. Defrost Cycle Consumption for Site 351, Five-minute Sample Frequency

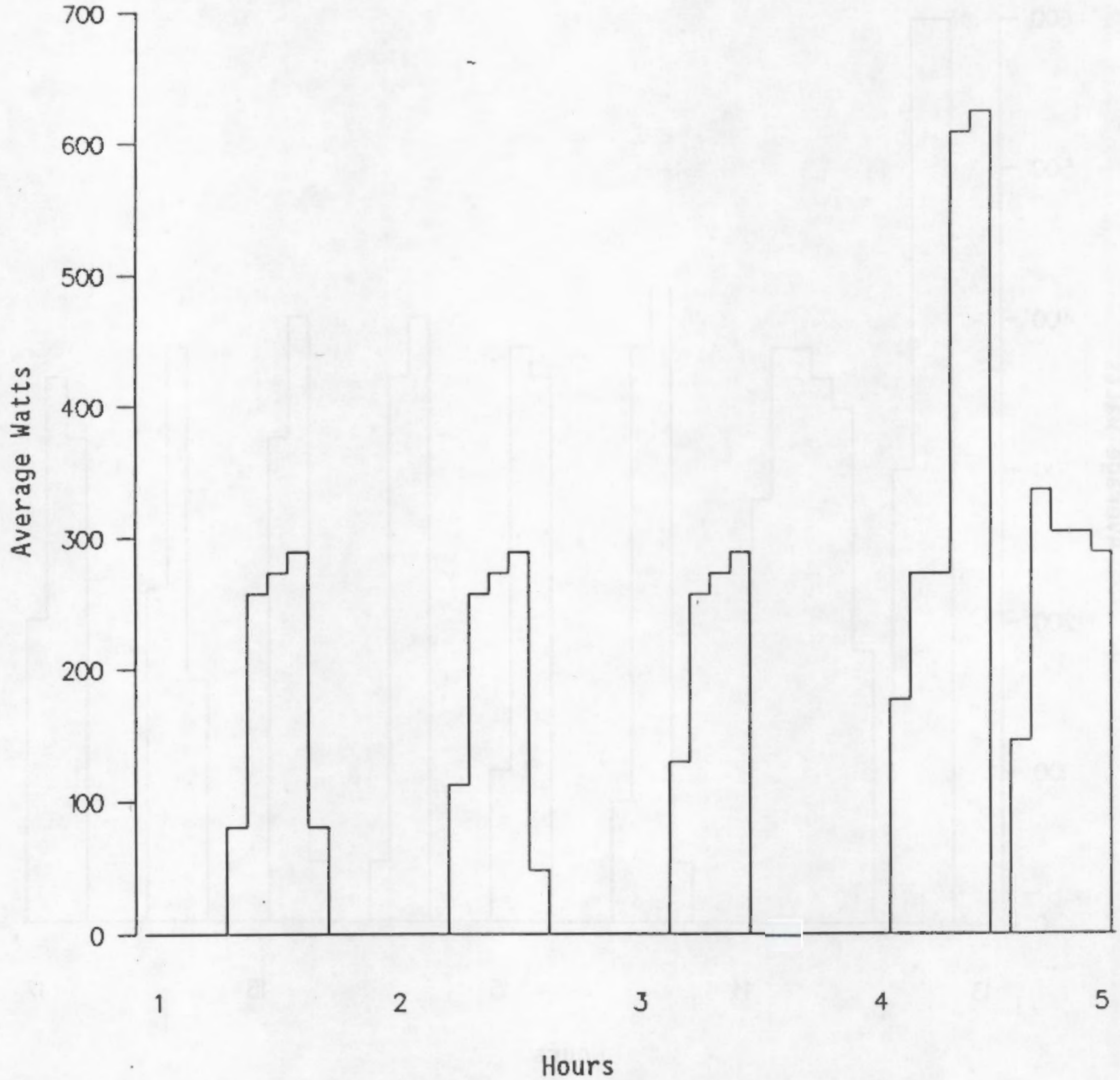

FIGURE A.3. Defrost Cycle Consumption for Site 304, Five-minute Sample Frequency

APPENDIX B

TEMPERATURE CORRELATION CURVES

APPENDIX B

TEMPERATURE CORRELATION CURVES

The correlation of daily consumption and indoor room temperature were plotted for several sites. Figures 3.1 and 3.2 in the text are the correlations for site 35 and 179. Figure B.1 illustrates the correlation for site 272. Note that the scatter disappears at low temperatures. The house may always be vacant when the temperature is low, thus the scatter caused by demand variability disappears.

Figure B.2 illustrates the correlation for site 141. This site is never as cool as other sites and occasionally is quite warm. The linear trend is apparent, even though the scatter is fairly large.

Figure B.3 illustrates the correlation for site 111, where the indoor room temperature typically does not vary. A few cool days, when the house is probably vacant, allow some idea as to the effect of temperature on consumption.

Figure B.4 illustrates a poor correlation for site 251. The flat response at higher temperatures indicates that the air temperature around the refrigerator is not following the temperature extremes indicated by the sensor. For this site, the sensor is located in the living/utility area, and it is assumed that this area must be hotter than the kitchen on certain days.

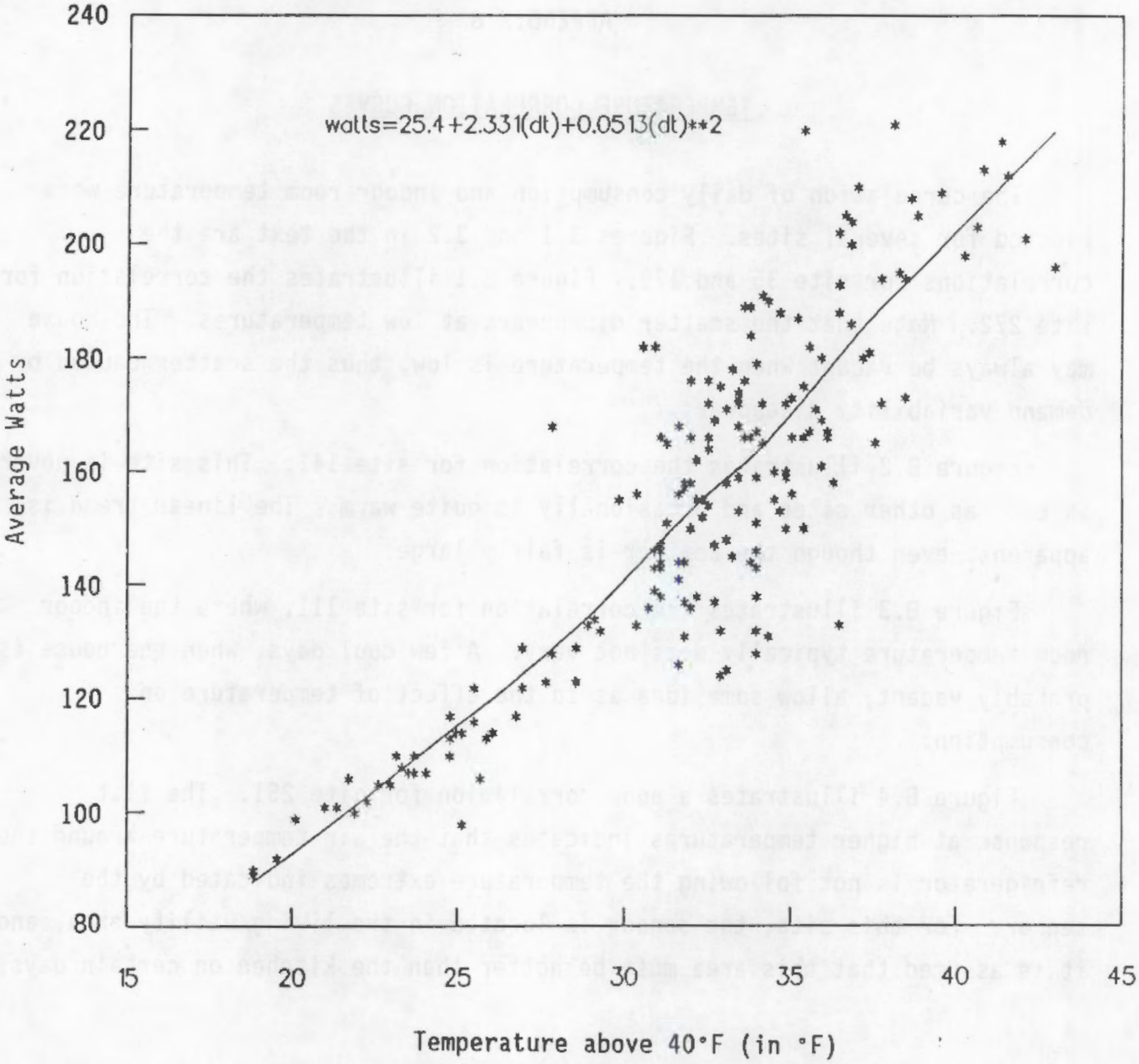

FIGURE B.1. Refrigerator Daily Consumption Versus Indoor Temperature for Site 272.

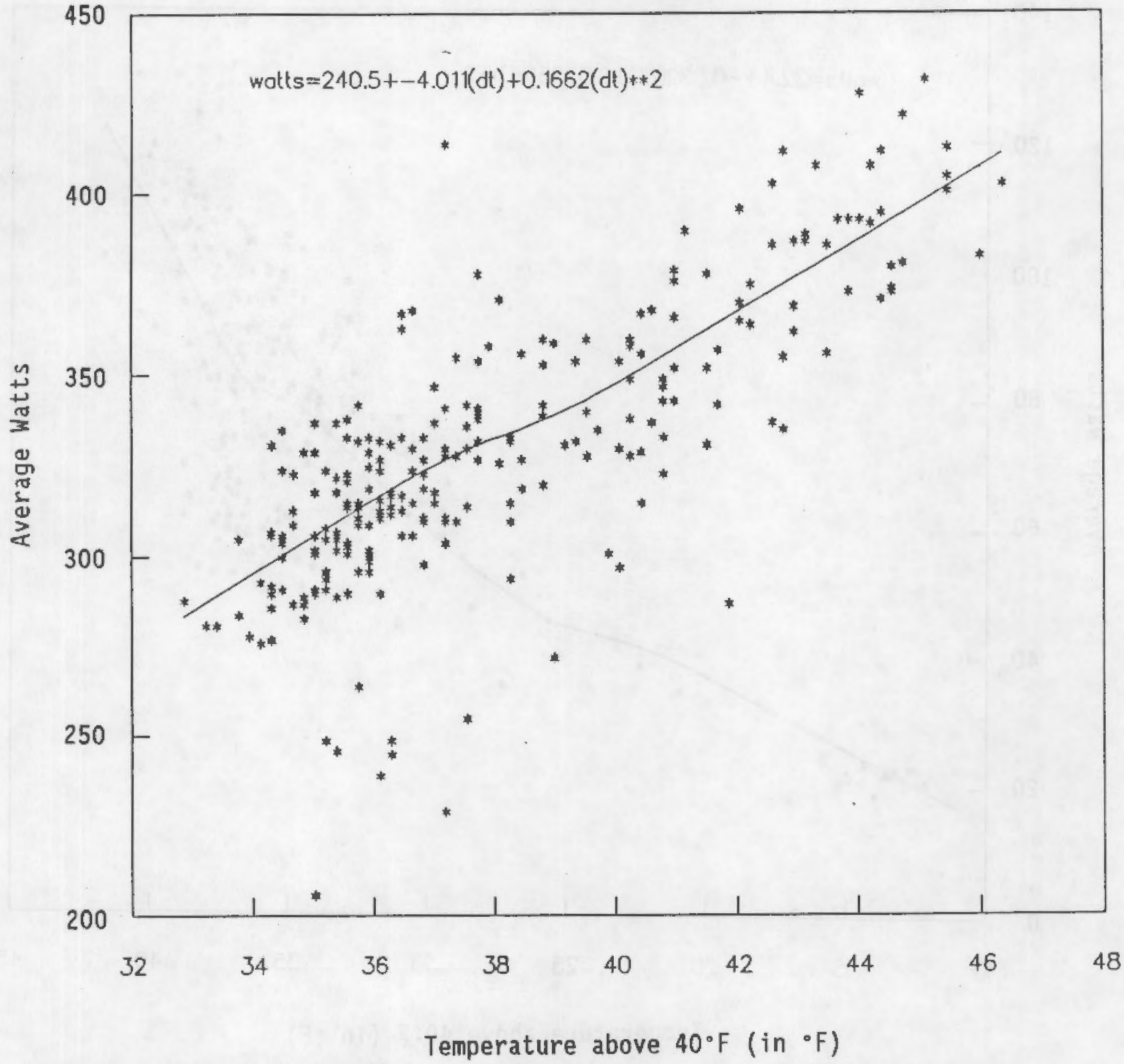

FIGURE B.2. Refrigerator Daily Consumption Versus Indoor Temperature for Site 141

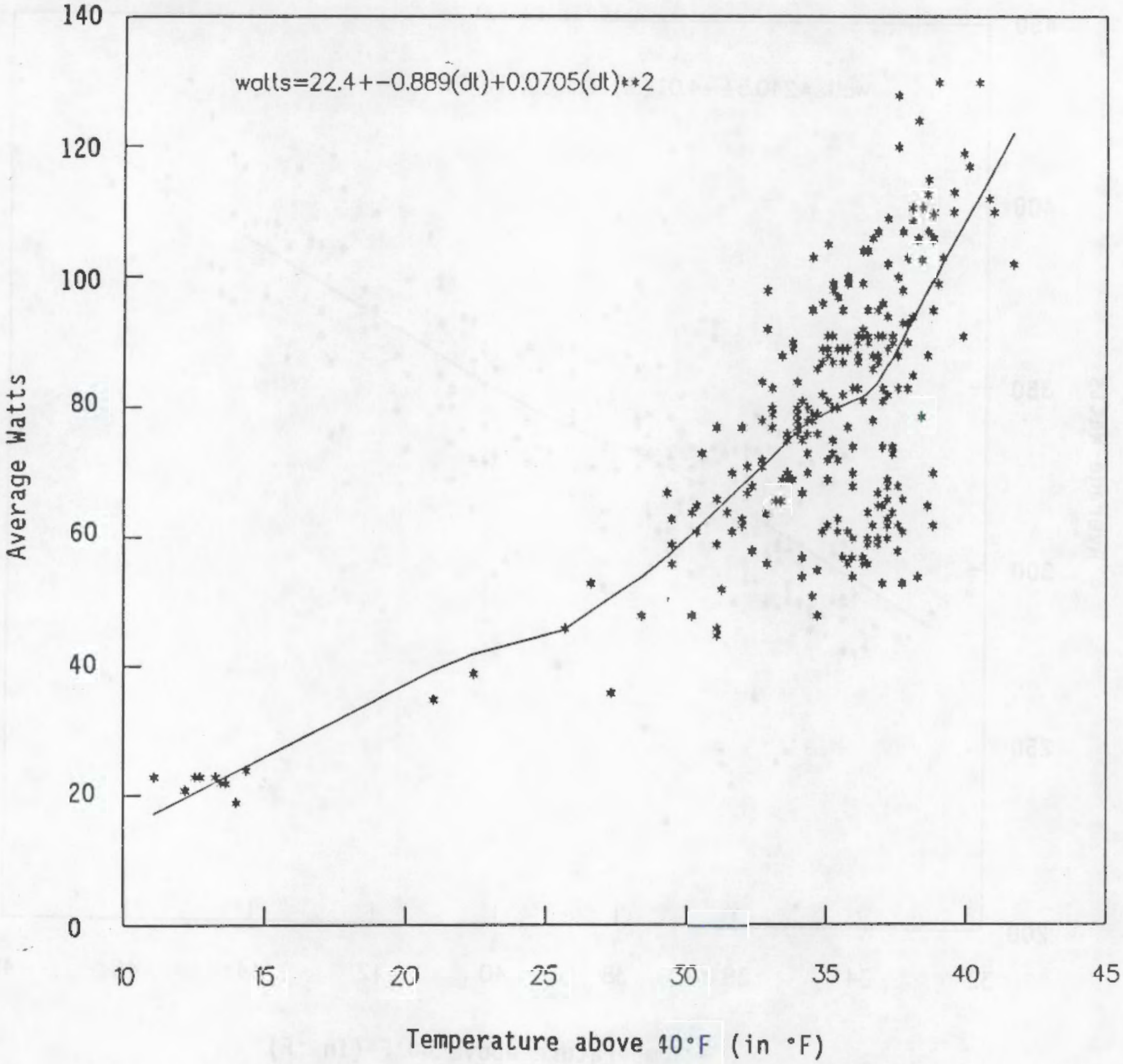

FIGURE B.3. Refrigerator Daily Consumption Versus Indoor Temperature for Site 111.

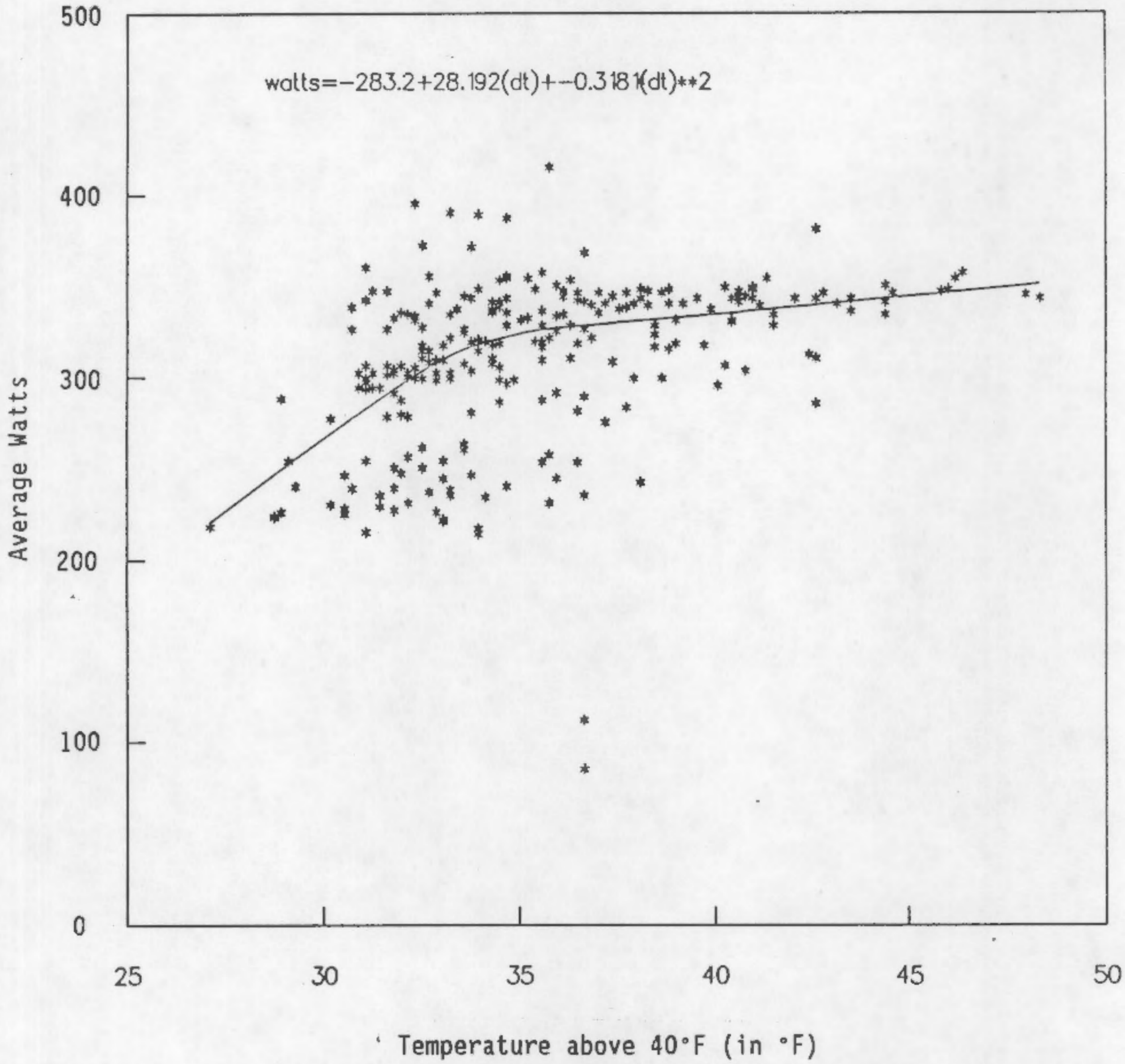

FIGURE B.4. Refrigerator Daily Consumption Versus Indoor Temperature for Site 251

APPENDIX C

ELCAP REFRIGERATOR/FREEZER SITE NUMBERS

APPENDIX C

ELCAP REFRIGERATOR/FREEZER SITE NUMBERS

Refrigerators End-use, Refrigerator	Refrigerators End-use, Mixed		Freezers End-use, Freezer
3	4	316	42
35	17	325	77
42	44	328	83
94	47	335	88
95	51	338	152
100	58	339	217
107	83	340	219
108	91	341	239
109	98	342	251
111	114	343	255
122	115	350	315
158	117	361	341
176	123	365	342
179	124	372	346
191	139	377	361
200	157	378	362
207	160	379	420
272	172	389	467
278	187	406	473
280	189	409	509
301	190	423	
304	193	425	
306	194	431	
309	195	432	
311	196	461	
314	201	464	
320	208	473	
337	213	479	
356	216	494	
357	218	495	
408	219	504	
410	220		
426	238		
436	240		
470	252		
476	259		
478	261		
480	263		
484	269		
489	279		
492	312		
522			

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