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UC-350

End-Use Load and Consumer Assessment Program

Characterizing Residential Thermal Performance from High Resolution End-Use Data

Volume II - Analysis

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June 1991

Prepared for
the Bonneville Power Administration
under a Related Services Agreement
with the U.S. Department of Energy
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TABLES

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PREFACE

This document is part of a two-volume set describing a series of thermal analyses of the residential buildings monitored under the End-Use Load and Consumer Assessment Program. Volume I describes in detail the thermal analysis methodology employed. Volume II presents the results of applying the methodology in a series of four distinct analyses: 1) an analysis of the first monitored heating season, 1985-1986, 2) an analysis of the second monitored heating season, 3) a comparison of first- and second-year analyses showing changes in residential consumption with changes in weather and evaluating the ability of the analytical technique to discriminate those changes, and 4) a continuation of the previous analyses evaluating the effects of foundation type and heating system type on the results.

SUMMARY

The End-Use Load and Consumer Assessment Program (ELCAP), managed by the Pacific Northwest Laboratory (PNL) under the sponsorship of the Bonneville Power Administration (Bonneville) is a study of how electricity is used by residential and commercial consumers within the Bonneville service area of the Pacific Northwest. Since 1986, a variety of information has been gathered on participating consumers, including metered loads for specific electrical end-uses, local weather data, physical data on the residence or place of business, as well as additional and demographic data describing the consumers themselves. The analyses in this study are to be used in conjunction with the companion report entitled *Characterizing Residential Thermal Performance from High Resolution End-Use Data - Volume I - Methodology*. It is intended that these data analyses be used to make informed decisions regarding the management of the Northwest's electrical resources, particularly as it pertains to energy conservation.

The sites included in the ELCAP sample are grouped into several categories: base structures, Model Conservation Standard (MCS) structures, MCS control structures, and post-78 structures.

The identification and measurement of various indicators of thermal performance have been a central focus for the thermal analyses. Chief among these analyses is the annualized estimated consumption (AEC). The studies in this report use three forms of temperature data for AEC calculations:

- inside-outside temperature difference
- standard inside temperature
- outside temperature alone.

Principal conclusions of these studies are listed below:

- Thermal performance characterizations, based on analyses of first-year data
    - The ELCAP base sample homes require roughly twice the total estimated electrical space-heating energy as do the MCS homes, while the Residential Standards Demonstration

Program (RSDP) control homes consume about 60% of the energy of the base homes.

- Even after normalizing floor area, space-heating energy estimates still display the base sample consumption as being more than double that of the MCS consumption.

- The thermal integrity of base home sample performance is less than that of the MCS' sample homes. The slopes for the MCS homes are roughly half those of the residential base slopes, with control-homes' slopes being 70% of the base sample slopes.

• Relation of thermal conductance of the buildings' effective conductance (UA) to energy consumption

  - Calculated UAs[(a)] and the apparent UAs[(b)] exhibit a high degree of bivariate plot scatter between the quantities.

  - On the average, nameplate UAs are larger than as-observed UAs, even though the nameplate UA calculation does not include infiltration.

  - Virtually all basement homes, heated or unheated, are performing better than predicted by the nameplate UAs.

  - Nameplate UAs are positively correlated to estimated annual electrical space-heating consumption.

• Heating system type effects

  - Heat pumps are the most efficient heating system type in climate zone 1.

  - In the more severe climate zones, sample homes with baseboard heaters appear to consume about two-thirds the estimated energy per square foot of residential surface area.

(a) These values obtained agree with normal engineering calculations. These calculations deal only with thermal conductance and will be referred to as "nameplate UAs."

(b) Values obtained from metered data include heat loss from conductance, internal gains, and effect of occupant activities. Values will be referred to as "as-operated UAs."

- Thermal performance characterizations, based on analysis of the second year data

  - The mean annualized estimated consumption, calculated using the as-measured inside air temperature, for the base homes is 7.62 kWh/ft^2-yr or 12,066 kWh/yr.

  - The as-operated UAs taken from six linear fits are, on the average, lower than the nameplate UAs that are calculated from audit data.

  - The mean as-operated UAs rank the order of the thermal integrity for the structure types as base < post-78 < control < MCS, where MCS has the lowest as-operated UA.

  - The mean building balance points indicate the same ordering of thermal integrity for the various structure types as do the slopes.

- Thermal performance characterizations, based on metered data from the 1985-1986 and 1986-1987 heating seasons, are contrasted for 127 Base and MCS homes.

  - Despite considerable weather differences between the 1985-1986 and 1986-1987 heating season, AEC calculations are fairly stable in the aggregate for the combined set of homes. The differences identified between the years appear to be due to the warmer, sunnier second-heating season and the limits of the methodology used to calculate the AECs.

  - A statistically nonsignificant difference of 0.4% is observed in the AEC_{iat} estimates between the two heating seasons for the combined sample of homes.

  - A statistically significant drop of 3.5% in AEC_{oat} is observed in the second year for the combined group of homes. The magnitude of the drop is very close to the magnitude of increased solar availability in the second year for the Pacific Northwest.

  - Some notable case study differences emerge from the AEC pairwise comparisons. The Base homes indicate the least amount of change, while the RSDP MCS homes exhibit the greatest sensitivity to weather conditions.

  - The slopes from the linear fits of daily heater load to daily inside-outside air temperature (or outside air temperature) are more resistant to weather changes than are the intercepts. The magnitude of the changes in the estimates from the linear fits are small and tend to be nonsignificant, with the exception of those from the MCS homes.

- Results of these analyses indicate that both heating system and foundation type are significant predictors of electrical consumption for space heating. Furthermore, interactions between the two factors preclude complete separation of their effects.

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FIGURES

1.0 FIRST-YEAR ANALYSIS

1.1 INTRODUCTION

The purpose of the first-year analysis study, managed by the Pacific Northwest Laboratory (PNL)[a], was to determine annualized residential energy consumption for those residences being metered as part of the End-Use Load and Consumer Assessment Program (ELCAP) conducted by the Bonneville Power Administration (Bonneville). It is intended that this information be used in conjunction with the companion report entitled *Characterizing Residential Thermal Performance from High Resolution End-Use Data - Volume I - Methodology* (Miller et al. 1990) to make informed decisions regarding the management of the Northwest's electrical resources.

This study provides a summary of the initial results and makes simple comparisons between the ELCAP residential base sample and the ELCAP Residential Standards Demonstration Program (RSDP) samples. Some early results are included on several determinants of electrical energy consumption for the pooled samples, as well as an evaluation of the relation of various demographic data to the derived parameters for the base sample. Finally, some preliminary observations are made relating the topology of the space-heating curve, as a function of indoor-outdoor temperature difference, to heating system type and foundation type for the ELCAP base sample.

This section describes the first of four studies carried out from 1986 through 1989. These studies focus on characterizing and comparing sets of data collected during the ELCAP project. The characterization and geographical distribution of the data used in these studies are discussed in Section 1.0, and the analytical techniques that the studies have in common are discussed in Section 1.2. Section 1.3 describes an additional study using 1985-1986 ELCAP residential data. This work primarily deals with thermal characterization of the sites and comparisons of homes constructed with different building standards. Section 1.4 is a quick analysis of the

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residuals after the data has been modeled as presented in Section 1.3. Section 1.5 describes several comparisons between the thermally derived parameters and the ELCAP residential survey data. Results of the second heating season characterizations are presented in Section 2.0. A comparison of the first- and second-year data is made in Section 3.0, and finally, Section 4.0 relates the effects of heating systems and foundation types on the thermal performance of ELCAP buildings.

The ELCAP residential studies include approximately 440 homes. About 280 of these are detached, single-family homes with permanent electrical space-heating equipment, and about 50 are case study homes, differing from the bulk of the sample by being renter occupied, attached, or by not having electrical space heat. (The base sample whose thermal performance is characterized in this report actually includes results from 6 rental homes, 3 manufactured homes, and 2 attached homes. The inclusion of these sites does not alter the conclusions drawn.) The remaining 110 homes were constructed as part of the RSDP to demonstrate the savings effected by stringent thermal construction standards. The RSDP sample is partitioned into two groups; the control group includes those homes built to current construction practices, while the Model Conservation Standards (MCS) group includes those homes built to the proposed standard.

The thermal performance characterization is based on an analysis of exterior temperature, interior temperature, and electrical space heat consumption data aggregated to the daily level. For each building, three data profiles are derived from the daily temperature and heating energy usage data:

- an estimated annual space-heating energy requirement under certain standard conditions
- two parameters from a fit of a linear model to the data
  - a slope giving the resistance of the envelope-to-heat transfer (apparent effective conductance [UA])[a]

(a) Later referred to as "as-operated UA."

- an intercept giving the inside-outside temperature difference that the structure can support without use of space-heating equipment (balance temperature difference)

- an average inside temperature which serves as a measure of occupant control strategy.

A linear model applied to data in this analysis used the inside-outside temperature difference parameter. Additionally, if a nonlinear region is detected in the low temperature difference region, it is automatically removed prior to the linear fit. (Failing to exclude these points tends to lower both the balance temperature difference and the slope from the linear fit.) Hence, the slope parameter retains the same meaning and still may be used as a measure of thermal integrity of the structure subject to a number of caveats. The balance point in the ELCAP analysis is really a balance temperature difference, which can be used as an estimate of the average inside-outside temperature difference supportable by the structure without use of space-heating equipment.

In the interest of assessing the stability and confidence limits of the estimated values for annual electrical space-heating consumption, a jackknife analysis was applied to the energy estimate computations for the residential base sample. For the residential base sample sites analyzed, the energy consumption estimate using all data points and the jackknifed value compared quite favorably. Over 90% of the sites are seen to have very stable fits. In addition, those sites with less stable fits do not represent anomalous points in the distribution for the energy consumption estimates presented in this report. A more detailed discussion of these results can be found in Appendix B. A discussion regarding the jackknife technique can be found in Volume I of this study (Miller et al. 1990).

1.2 SAMPLE CHARACTERISTICS

This section compares the geographical distributions for the analyzed sample sites and RSDP samples. In addition, survey data on wood-use habits is reported for the samples studied. Finally, the inclusion of sample sites in the final results for the RSDP sample is examined in terms of occupant-reported, wood-use habits.

1.2.1 Geographical Distribution

The geographical distribution of the sample sites used in this analysis is presented in Table 1.1. This table displays percentage distributions by sample and climate zone for those sets of homes included in the final results for the first-year characterizations. For reference, the top row in Table 1.1 includes a similar data profile for the entire ELCAP residential base set of homes--not just those with thermal characterizations presented in this report. Observe that the climate zone 1 residential base samples are much more heavily represented, at 70%, than the RSDP samples which together draw about half of their sites from the more severe climate zones.

1.2.2 Effects of Wood Burning on Sample

Any thermal performance characterization of the residential base sample must deal explicitly with the high saturation rate of wood-burning equipment throughout the region and high incidence of wood-burning as reported by the residents. In this study, the thermal performance characterizations exclude days when wood-burning equipment is used. In Table 1.2, results from a survey are summarized where occupants were asked to report on the heating system used most to heat their homes. Not all those who received surveys in the analyzed samples responded to the surveys. The percentages are based on occupant responses to the survey. The entries in the rows give the percentage of answers falling in each heating category for the ELCAP samples included in the final aggregation of thermal performance results. The categories in Table 1.2 are electric forced-air furnace, baseboard heaters, radiant electric heat, electric heat pumps, nonelectric furnaces and heat pumps, kerosene, and wood.

TABLE 1.1. Climate Zone Distributions for the Entire Sample of ELCAP Base Homes and the Analyzed Home Samples

Sample Analyzed	Zone 1	Zone 2	Zone 3		Total
Entire ELCAP Residential Sample	60%	29%	11%	=	100%
Base (n = 127)	70%	24%	6%	=	100%
MCS (n = 51)	55%	31%	24%	=	100%
Control (n = 26)	46%	31%	23%	=	100%

TABLE 1.2. Heating Systems Most Frequently Used for the Entire Sample of ELCAP Base Homes and the Sites Analyzed

	Heating System Type							
Sample Analyzed	Forced Air	Baseboard Heat	Radiant Heat	Heat Pump	Nonelectric	Kerosene	Wood Burning	
Entire ELCAP Base	22%	29%	6%	7%	6%	4%	26%	= 100%
Base (n = 127)	32%	37%	9%	11%	2%	0%	10%	= 100%
MCS (n = 51)	20%	55%	10%	13%	0%	0%	3%	= 100%
Control (n = 26)	25%	65%	5%	5%	0%	0%	0%	= 100%

The first row presents responses for the entire ELCAP base study. Baseboard heaters and forced-air furnaces together compose the majority of the heating systems across all sites included in the analysis. Of the 127 sites included in the final base home analyses, 90% responded to this survey question. For the most part, the occupant responses reflected in Table 1.2 are corroborated by the metered data. Note that although all of these homes have permanent electrical space-heating equipment in place, a substantial number appear not to use it, especially in the larger ELCAP base sample of homes. Specifically, the last three columns can be totaled by row to give an index of fuel switching potential from electric to nonelectric heating and vice versa. It would appear from the larger sample (row 1), that one-third of these homes can significantly alter their space-heating electrical consumption patterns in either direction by cutting or increasing loads.

The penetration of wood-burning equipment and wood-burning habits noted from occupant survey reporting serves to further highlight the potential for fuel switching in the region. Table 1.3 displays the percentages for types of wood-burning equipment present in the home for the same samples as in the two previous tables. Columns 1 through 3 report the type of wood-burning equipment present in the home, if any. Column 4 displays the percentage of homes that report burning wood; and Column 5 displays the percentage of homes with either minor or major wood-burning equipment in the homes that report using it, at least part of the time, to heat their homes. Approximately three-fifths of the final sample used to characterize the base thermal performance

TABLE 1.3. Wood-Burning Equipment Penetrations and Occupant Reported Wood-Use Habits

Sample Analyzed	Equipment Present, % None	Minor	Major	Homes that Report Wood Burning, %	Homes with Utilized Wood-Burning Equipment, %
Entire ELCAP Base	19	25	56	68	84
Base (n = 127)	28	38	33	57	79
MCS (n = 51)	54	34	12	4	9
Control (n = 26)	68	32	0	16	50

(row 2) have wood-burning equipment in the home, and nearly four-fifths of those homes reported using that equipment. The trend in the larger ELCAP base sample is much the same as the trend in the final sample. The chief difference is that the incidence of wood-burning equipment is even higher, and the bulk of that equipment is defined as major wood-burning equipment such as a wood stove, wood furnace, or fireplace insert. Minor wood-burning equipment is defined as a fireplace or fireplace with a heatalator.

1.2.3 Selection of Sites for Final Analysis

Although only 127 base residential sites make up the sample sites in the aggregation of final thermal characterizations, many more homes were available for analysis and were studied in great detail. The reasons for the site exclusions are discussed below.

About half of the sites available for analysis were included in the final aggregation of results for the base thermal analysis. A very small number of sites (less than 4% of those available for analysis) were rejected because of an inoperative indoor temperature sensor, no available outside temperature, no reliable information on floor area, or a data-quality problem discovered during the analysis. Another 4% of the sites available had switched entirely to a nonelectric permanent space-heating system in the house. However, the bulk of the rejections, two-fifths of the sites, were removed because of

- poor thermal characterizations where the heater load could not adequately be predicted from the inside-outside temperature difference. The daily heater load versus the daily temperature difference plots looked like a wedge in these cases, presumably from use of supplementary fuel sources or perhaps plug-in wall heaters.

- wood use either totally displacing space-heating electrical consumption or supplementing electrical consumption such that when wood-use days were removed, insufficient data remained to characterize the site.

For the homes with wood-burning equipment in place and no functional wood-stove sensor in place, the scatter plots were inspected in conjunction with survey data relating the occupants' wood-burning habits and type of wood-burning equipment. If serious distortions in the consumption data were observed, the site was not included in the final analysis results.

Base sample homes, available for thermal performance characterizations, are classified into several categories. A subset of these categories is listed below, ordered by increasing difficulty in performing the thermal characterizations. (A complete discussion for all category selection, including those not discussed here may be found in Appendix A, along with a more detailed discussion of category definitions.)

Category 1: This site is one of the 127 sites reported in the thermal performance results and represents 53% of those sites available for analysis or approximately 40% of the ELCAP base sites.

Category 2: Thermal characterizations were performed at this site, but wood use or nonuniform heating system operation made results unreliable. These results represent 19% of the sites available for analysis or approximately 15% of the ELCAP base sites.

Category 3: This site could not be used in the analysis at all, typically because of heavy wood use. This represents 17% of those sites available for analysis or approximately 13% of the ELCAP base sites.

Category 4: This site depended 100% on wood or kerosene use and represented 4% of those sites available for analysis or approximately 3% of the ELCAP base sites.

Category 5: This site appeared to have switched to permanent, nonelectric space-heating equipment and represented 4% of those sites available for analysis or approximately 3% of the ELCAP base sites.

Table 1.4 displays the percentage of sites in each of the five analysis categories that fall into the specific climate zones. The actual number of homes in categories 2 through 4 is fairly evenly split between climate zone 1 and the other two climate zones combined. However, categories 3 and 4, with the largest space-heating displacement, display an increasing trend to be clustered in the more severe climate zones. The bulk of the homes that switched to the permanent nonelectric space-heating equipment were predominantly in climate zone 1.

Table 1.5 displays the percentage of homes in the five analysis categories defined above and is subdivided into survey-reported, wood-use habits. Column 1 represents the percentage of respondent homes having wood-burning equipment present in the home. Column 2 represents the percentage of each sample that these potential burners represent. The percentage of those homes with wood-burning equipment in place that report using it to heat their homes is represented in Column 3. A trend of increasing wood-usage potential is seen in both the equipment present and in the occupants' tendency to use wood to heat their homes in categories 1 through 5.

To assess possible bias in the base sample of homes thermally characterized, categories 1 through 5 are compared on the basis of home size, home

TABLE 1.4. Climate Zone Distributions Within Major Analysis Categories for the Residential Base Homes

Sample	Zone 1 %	Zone 2 %	Zone 3 %
Sites Selected (n = 127)	70	24	6
Analyzed but Excluded (n = 47)	72	17	11
Not Analyzed, Heavy Fuel Switch (n = 39)	44	38	18
Not Analyzed, 100% Fuel Switch (n = 10)	20	30	50
Not Analyzed, Heating System Switch (n = 10)	70	30	0

TABLE 1.5. Reported Wood-Use Habits Within Major Analysis Categories for the Residential Base Homes

Sample	Homes with Equipment Available, %	Homes that Report Wood Burning, %	Homes with Utilized Wood-Burning Equipment, %
Sites Selected (n = 127)	71	57	79
Analyzed but Excluded (n = 47)	81	71	81
Not Analyzed, Heavy Fuel Switch (n = 39)	93	85	92
Not Analyzed, 100% Fuel Switch (n = 10)	100	90	90
Not Analyzed, Heating System Switch (n = 10)	80	80	100

age, and occupants' perception of their home's thermal integrity using survey data. The median home size tended to become enlarged after reviewing analysis categories 1 through 5 (this is noted later in the report as a trend in the climate zone 2 and 3 homes). Median perceptions of home energy efficiencies for categories 4 and 5 are different from categories 1 through 3. The median, and most frequent survey response from category-4 and -5 occupants regarding home efficiency levels, was that little improvement could be made to the home. Categories 1 through 3 had median and most frequent responses stating that moderate improvement could be made to the energy efficiency of their home. The median and most frequent vintage classification was from 1960 to 1978 for all the categories with the exception of category 5, those homes using dual-heating capabilities. These homes fell predominantly into the pre-1960 vintage category.

The average daily space-heating energy consumption for those sites in categories 1 and 2 is displayed in the box plots of Figure 1.1. Sites in category 1 are included in the results for this report. Sites in category 2 were not included in the final aggregation of results because of nonuniform operation of the heating system or wood-use problems. The median consumption of the excluded sites is about half that for the sites included. A systematic

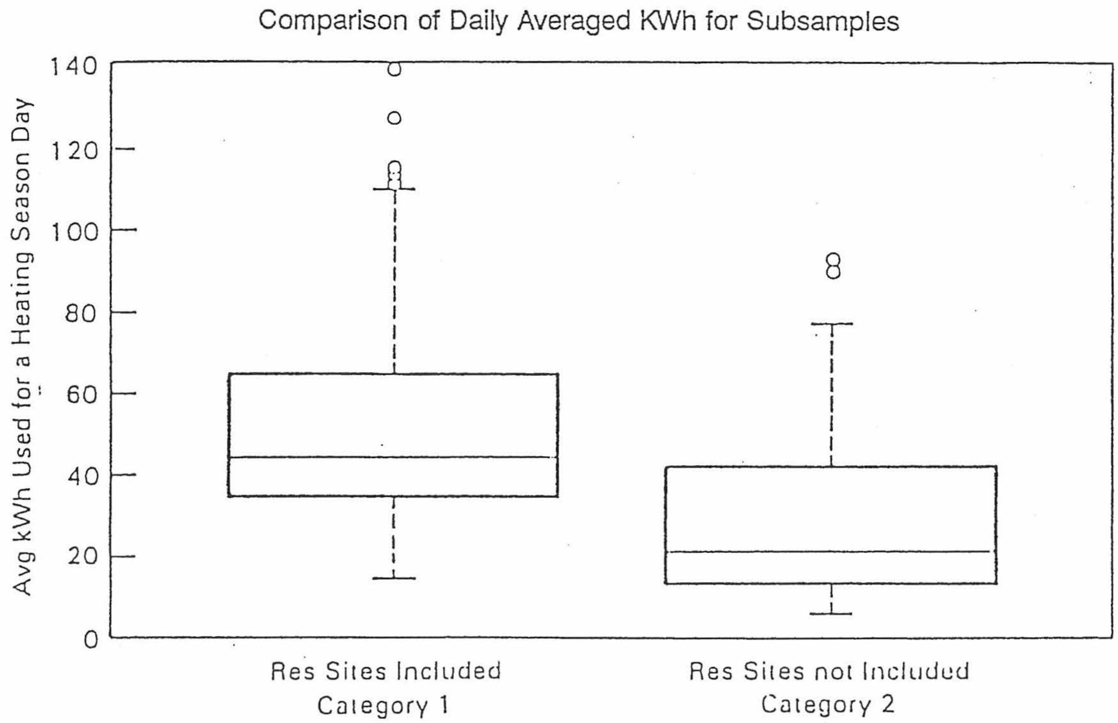

FIGURE 1.1. The Averaged-Metered Space Heating for Residential Base Sites in Analysis Categories 1 and 2

bias may exist in the thermal characterization results because of the nonrandom exclusion of low heat use structures. These data summarize the metered data over the 9-month heating season. The median consumption for those excluded sites in category 2 is about half that of those sites retained for the analysis. It would appear that a systematic bias may be expected in the thermal performance characterizations of the base sites because of the nonrandom exclusion of low heating consumption homes.

1.3 SUMMARY RESULTS AND INTER-SAMPLE COMPARISONS

In Section 1.3.1, the computed measures of thermal performance for the various groups of homes are compared. Differences in thermal performance characterizations, such as those in the estimates for space heat consumption, are considerable across the various samples and appear to be from differences in construction rather than occupant control strategy. In Section 1.3.2, estimates of electrical consumption used in the 1986 Northwest Power Plan are compared to the ELCAP base estimates summarized in Section 1.3.1.

1.3.1 Comparison of Residential Base Results with Model Conservation Standards and Control Homes

To facilitate comparison of the ELCAP base sample with the RSDP samples, several results are presented with the base sample partitioned on the basis of the climate zones defined for the MCS. Of the sites included in the base aggregation of results, 70% are located in climate zone 1, with the balance in climate zones 2 and 3. By contrast, for the RSDP sites included in the aggregation of results, 55% of the MCS and 46% of the control homes are in climate zone 1.

For point of reference, in the 1986 Northwest Power Plan, the weight assigned to climate zone 1 and the existing single-family dwellings was 84% (Northwest Power Planning Council 1986). Thus, the results presented in this document for the residential base sample slightly underweight those of climate zone 1 homes when compared to the 1986 Northwest Power Plan estimates.

All parameter estimates for the residential base sample are derived for the case of no supplementary wood heat and no period of extended vacancy over the heating season. Estimates are not adjusted to any standard level of internal gains or for weather factors other than temperature.

Total annual electric space-heating consumption was estimated for each site based on averaged, measured interior temperature readings and temperatures from the appropriate reference typical meteorological year (TMY) weather data. Weather data were used for sites located in climate zone 1 in Seattle, Washington. Weather data were used for sites in climate zones 2 and 3 in Spokane, Washington; and Missoula, Montana, respectively. The distribution of these estimates is displayed in Figure 1.2 for the analyzed base, MCS, control, and post-78 samples. (The post-78 results are also included in the base results.) The base median estimate is a little more than 10,000 kWh/yr, with over 70% of the sample falling between 5,000 and 15,000 kWh/yr. There is a long tail toward higher consumption; hence, the mean estimated value of 12,101 kWh/yr exceeds the median estimate by 1000 kWh/yr. This mean estimate

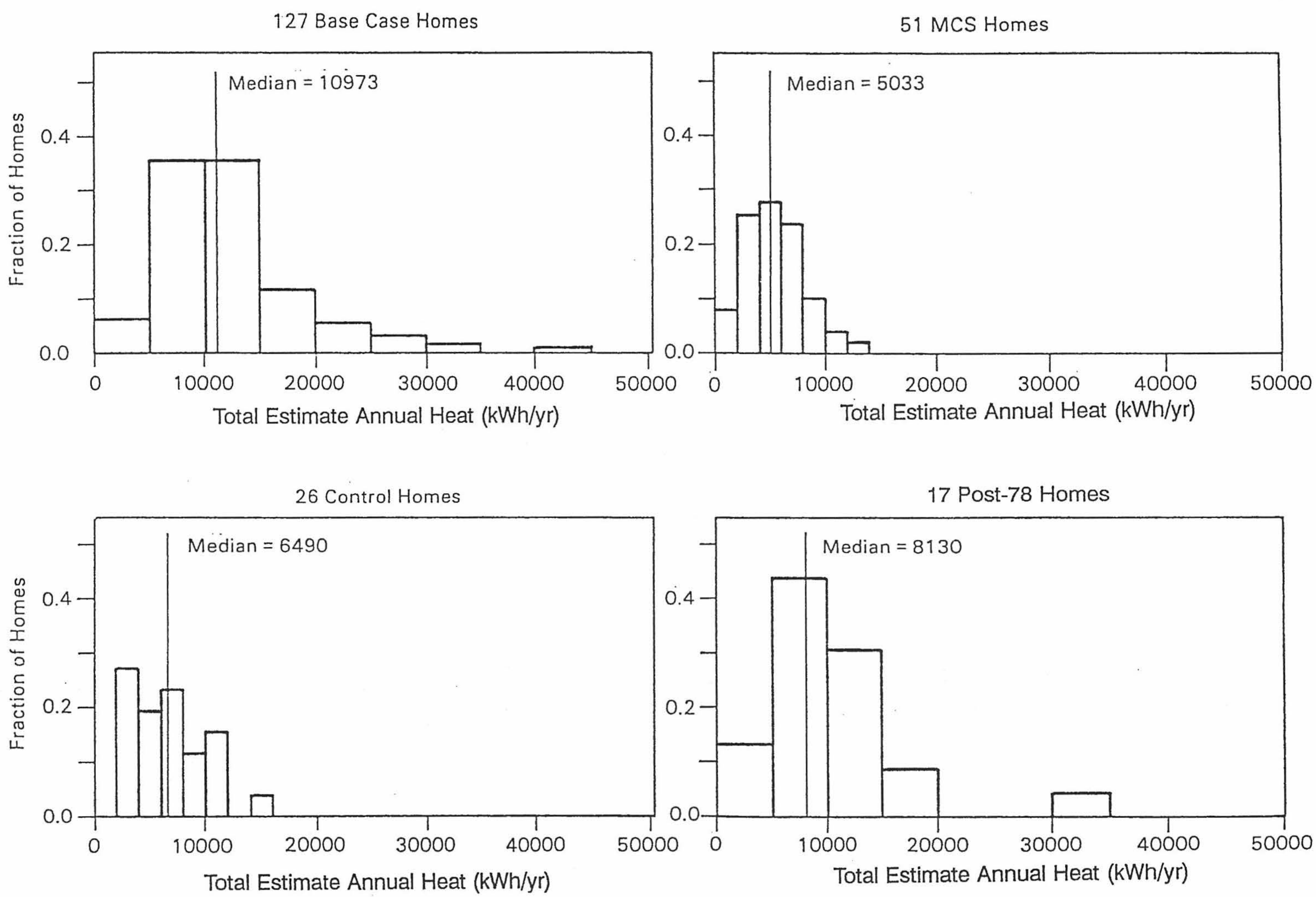

FIGURE 1.2. Distribution of Total Estimated Space-Heating Consumption by Structure Type

comes very close to matching the engineering estimate of 11,742 kWh/yr reported for the regionally weighted, single-family current construction in the 1986 Northwest Power Planning Council. This Power Plan engineering estimate of 11,742 kWh/yr was derived assuming no wood use, a standard level of internal gains, and an average thermostat setpoint of 65°F. A simple summary of performance statistics is presented in Table 1.6 for the residential base, MCS, and control-home samples to facilitate cross-sample comparison.

Figure 1.2 depicts the MCS homes, which were constructed to an aggressively proposed building code, and the control homes, which were intended to represent current building practice in the region. Figure 1.2 also exhibits substantially less variation in estimated annual space-heating requirements. A dramatic difference in the total estimated space-heating requirements is

TABLE 1.6. Summary Performance Statistics

Parameters	Measure	Base Sample	MCS	Control
Sample size		126	51	26
Annual Energy Conservation				
AEC_{iat}[a]	mean median	12,101 10,973	5,520 5,033	6,535 6,490
AEC_{iat}/ft^2	mean median	7.66 7.64	3.38 3.36	4.71 4.56
AEC_{65}/ft^2	mean median	5.77 5.41	2.68 2.55	4.11 3.94
Slope derived from linear model (kWh/ft^2-day-°F)	mean median	0.00198 0.00196	0.00098 0.00097	0.00138 0.00127
Inside temperature 9/01 to 5/30 (°F)	mean median	69.1 69.3	68.7 69.0	67.0 67.8
Conditioned floor area (ft^2)	mean median	1,690 1,540	1,676 1,620	1,389 1,417

(a) iat = indoor air temperature

demonstrated between the base sample and the RSDP homes. The median estimate for the MCS homes is close to half that of the base sample, while the median estimate for the control homes is 60% of the base median estimate. The long inclination towards higher consumption in the base case is absent from these two distributions. Hence, the mean estimates are much closer to the median estimates. The set of post-78 homes was used in the RSDP analysis as yet another "control" group to display the estimated total consumption between the control group and the base case. (Actually, the total for the post-78 homes is indicative of the larger home size of this sample of homes and disappears when consumption estimates are normalized by conditioned floor area.)

Dwelling size has a direct bearing on space heating energy requirements. Therefore, the results in Figure 1.2 have been standardized in Figure 1.3 using the conditioned floor area for each site. Figure 1.3 displays the median consumption of the base sample, 7.6 kWh/ft^2, as being almost twice the value of the MCS group. This figure can be compared with the Power Plan forecasting estimate of 7.1 kWh/ft^2 (includes wood-stove use) or engineering estimate of 8.4 kWh/ft^2 (excludes wood-stove use) for newly constructed homes (Northwest Power Planning Council 1986). The control group falls about two-thirds of the way from the base mean estimate to the MCS mean estimate. The variability in the base sample estimates reflects the changes in construction practices that have occurred over time.

The distribution of space heating kWh/ft^2 estimates are further disaggregated by major climate zones in Figure 1.4. Climate zone 1 results are qualitatively similar to those for climate zones 2 and 3 in terms of the relative performance of base sample and MCS homes. In general, homes in the more severe climates are estimated in the median to require about 0.5 kWh/ft^2 more annually than those in climate zone 1.

Figure 1.5 compares the derived slopes from the base sample with those of the MCS and control groups across climate zones. Performance is substantially improved (by almost a factor of 2) in the median slopes from the MCS group relative to the ELCAP base sample. Not surprisingly, the lower slopes for each of the three groups in the more severe climate zones indicate that the homes are thermally tight in these areas. (This observation is

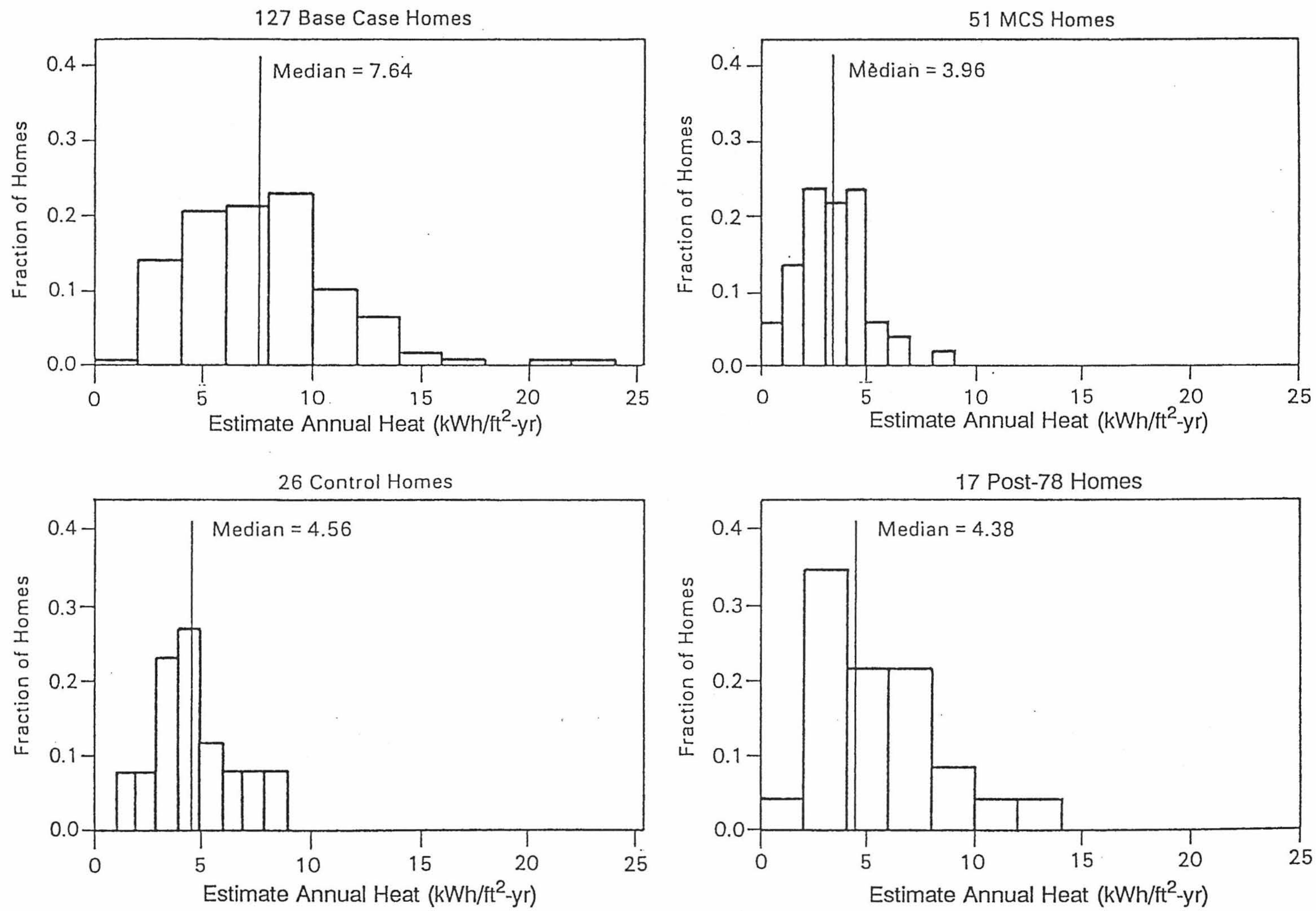

FIGURE 1.3. Distribution of Floor Area Normalized Space-Heating Consumption by Structure Type

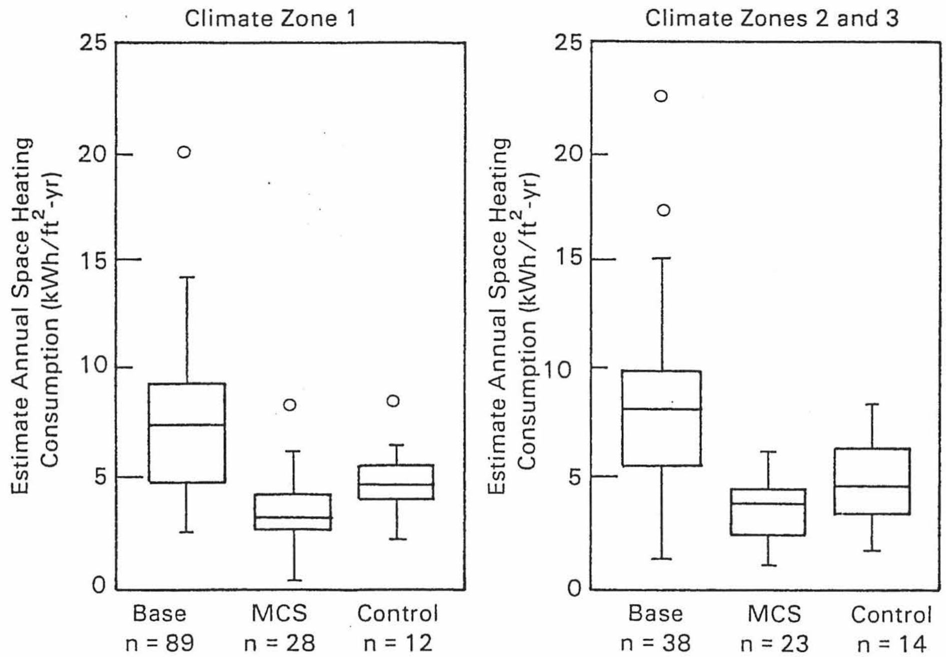

FIGURE 1.4. Floor Area Normalized Annual Heating Consumption Results for the ELCAP Base, Model Conservation Standards, and Control Samples

corroborated by a decrease in heat loss values computed from audits [physical inspection] data for the same homes.) The variance in the base sample results is somewhat larger than that in the MCS and control groups, although some of the spread in values may be because of the unequal sample sizes.

Figure 1.6 displays the distributions of conditioned floor area for the analyzed base, MCS, and control samples. With the exception of climate zone 2 and 3 control homes, the balance of climate zone 2 and 3 homes tends to be somewhat larger than the climate zone 1 homes. Within climate zones, however, there is little difference in mean or median conditioned floor area between the MCS and base sample sites. Mean square footage for the combined sample is about 15% smaller than the Council's estimate of 1,400 ft^2 for new and existing stock (Northwest Power Planning Council 1986). Although the ELCAP sample square footage differs, these numbers are close enough to invite comparisons between the ELCAP estimates and Power Plan estimates (see Section 1.3.2).

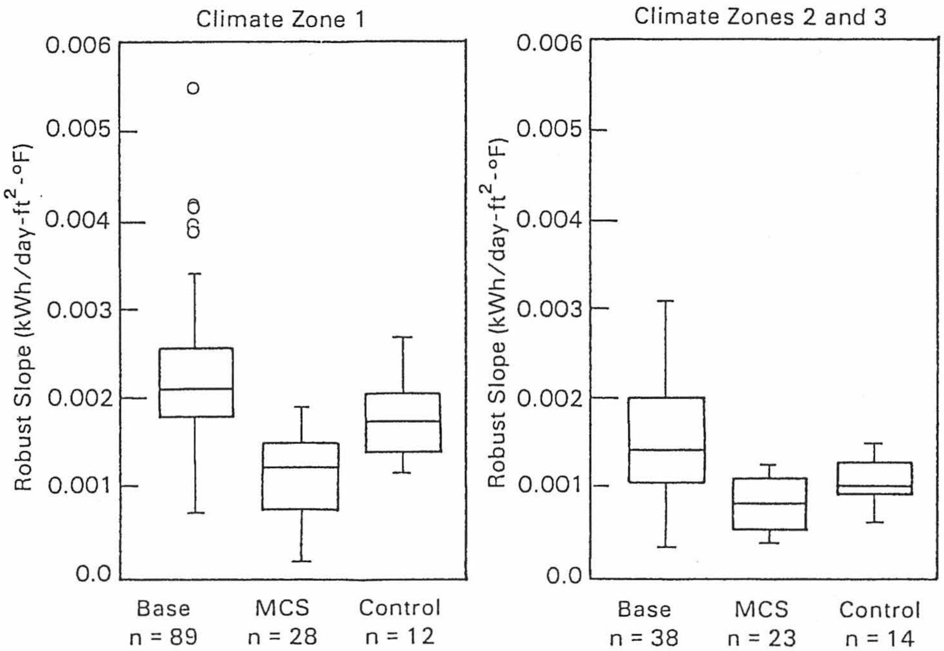

FIGURE 1.5. Derived Slopes from the Base Sample Compared with Those at the Model Conservation Standards and Control Groups Across Climate Zones

The mean indoor temperatures, displayed in Figure 1.7, are averaged over the period from August 30, 1985, to May 30, 1986, for the various samples. The temperature distributions are not exactly comparable, since the MCS and control temperatures are typically calculated based on the average of three temperature sensors located in various parts of the homes, while the base sites have only a single interior temperature sensor. For the most part, there are probably no dramatic cross-sample differences in average interior temperature.

The balance points derived from fitting the robust linear model to daily space-heating data versus daily inside-outside temperature difference are displayed by climate zones across the various samples in Figure 1.8. The balance points represent the cross-shell temperature difference that can be supported by the structure, given its level of internal gains, without use of space-heating equipment. In Figure 1.8, note that cross-sample differences in the balance points appear to be modest.

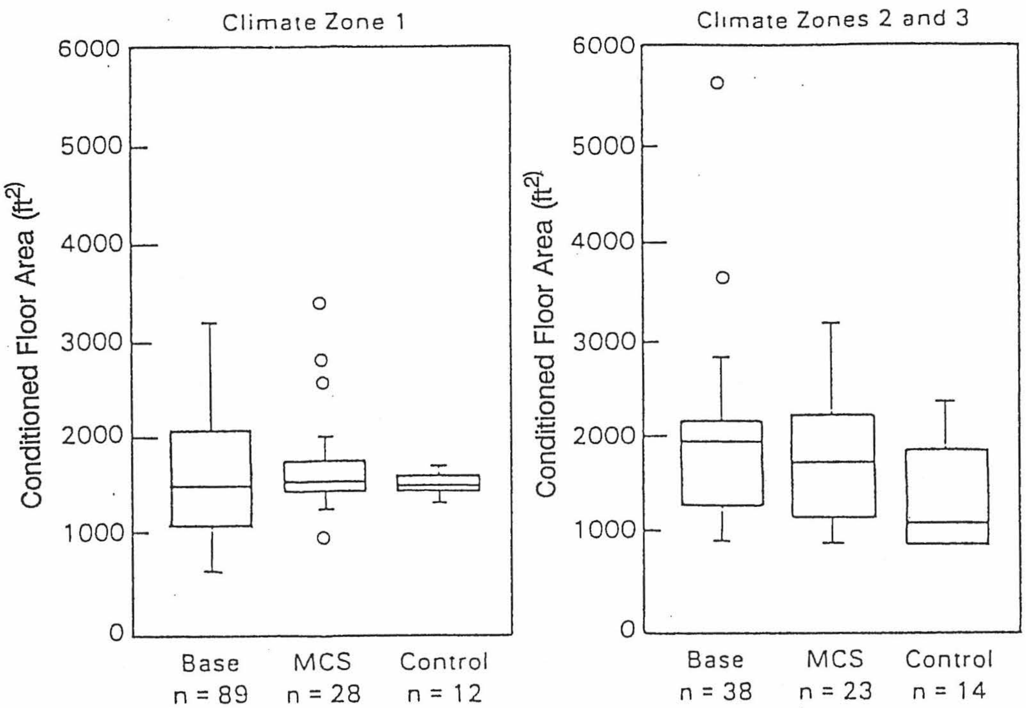

FIGURE 1.6. Distributions of Conditioned Floor Area for the ELCAP Base, Model Conservation Standards, and Control Samples

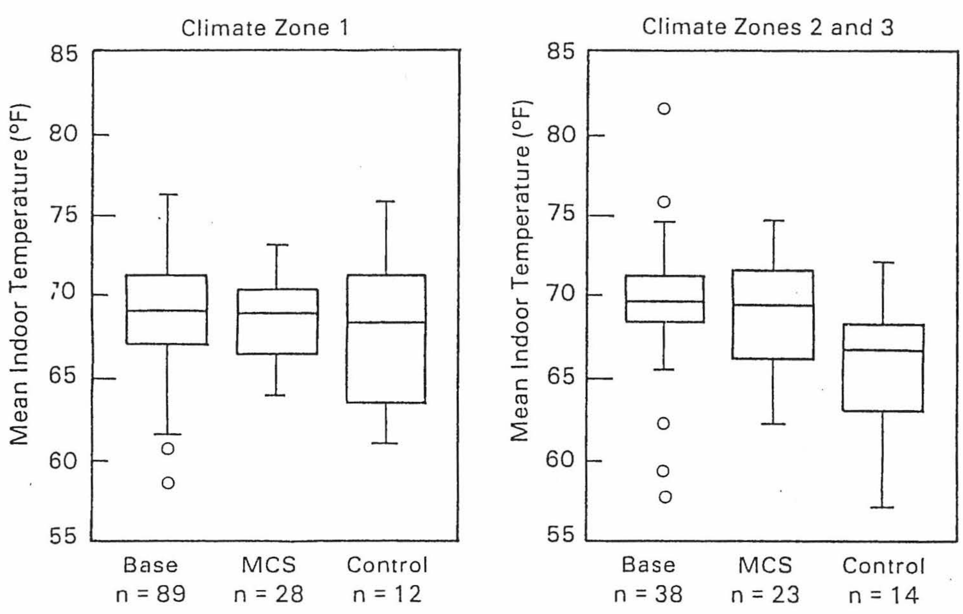

FIGURE 1.7. Mean Indoor Temperatures Averaged from August 30, 1985, to May 30, 1986, for the ELCAP Base, Model Conservation Standards, and Control Samples

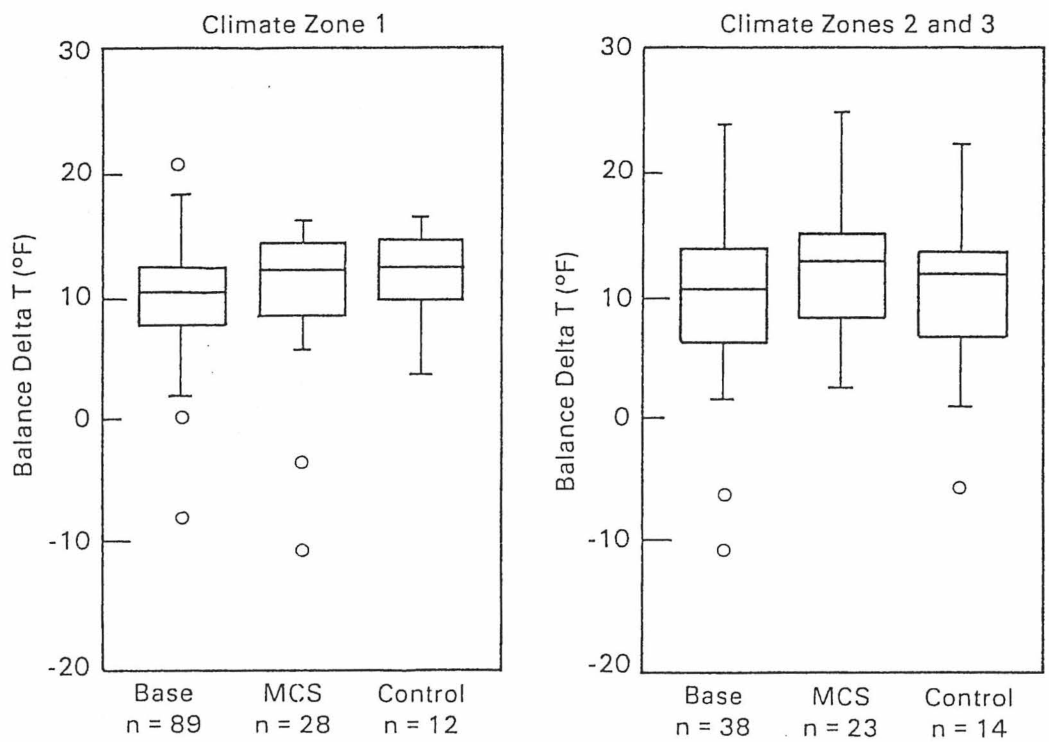

FIGURE 1.8. Balance Points Versus Daily Inside-Outside Temperature Difference for the ELCAP Base, Model Conservation Standards, and Control Samples

1.3.2 Power Council Comparisons

The Council's estimates for new dwellings are both quite close to the median estimated annual space heating electrical consumption figures generated for the ELCAP base case of 7.64 kWh/ft^2-yr. It should be noted, however, that the base sample includes only 17 post-78 homes and the median floor area for those homes is 1540 ft^2. Furthermore, the ELCAP base sample estimated annual space-heating consumption figure, 7.4 kWh/ft^2-yr, has extended vacation periods removed and wood-use days removed and represents a median operating temperature close to 69°F.

To gauge the conservation potential in buildings built before 1979, the Council estimated the typical, regionally weighted, not fully weatherized single-family house surviving in the year 2005 to use 8.2 kWh/ft^2-yr for electrical space-heating consumption (Northwest Power Planning Council 1986).

Houses in this category retrofitted to the regional cost-effectiveness limit were estimated to use 4.5 kWh/ft^2-yr. The difference in electrical consumption, when multiplied by the region's potential number of homes, yielded a conservation potential of 385 average megawatts. The estimated space-heating consumption figures for the ELCAP residential base sample may indicate the baseline consumption estimate used in that Power Plan could be too high. This would result in overestimating the savings potential in the region by as much as 14%.

Several observations follow from comparisons to the 1986 Power Plan:

- The Council's regionally weighted estimate of energy consumption for existing stock, new stock, and the residential base sample estimates are in fairly close agreement.
- The Council's engineering estimate of 8.4 kWh/ft^2-yr for new homes might be slightly high given that the ELCAP residential base median estimate of 7.64 kWh/ft^2-yr
  - excludes wood use
  - is composed predominantly of homes built before 1978
  - is more heavily weighted toward the more severe climate zone.
- The set of crawlspace homes characterized from the ELCAP residential base sample falls within the conservation measure boundaries set by the Council, but, the set also falls below the base case.

1.4 COMPARISON OF AS-OPERATED AND NAMEPLATE EFFECTIVE CONDUCTANCES

The total UA of a home has often been used as a measure of thermal integrity or the resistance to heat loss. Audit (physical inspection) data for a large number of ELCAP homes has been used to compute UA values for the bulk of the ELCAP residential base and RSDP homes (Conner, Lortz, and Pratt 1990). The term "nameplate" will be used to refer to this UA, which is the sum of the UAs for the separate components of the home. The UA of each component is the product of the surface area of that component and the associated heat conductance or heat loss coefficient (U)-value. The nameplate UAs do not have an infiltration component or include aspects of solar gain or occupant effects. Infiltration is an additive factor which makes the UA larger. (Infiltration at 0.4 air change per hour for a 1540-ft^2-house with 8-ft ceilings adds 89 British thermal units [Btu]/hr-°F to the nameplate UA.)

Part of the thermal characterization for each ELCAP home consists of a robust linear fit of electrical space heat consumption to inside-outside temperature difference. The slope from that regression line may be used to compute an as-operated UA. This as-operated UA can be interpreted as the conductive UA divided by heating system efficiency[(a)]. Figure 1.9 displays the scatter plot of nameplate UAs versus as-operated UAs. The sample of points displayed includes the residential base, MCS, and control homes, characterized in the earlier sections of this report, for which nameplate UAs have been calculated. The general trends indicate a positive correlation between the two UA values. Approximately one-third of the points are seen to

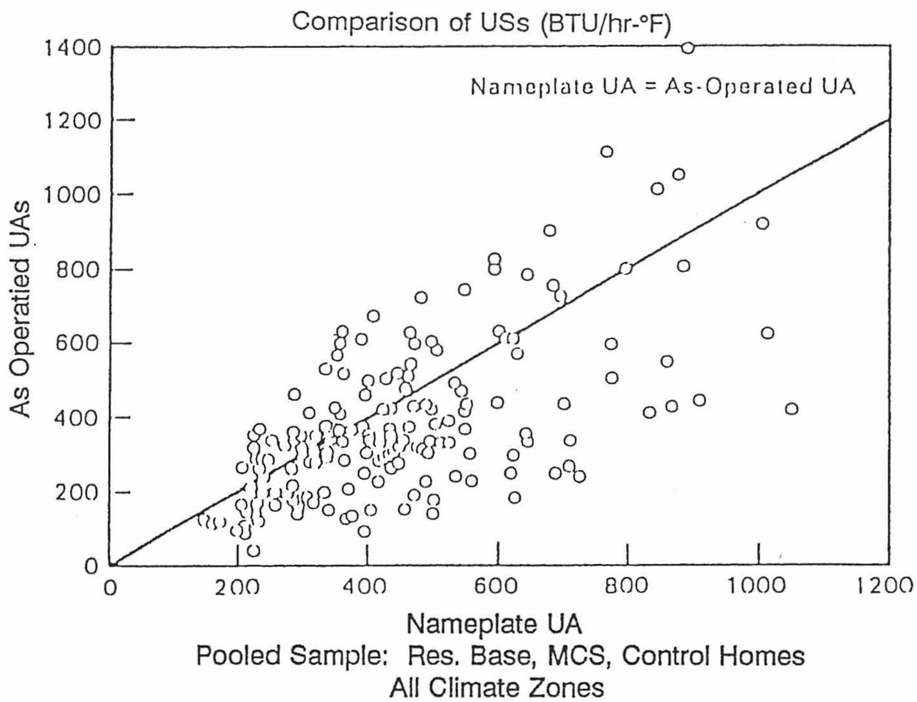

FIGURE 1.9. Nameplate Effective Conductances Versus As-Operated Effective Conductances

(a) Using this approach, aspects of internal gains and occupant effects are included.

lie above the equality line, indicating that the as-operated UA is larger than the nameplate UA. Points lying above the identity line are performing worse (i.e., more energy for space heating) than the nameplate UAs would predict. The balance and the majority of the points lie below the line, indicative of as-operated performance exceeding the nameplate performance. Because the as-operated UAs contain the multiplicative factor of 1 divided by the heating system efficiency, all points are not expected to fall on the line. However, two-thirds of the as-operated UAs occurring below the nameplate UAs indicates a fairly dramatic result. Because nameplate UAs do not contain an infiltration component or account for internal gains and occupant effects (zoning) as do the as-operated UAs, Figure 1.9 understates the difference between nameplate and as-operated UAs. An infiltration component, if added to the nameplate UA, would increase both the number of points lying below the equality line in Figure 1.9 as well as the average point distance from the line.

1.4.1 Role of Heating System

Because the as-operated UAs incorporate heating system efficiency, Figure 1.10 displays nameplate UAs versus as-operated UAs divided according to major heating system type. Mild climate zone sites are indicated by triangles, and the more severe climate zone sites are indicated by circles. Baseboard heaters are the most prevalent heating system type for homes with both nameplate and as-operated UAs available, forced-air systems are the second most common system. Small samples of heat pump and radiant heat homes are also displayed in Figure 1.10.

In Figure 1.10, the scatter above and below the line of equality for the forced-air homes is fairly evenly distributed across climate zones. For the baseboard heater homes, the majority of the points are either on or below the identity line; this is certainly the case for all climate zone 2 and 3 sites. The radiant heat homes match the performance of baseboard heater homes for the most part. The heat pump homes tend to be below the identity line for climate zone 1 sites and above for all three climate zone 2 and 3 heat pump homes. Thus, the baseboard heater, radiant, and the climate zone 1 heat pump homes clearly outperform nameplate UA-based expectations, while the forced-air

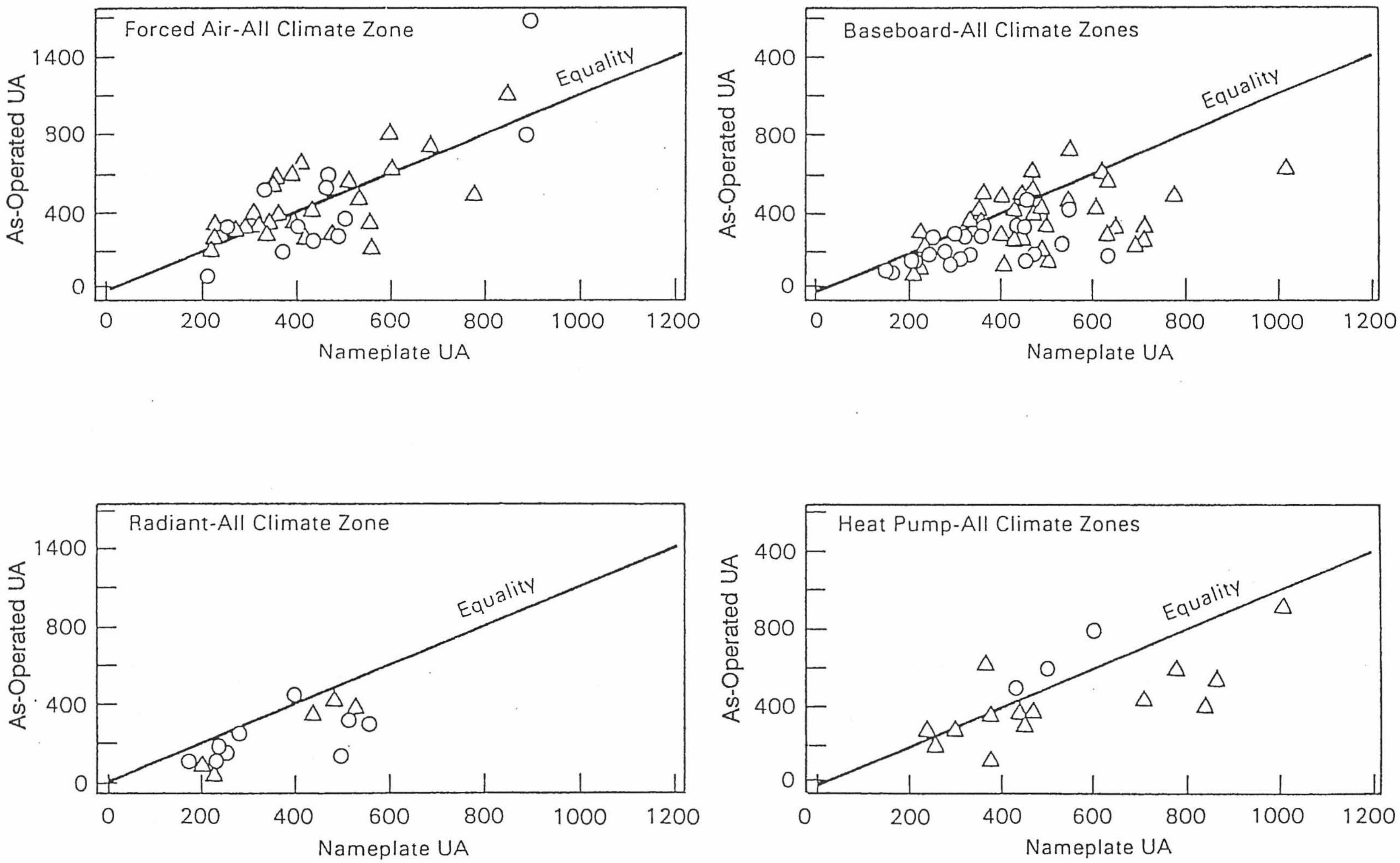

FIGURE 1.10. Nameplate Effective Conductances Versus As-Operated Effective Conductances According to Heating System Type

homes, as a class, display no trends. In addition, all the climate zone 2 and 3 heat pumps (3 units) are performing worse than the nameplate UAs predicted.

The box plot of Figure 1.11 displays the residual difference between the nameplate UAs and the as-operated UAs for the same sites as those found in Figure 1.10. The residual has been scaled by the nameplate UAs so the percentage difference is displayed according to heating system type. Nonoverlapping notches for pairs of boxes indicate a statistically significant difference in the median heating system's performance at $\alpha = 0.05$. Forced-air systems are clearly distinguished from baseboard heaters and radiant-type heating systems. In the median, the residual distributions indicate that the baseboard heater homes are performing about 35% more efficiently than the forced-air homes.

Assuming other contributing factors are equal across the samples of different heating system types presented here, the difference in the residual distributions for the nameplate and as-operated UA gives substantial evidence to indicate a lower as-operated efficiency for the forced-air homes when

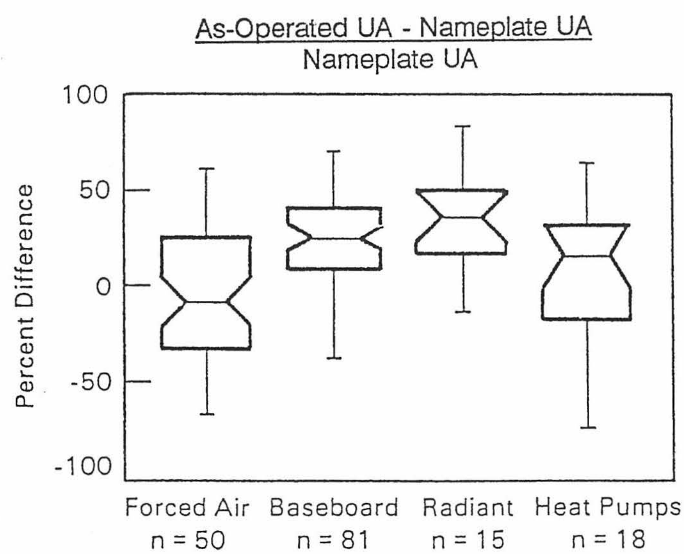

FIGURE 1.11. Residual Difference Between Nameplate Effective Conductances and As-Operated Effective Conductances

compared to the other heating system types. These differences are thought to encompass both physical differences in the heating systems, such as duct and pressure losses associated with forced-air systems, as well as occupant behaviors, such as zoning, which are assumed to be more prevalent in the baseboard and radiant-heat homes.

1.4.2 Role of Foundation Type

Figure 1.12 displays the distribution of the difference between the nameplate UAs and as-operated UAs divided by the nameplate UA (the percent residuals) according to foundation type with all climate zones combined. Only homes with a single foundation type have been included in Figure 1.12. Homes with a mixture of foundation types (e.g., split-level houses with both a basement and a slab-on-grade) were excluded. The pure foundation types illustrated in Figure 1.12 are heated basement, unheated basement, slab, and crawlspace. Note that more than three-fourths of the basement homes appear to be performing better than the nameplate UAs would indicate. The 20 heated basements appear to be performing significantly better than the 65 crawlspace

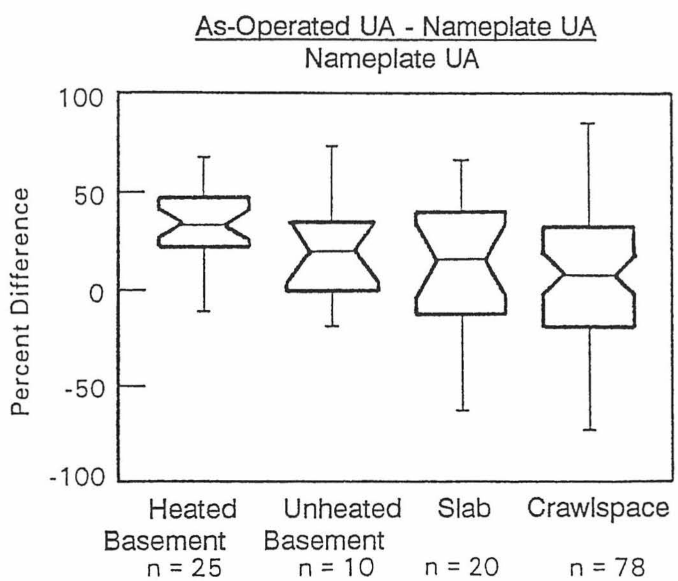

FIGURE 1.12. Nameplate Effective Conductances and As-Operated Effective Conductances by Foundation Type

homes. Nameplate UAs appear to be sensitive to basement types. The superior performance of the heated basement category may indicate prevalent zoning--that the basement is not actually heated to the same temperature as the remainder of the house.

1.4.3 Heating System Efficiencies and Estimated Annual Electrical Consumption

From Section 1.4, the percent difference between the nameplate and as-operated UAs gives strong evidence of a difference in performance between the forced-air heating system homes and the other heating system type homes across climate zones. In this section, differences in heating system performances are sought in terms of the annualized estimated consumption (AEC) requirements for space heating. This measure of thermal performance, defined in Section 1.1, is derived from the LOWESS (Robust Locally Weighted Regression and Smoothing Scatterplots [Cleveland 1979]) fit of daily space heat to inside-outside temperature difference using either the occupants' mean heating season inside air temperature or an assumed 65°F, denoted as $\mathbf{AEC_{iat}}$ and $\mathbf{AEC_{65}}$, respectively, in this section.

Figure 1.13 displays AEC_{iat}/ft^2 split by major heating system types across the major climate zones for the residential base homes. Electric forced-air furnaces, baseboard heat, radiant heat, and heat pumps are the heating systems displayed. The AEC estimates for the climate zone 1 homes in Figure 1.13 do not indicate much difference in estimated heating requirements between the baseboard heater and forced-air homes. The 10 heat pump homes are using the least estimated kWh/ft^2-yr, with the consumption of the 3 radiant heat homes between the median levels of consumption for the forced-air and baseboard heater homes. In climate zones 2 and 3, the baseboard heater homes appear to require the greatest estimated kWh/ft^2-yr in the median. These plots may seem surprising given the results of the previous section. There are, however, some systematic differences between baseboard heater and forced-air home characteristics that affect the AEC_{iat} numbers. The baseboard heater homes tend to be smaller than the forced-air homes; this can easily be observed in Figure 1.14. In the mean across climate zones, this difference amounts to about 375 ft^2. The heat pump homes tend to be the largest homes.

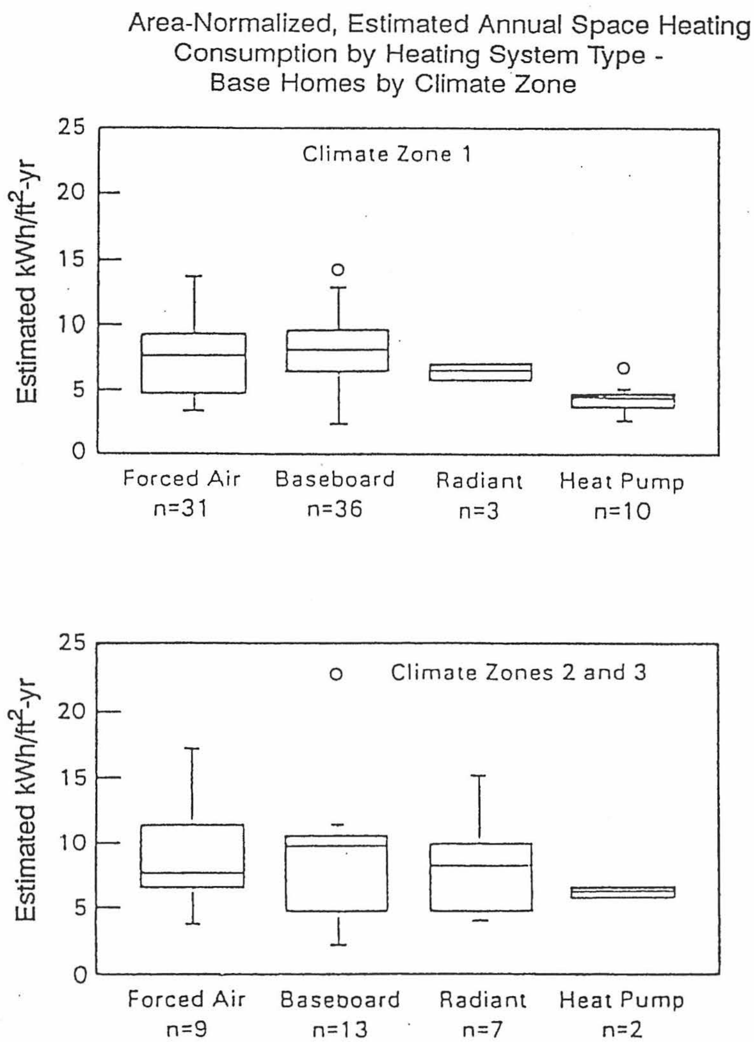

FIGURE 1.13. Annualized Estimated Consumption for the Residential Base Sample

Conventional wisdom attributes an extra savings in heating requirements for larger homes--the larger the home the greater the savings. However, the baseboard heater homes have higher effective U-values (leakier or greater tendency to lose heat) in both climate zones (see Figure 1.15). (U-value was computed by dividing the nameplate UA by the surface area of the residence.) From Figure 1.16, the distributions for mean heating season inside air temperatures for the various heating system types have quite wide yet similar ranges. Thus, to estimate AEC-based differences in performances between

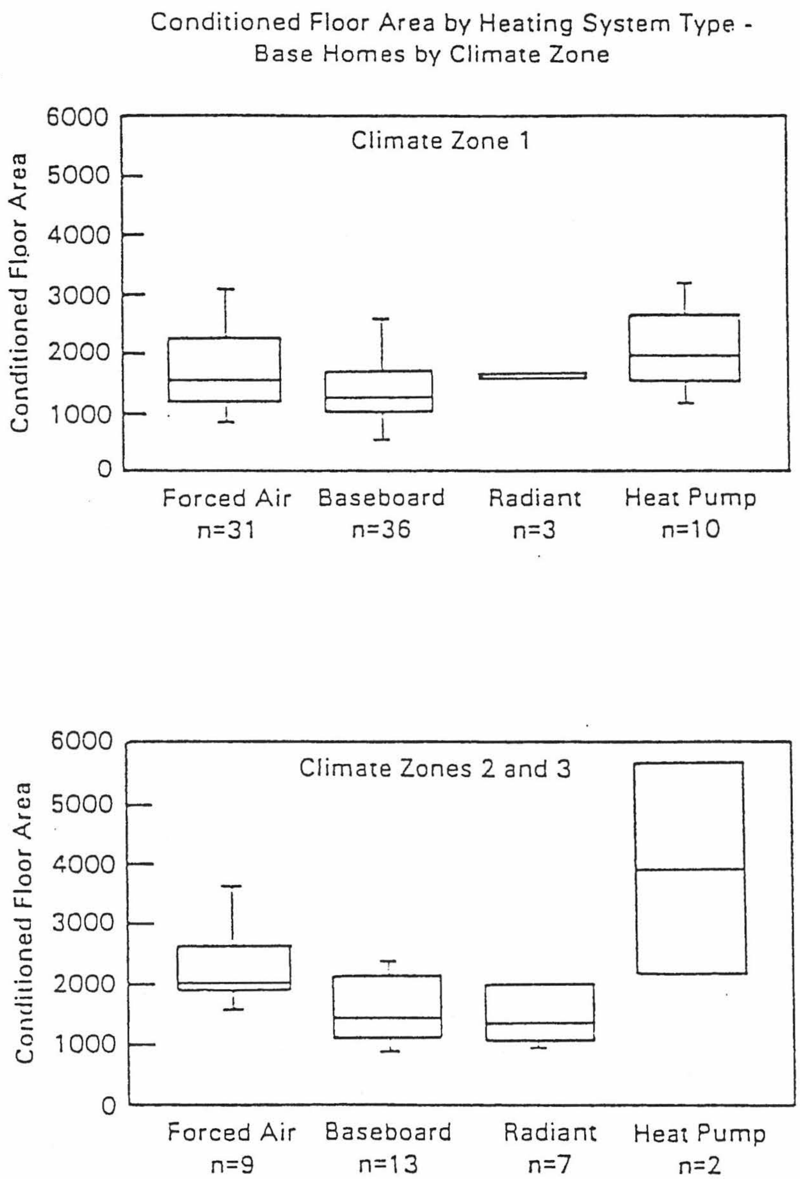

FIGURE 1.14. Conditioned Floor Area Distributions for the Residential Base Sample

heating systems, such factors as home size, U-value, mean heating season inside air temperature, climate zone, and possibly foundation type should be incorporated.

Several two-way analysis of variance tests are used to explore differences in operational AEC efficiencies between the various heating system types. (See companion document *Characterizing Residential Thermal Performance* *from High Resolution End-Use Data - Volume I -Methodology* [Miller et al. 1990] a detailed explanation of this technique.) In this work, estimates of annual electrical consumption, based on an assumed 65°F inside air temperature, are used to control for occupant-induced differences in thermostat settings that may be present in the AEC_{iat}/ft^2 estimates displayed in Figure 1.13. Additionally, because overall heat loss in the home is more closely correlated with the surface area of the structure rather than the conditioned floor area, estimated annual electrical space-heating consumption per ft^2 of surface area

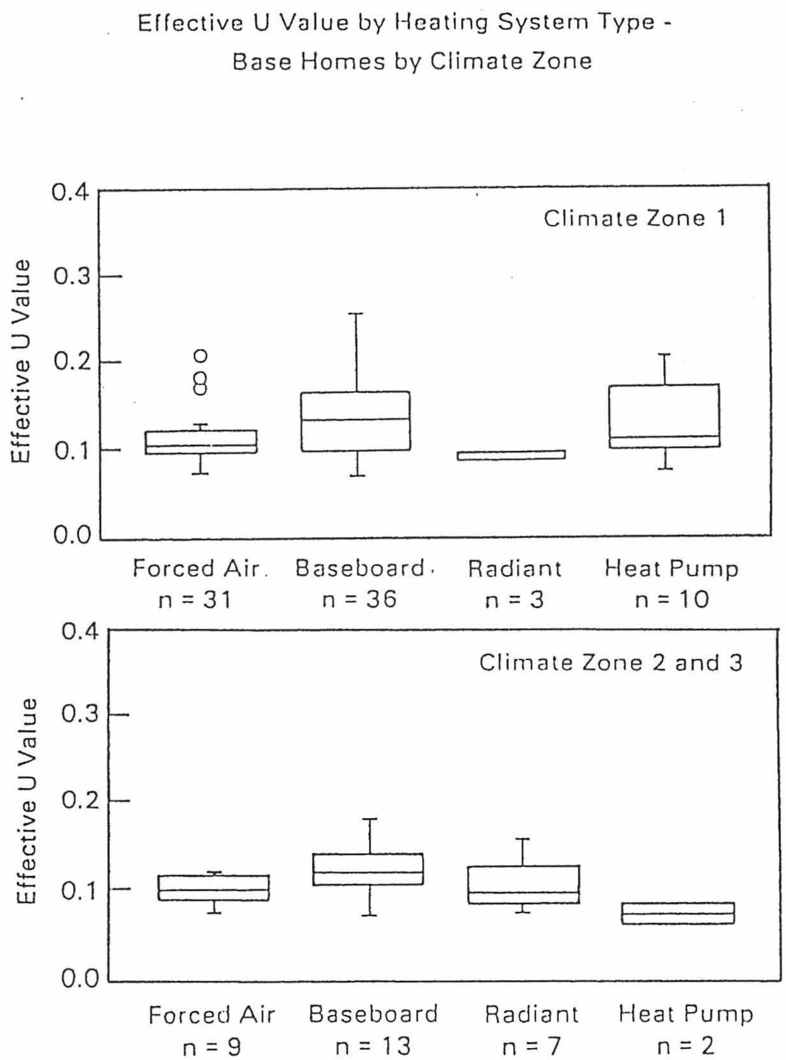

FIGURE 1.15. Effective U-Value Distributions for the Residential Base Sample

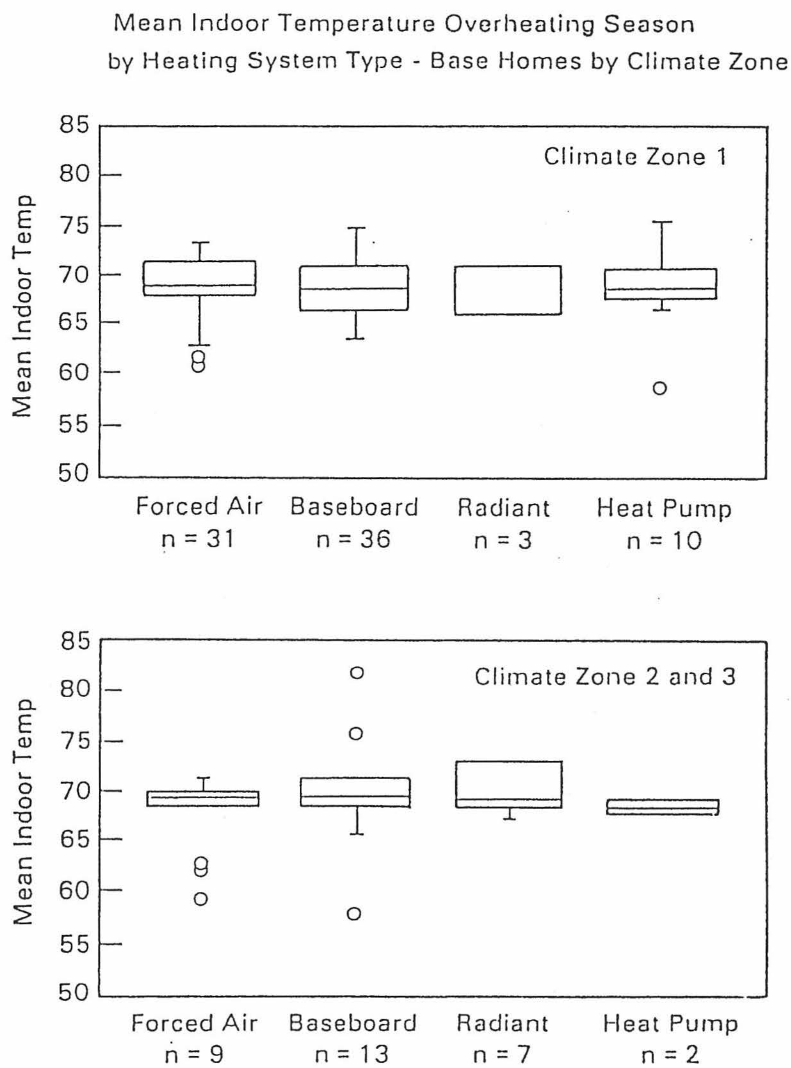

FIGURE 1.16. Average Indoor Temperature Distributions Over the Heating Season

is selected as the observation variable. Thus, the observation variable for the homes analyzed is annual heating season requirements, kWh/ft^2-yr, such that

- a constant inside air temperature over the heating season of 65°F is assumed
- the annual space-heating estimate, AEC_{65} is normalized by the surface area of the home.

The factors used in the first two analyses are

- heating system type
- effective U-value.

The outcome of each test is to decide if the heating system effects are equal within each of the U-value categories. Because an effective U-value incorporates the thermal integrity of the structure, the pooled sample of homes (base, MCS, and control) is used for this analysis.

In the first test, the estimated heating requirements for climate zone 2 and 3 homes are categorized by the heating system types; baseboard heater and forced-air systems; and U-values, low, medium, and medium high. Not enough heat pump homes are available in climate zones 2 and 3 to include them as a heating system type. A summary table in Appendix C, Table C.1, contains the median estimate for the classes used in the analysis of variance tests. For these more severe climate zone homes, both heating system and U-value are found to be significant ($\alpha = 0.05$) in explaining differences in consumption. The baseboard heater systems require significantly less kWh per ft^2 for space heat than do forced-air homes within comparable U-value classes. The average difference in consumption for the baseboard heater homes is about two-thirds the estimated kWh per ft^2 for the forced-air homes in climate zones 2 and 3.

In the second test, the estimated heating requirements for climate zone 1 homes are categorized by heating system types; baseboard heaters; forced air, and heat pumps; and U-values, low, medium, medium high, and high. The summary table used in this test can be found in Appendix C, Table C.2. The median estimate for each of the 12 cells found in the summary table is used to represent the classes in the analysis of variance tests. Climate zone 1 heat pump efficiency is significantly ($\alpha = 0.02$) greater than that of both baseboard heater and forced-air systems. The differences between forced-air and baseboard heater systems are not distinguished from one another in a statistically significant way and present no clear trends. The heat pumps take an average of about 70% of the estimates used for the other heating system types in climate zone 1 (see Volume I [Miller et al. 1990]). Both heating system type (heat pumps, in particular) and U value are still seen as significant factors in accounting for the differences in consumption.

For the mild climate zone homes, a statistically significant difference between baseboard heated and forced-air homes is not clearly established unless foundation type is incorporated into the analysis. Climate zone 1 forced-air and baseboard heated homes with U values between 0.08 and 0.12 are selected. This medium U-value category contains the greatest number of both baseboard heated and forced-air homes (see Figure 1.15). The factors for this third test are heating system type and pure foundation type for the selected homes. The foundation types available were crawlspace, slab, and heated basement see Appendix C, Table C.3. The number of sites falling into each cell is not evenly distributed across the foundation bins, and the number of observations is quite small. These caveats limit the generality of the conclusions of this test to the particular set of homes used in this example; however, both heating system type (α = 0.01) and foundation type (α = 0.02) come out highly significant in accounting for the variation in heating requirement observations. Heated basements make the biggest differences among foundation types in the consumption heat estimates. Baseboard heated homes require three-fourths the kWh per ft^2 as do the forced-air homes in climate zone 1 when foundation type is incorporated into the analysis.

The most general conclusion for all three tests is that estimates of annual heating requirements do not tell the complete story for heating system efficiencies. Estimates must be adjusted for other factors before differences between heating system types can be observed. These factors include mean heating season inside air temperature, U-value of the home, home size, climate zone, and foundation type. It is this preliminary analysis that suggested the follow-up work reported in Section 4.0.

1.4.4 Internal Temperature Settings and Estimated Annual Electrical Consumption

In a given residence, an increase in internal temperature setting causes an increase in electrical space-heating requirements when all other things are held constant. Two mean heating consumption estimates are provided for each sample of homes in Table 1.6. Sizable drops in consumption occur within a given sample (see Table 1.6) when the AEC_{65}/ft^2 estimate is compared to the AEC_{iat}/ft^2 estimate.

The range of mean heating season inside air temperatures for the ELCAP sites is quite wide (see Figure 1.7), with the median value substantially higher than 65°F. Figure 1.17 displays the estimated annual electrical space-heating consumption, AEC_{iat}/ft^2, versus the average heating season inside air temperature for the pooled sample of sites. A large amount of scatter is apparent around the line fit to these data points, and the expected

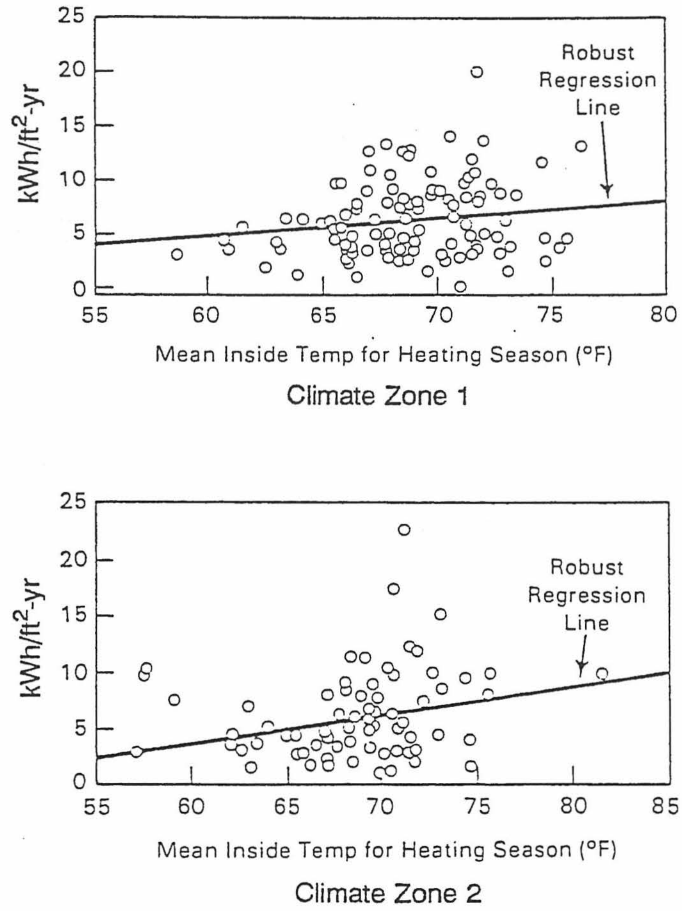

FIGURE 1.17. Comparison of Area-Normalized, Estimated Annual Space-Heating Consumption to Average Indoor Temperature for Base, Model Conservation Standards, and Control Homes

upward trend is revealed. Partitioning the sites into the base, MCS, and control subsamples does not, however, reduce the apparent scatter. A large part of this scatter is from UA effects.

For the two major climate zones, nameplate UA values are plotted against the total estimated energy consumption, AEC_{iat}, in Figure 1.18. Each point represents a single home and is drawn from the pooled sample of residential base, MCS, and control homes. As expected, there is a trend of increasing consumption as UA values increase. However, there is a sizable amount of variation in this relation. For any individual site, the predictive

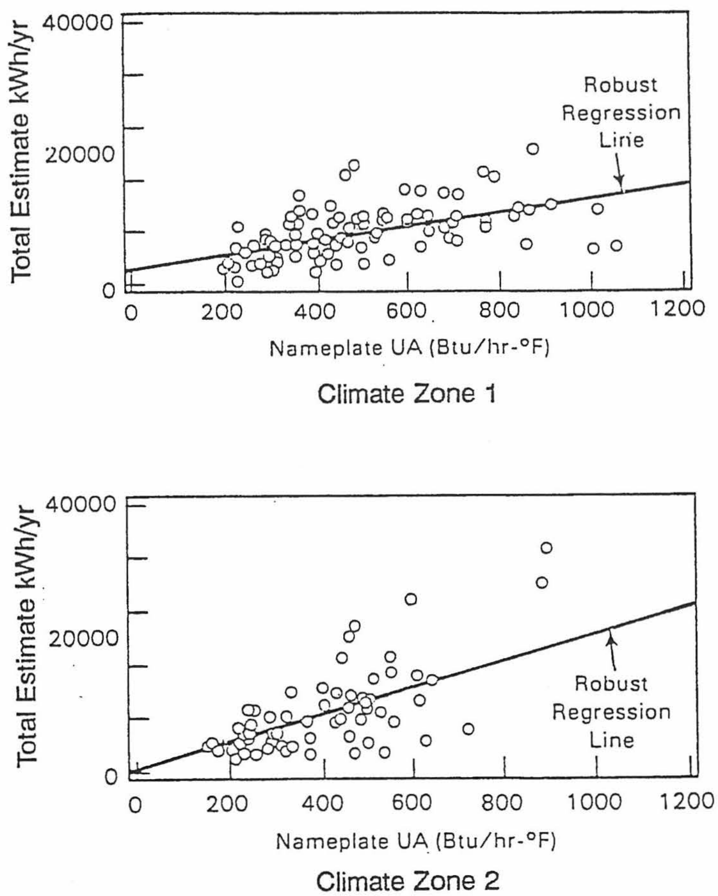

FIGURE 1.18. Comparison of Total Estimated Annual Space-Heating Consumption to Nameplate Effective Conductances for Base, Model Conservation Standards, and Control Homes

capability afforded by the linear fit of the space-heating consumption estimate to the nameplate UA values is quite unreliable. Clearly, UA alone is not a sufficient predictor of total consumption.

The slope value from the robust linear fit displayed in Figure 1.18 for the more severe climate zone sites is substantially greater--nearly a factor of 2 greater than that for the mild climate zone fit (climate zone 1). The ratio of slopes is indicative of the ratio of heating degree days (HDDs) for the reference TMY data for the two climate zone categories. In a simple model, total energy for space heating equals the UA times total heating-degree days, (Q = UA*HDD). One might expect the ratio of slopes for the two regression lines to approach a value close to 2.0 as the ratio of the Spokane TMY HDD to Seattle TMY HDD, to a 55°F base, is 4301/2309 or 1.9. Similar ratio computations for Missoula and Seattle yield a value of 2.3. A base temperature of 55°F is appropriate for these ratios because it is suggested by the typical operating conditions in the monitored homes--the average heating season interior temperature (69°F) less the average balance temperature difference (12°F) is 55°F.

To study the relation of estimated electrical space-heating consumption to both nameplate UA and mean inside temperature over the heating season, a two-way analysis of variance is used. The observation values selected for the classes in the two-way analysis of variance are median AEC_{iat}/ft^2. The factors used are the floor area normalized nameplate UA (binned into two levels, high and low) and the mean heating season interior temperature (also binned into high and low levels). Separate tests are performed for the mild and severe climate zone homes. The table for the climate zone 1 homes can be found in Appendix C, Table C.4. This analysis, especially for climate zone 1, indicates both UA/ft^2 and mean heating season temperature are strongly associated with the estimated kWh/ft^2 required for electrical space heat. This is the expected result, with higher UAs and higher temperatures associated with the highest consumption and lower UAs and lower temperatures associated with lowest consumption. This result was easily established for climate zone 1 homes, with UA/ft^2 (α = 0.01) and inside air temperature (α = 0.03), with the UA effects dominant. This result was only weakly established for climate zone 2 and 3 homes, with UA/ft^2 ($\alpha = 0.25$) and temperature ($\alpha = 0.35$) with the magnitude of the UA and temperature effects approximately the same (see Appendix C, Table C.5).

1.5 MISCELLANEOUS OBSERVATIONS

The derived estimates of thermal performance, in conjunction with responses to survey questions for the residential base sample, provide little evidence that occupants accurately perceive the thermal integrity of their homes (see Volumes I [Miller et al. 1990]). During a survey, occupants were asked to respond to a question evaluating the energy efficiency level of their homes by responding in one of five preselected ways. Response choices varied from the home being as energy efficient as possible, to a response indicating that lots of improvements could be made. Also included was the response indicating that the occupants could not make an accurate assessment of the efficiency of their home. There is no clear relation between the occupants' home-efficiency responses and the annualized space heater estimates, as-operated UAs, or effective U-values (calculated from audit data). There is also no clear relation between the thermal parameters and whether or not the home has been subjected to an energy audit by a professional.

For the residential base sample, those occupants in the lower-income categories appear to live in smaller, less thermally efficient homes. In the box plot of Figure 1.19, floor area normalized electrical space-heating consumption, AEC_{iat}/ft^2, is split by income levels; and in Figure 1.20 the derived slope parameter is similarly partitioned. From Figures 1.19 and 1.20, high thermal integrity is directly related to increasing levels of income--except for the highest income class. Note that this trend is reversed in the box plot of Figure 1.21, where a decrease in income is accompanied by a decrease in median conditioned floor area for the lower-income brackets.

A decrease in normalized estimated annual electrical space-heating consumption is observed with newer vintage homes in the base sample. As expected, the newer homes are consuming slightly less energy for electrical space heating in the derived estimate, this is partially offset by the increase in size of newer homes.

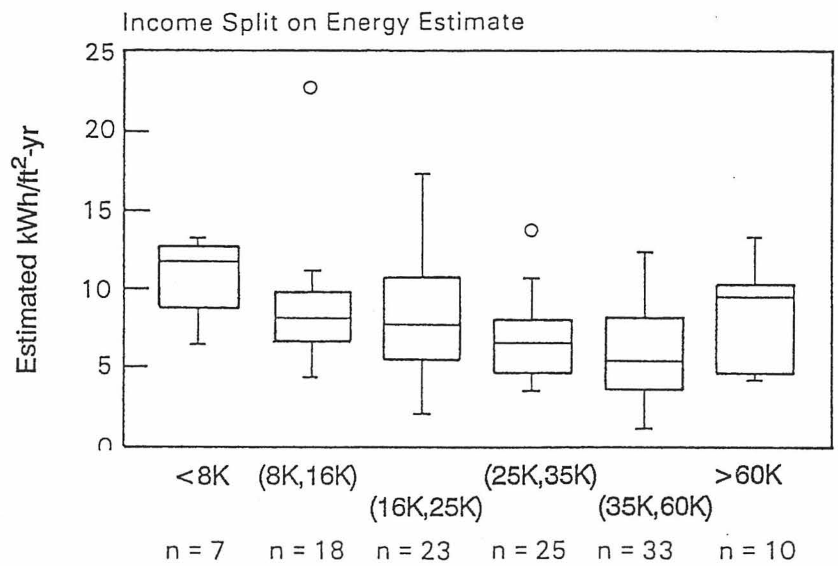

FIGURE 1.19. Floor Area Normalized, Electrical Space-Heating Consumption Divided by Income Levels

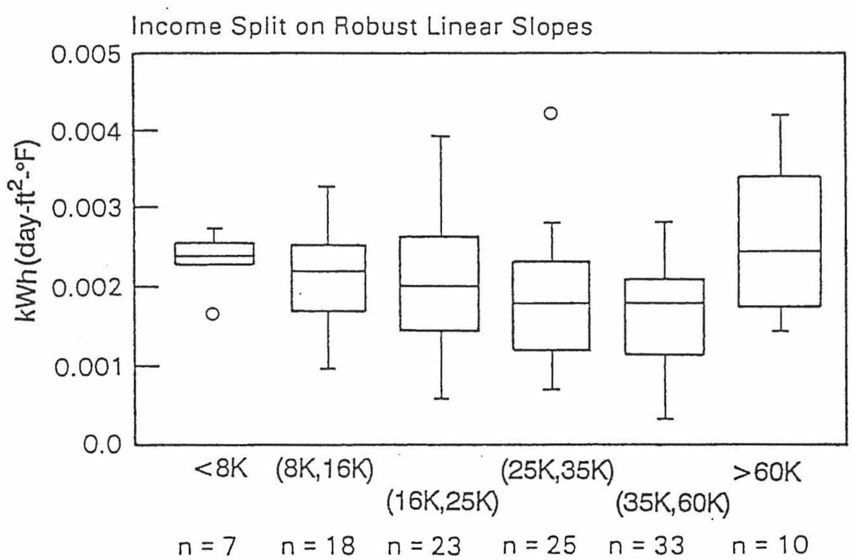

FIGURE 1.20. Derived Slope Parameter Divided by Income Levels

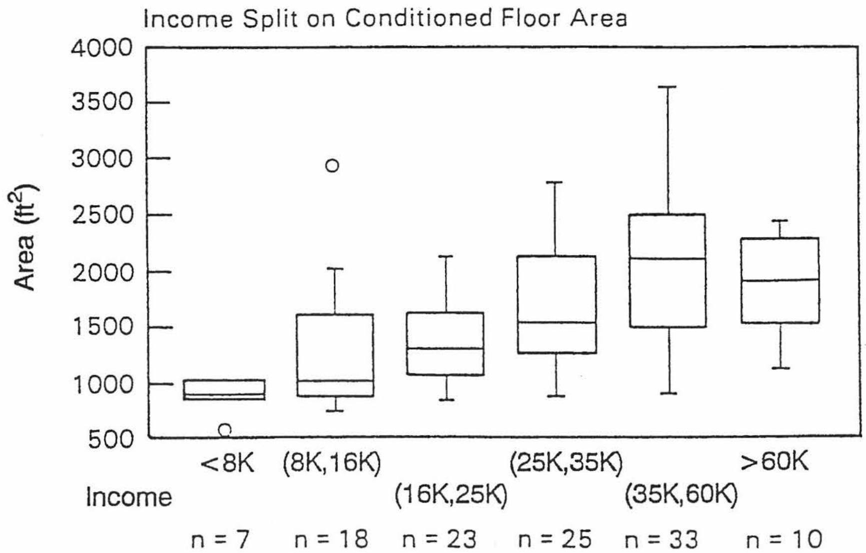

FIGURE 1.21. Conditioned Floor Area by Income Category for the Residential Base Sample

2.0 SECOND-YEAR ANALYSIS

2.1 INTRODUCTION

End-use metered data from a second heating season, 1986-1987, are used to build thermal performance characterizations for a number of residences participating in ELCAP. The results of the second heating season characterizations are summarized in this section. This set of characterized residences includes residential base homes and homes that were built as part of the RSDP. In addition to providing a second year's data for comparison with the first-year results in Section 1, this section examines the potential biases that may result from the independent variables and analysis techniques selected for the original analyses.

2.2 THE ELCAP THERMAL ANALYSIS METHODOLOGY

Three methods of AEC calculation are used in this analysis: inside-outside temperature difference (AEC_{iat}), standard inside temperature-outside temperature difference (AEC_{65}), and outside air temperature (OAT) alone (AEC_{oat}). In all three estimates, some data points with zero heating load are also included to more accurately model consumption during the early fall and late spring periods when the structure is near its balance point. Previous analyses considered only days with a positive heater consumption. See Table 2.1 for the comparison of the first- and second-year analysis approaches.

Similarly, the linear fits are performed with heater predictions based on outside air temperature in addition to inside-outside air temperature difference. Because of slope changes previously observed in the space heating characterization curves at the low and high ends of consumption, three types of linear fits are used for this year: a standard least squares fit to all points, a modified robust fit with the possible automatic exclusion of points within the low consumption region, and a standard least squares fit to points from the middle temperature range only. These enhancements are summarized in Table 2.2.

TABLE 2.1. Annualized Estimated Consumption Computations from Past and Present Work

Days Selected for Use	Predictor Variable Used: Inside-Outside Temperature Difference	Predictor Variable Used: Outside Air Temperature
Only Positive Heater Days	85-86 AEC_{iat}, 85-86 AEC_{65}	
Zero Heater Days Included	86-87 AEC_{iat}, 86-87 AEC_{65}	86-87 AEC_{oat}

TABLE 2.2. A Summary of Regression Methods for Past and Present Characterizations

Type of Fit	Predictor Variable Used: Inside-Outside Temperature Difference	Predictor Variable Used: Outside Air Temperature
Robust with Cutoff	85-86, 86-87	86-87
Standard Least Squares	86-87	86-87
Middle Domain Least Squares	86-87	86-87

2.3 SAMPLE CHARACTERISTICS

Approximately 40% of the homes available for analysis are impossible to characterize because of heavy wood usage, little or no heater load, or too much scatter in the heater thermal characterization curve, as indicated in Figure 2.1. The heating characterization curve, based on inside-outside temperature difference for the homes with enough data to analyze, is automatically classified into one of four categories: strictly linear, concave up, nonlinear foot at the low consumption end, or concave down at the high consumption end. Only about one-third of the heating characterization curves are completely free from nonlinear regions at either the low end or high end of consumption. Those curves classified as concave downward (roll off) at the high consumption end tend to have more scatter in their heater characterization curve than the other classes. This concave downward bend at the high end of consumption may be associated with intermittent zoning, especially in the case of homes with heated basements.

In Figure 2.2, the average metered heating load is compared for three groups of sites: those characterized, those not characterizable, and those excluded for logistic reasons (may include problems such as lack of reliable

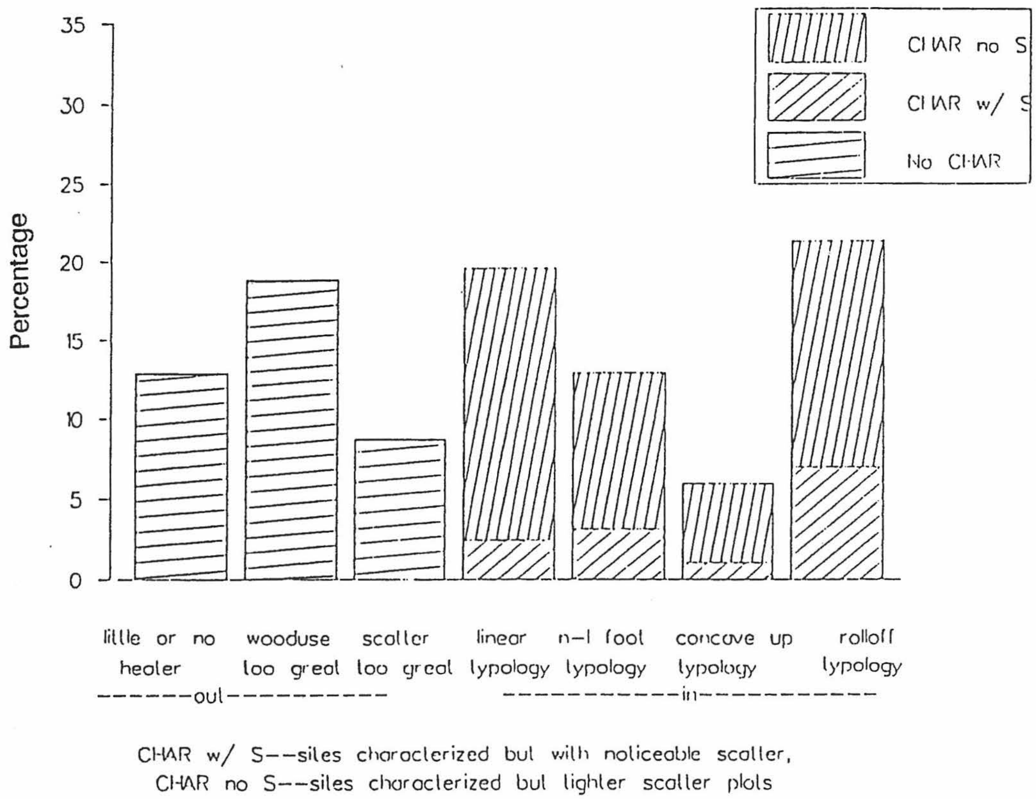

FIGURE 2.1. 1986-1987 ELCAP Residential Sample Characterization Disposition of Sites with Data Available for Analysis

inside or outside air temperature data or no floor area estimates). The median annual metered heating load for the characterized sites is observed to be about twice the median load for those sites not characterized (this replicates the observation made for the first-year characterization [see Section 1.2.3]). Hence, the results presented may be more applicable to those homes using more electricity for space heating. Figure 2.2 indicates that the set of homes excluded for logistic consideration exhibits no bias in mean heating loads towards either the characterized or noncharacterized homes.

Several results are partitioned on the basis of the Northwest Power Planning Council's climate zones. About two-thirds of all characterized homes are located in climate zone 1--59% for the MCS group and approximately 70% for the other classes of structures. As a reference point in the 1986 Northwest Power Plan, the weight assigned to climate zone 1, existing single-family homes, is 84% (Northwest Power Planning Council 1986).

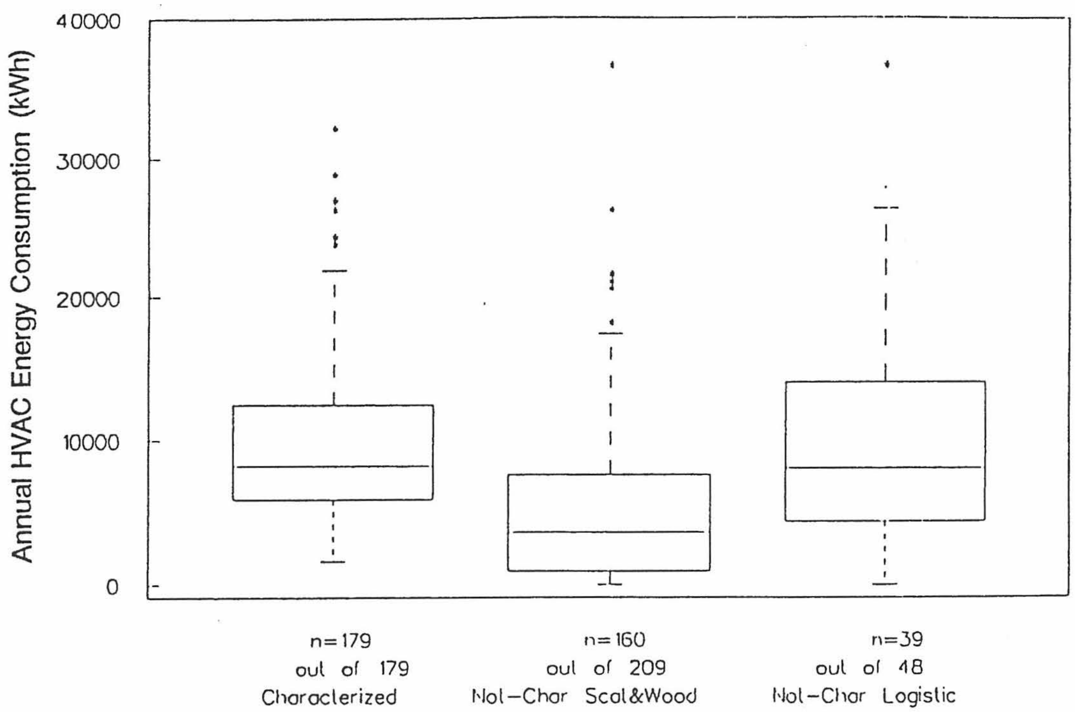

FIGURE 2.2. 1986-1987 ELCAP Residential Sample Characterization Heating Season - Heating, Ventilation, and Air Conditioning (HVAC) Total

For the set of characterized homes, the heating system type is predominantly baseboard heater, followed in frequency by forced air, heat pump, and radiant heat, respectively. The balance of heating systems are combinations of these. The foundation types for these homes are predominantly crawlspace in climate zone 1 and heated basement in climate zones 2 and 3, although slabs, heated basements, and all possible combinations of these foundation types do occur.

The conditioned floor area distributions for characterized homes are displayed in Figure 2.3 by structure type and climate zones. Summary statistics for these distributions are provided in Appendix F, Table F.1. Comparison of mean or median conditioned floor areas indicates that base and MCS homes are of comparable size. When averaging dwelling size across climate zones within each structure class, it is revealed that, on the average, the post-78 homes are about 200 ft^2 larger than the MCS and base homes. The

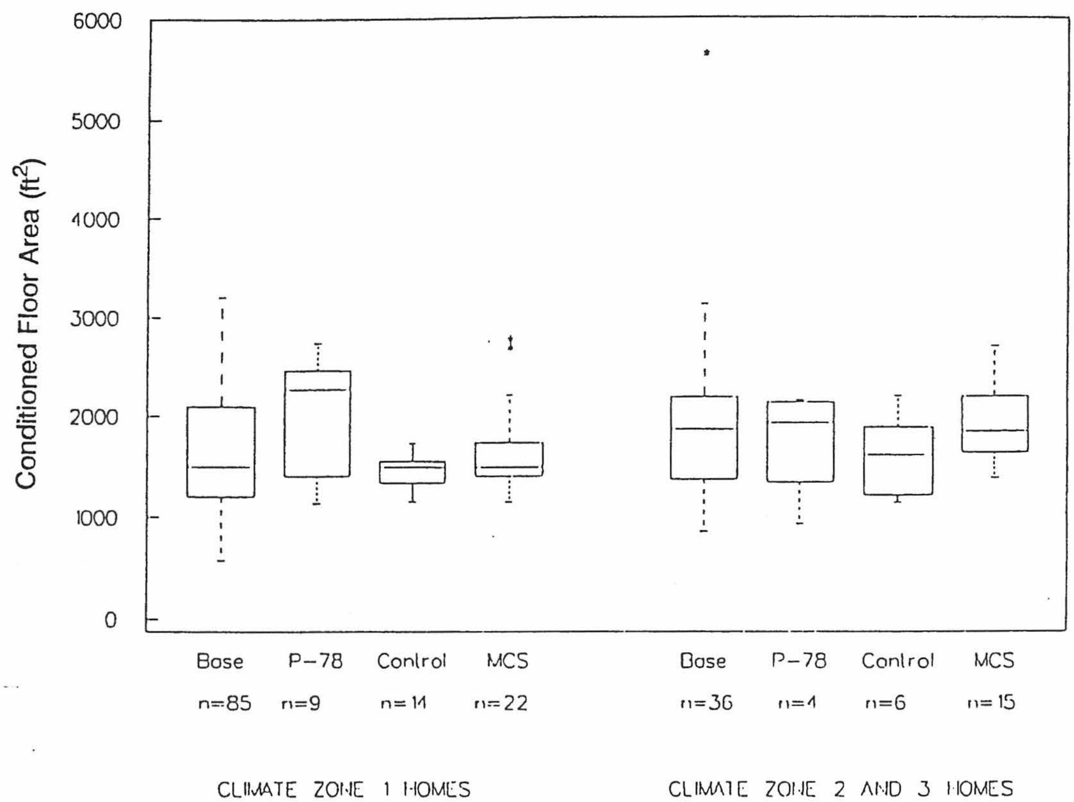

FIGURE 2.3. 1986-1987 ELCAP Residential Sample Characterization Total Conditioned Floor Area

control homes tend to be the smallest homes, again, by several hundred square feet when compared to MCS or base home size. Homes located in the more severe climate zones tend to be bigger except for the small set of post-78 homes where the trend reverses.

2.4 MAIN RESULTS FROM THE 1986-1987 HEATING SEASON CHARACTERIZATIONS AND ENHANCEMENTS

A summary of the major trends for the current thermal performance characterization work follows. In Section 2.4.1, the results related to the AEC calculations are presented. The results from the linear fits are summarized in Section 2.4.2, and observations from the analysis enhancements are integrated in the appropriate sections. Section 2.4.3 summarizes some simple performance statistics, provides a quick reference of mean calculations split by structure type, and is averaged across climate zones.

2.4.1 Annualized Estimated Consumption-Related Results

In this section, the mean heating season inside air temperatures for the various groups of structures are summarized. Comparisons are made between the three types of consumption estimates, AEC_{iat}, AEC_{65}, and AEC_{oat}. The distributions for AEC_{iat} are also presented and divided according to structure type and climate zone designations.

2.4.1.1 Mean Heating Season Inside Air Temperatures

The mean heating season inside air temperature distributions for the characterized homes are displayed in Figure 2.4. All available inside air

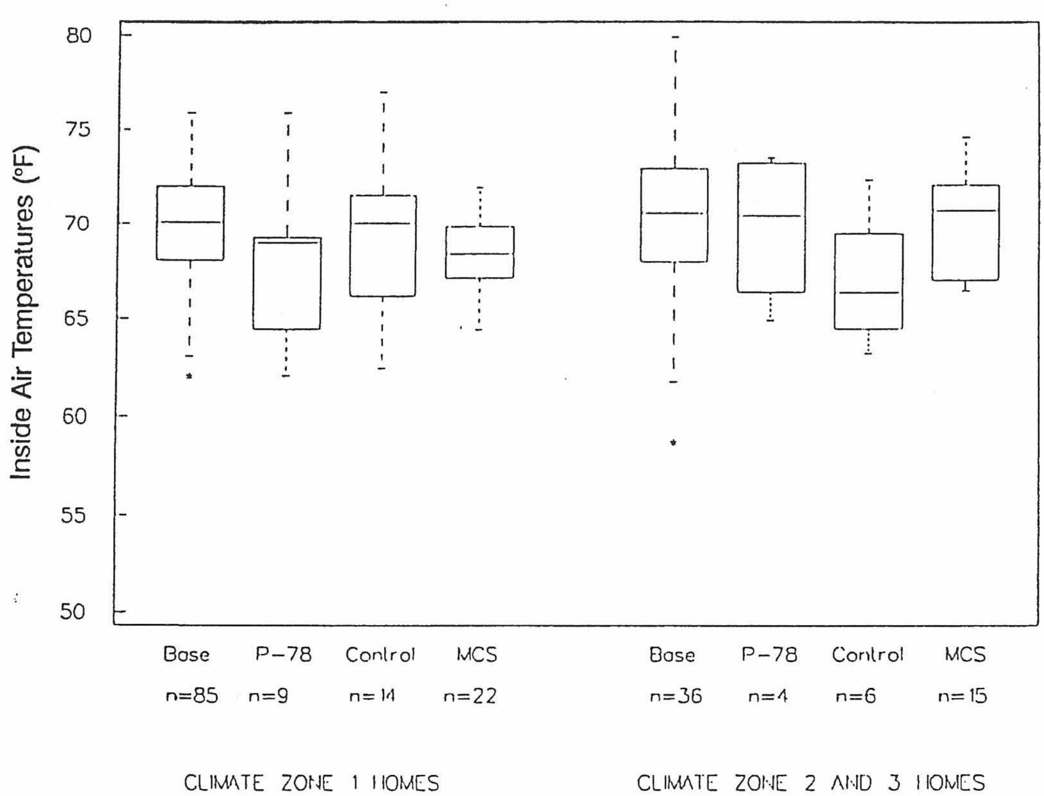

FIGURE 2.4. 1986-1987 ELCAP Residential Sample Characterization Mean Heating Season Inside Air Temperature Used in Annualized Estimated Consumption

temperature sensors at each residence are averaged for days used in the AEC_{iat} estimate to produce the mean temperatures displayed. The RSDP homes typically have two sensors installed in addition to the sensor installed in the main living area. The base homes typically have only one sensor, located in the main living area. Mean heating season inside air temperature for the combined sample of homes is about 69°F. No large cross-sample differences appear to exist in the median except for the cooler temperatures found in the control homes located in the more severe climate zone. There is, however, a considerable amount of variation in mean heating season inside air temperatures across the sample of homes characterized.

2.4.1.2 Comparison of the Three Types of Annualized Estimated Consumption Calculations

A comparison of AEC_{iat}/ft^2, AEC_{oat}/ft^2, and AEC_{65}/ft_2 may be found in Table 2.3. These point estimates are computed by averaging the floor area normalized AECs across structure type and climate zones for all characterized homes.

Estimates based on outside air temperature alone tend to be about 3% lower than those based on an inside-outside temperature difference. The AEC_{65} estimates, on the average, are 30% lower than estimates based on the observed mean heating season inside air temperature.

2.4.1.3 Structure Type and Climate Zones Results

Averaged across climates zones, the mean AEC_{iat}/ft^2 estimate for base homes (7.62 kWh/ft^2-yr) is more than twice that for the MCS homes (3.32 kWh/ft^2-yr). The post-78 homes (5.72 kWh/ft^2-yr) and control homes (5.25 kWh/ft^2-yr) are nearly indistinguishable with a mean estimate

TABLE 2.3. Mean Annualized Estimated Consumption Comparisons by Method Across Structure Types and Climate Zones, kWh/yr-ft^2

AEC Comparisons	AEC_{iat}/ft^2	AEC_{oat}/ft^2	AEC_{65}/ft^2
Mean	6.46	6.24	4.53
Median	5.53	5.37	3.93

approximately two-thirds of that for the base homes. Figure 2.5 displays the AEC_{iat}/ft^2 distributions split according to climate zone and structure type. The MCS and base distributions are fairly similar across climate zones. Distribution trends somewhat reverse for the post-78 and control homes between the mild and more severe climate zone groupings. Appendix F, Table F.3, provides accompanying summary statistics for Figure 2.5.

Only when (total) AEC_{iat} is considered, do the control homes (7,628 kWh/yr) appear to consume less energy for space heat than the larger post-78 homes (10,076 kWh/yr). The AEC_{iat} for the MCS homes (5,677 kWh/yr) is, again, less than half that of the base estimates (12,066 kWh/yr). (In Appendix G, Figure G.1, the distributions for AEC_{iat} split by structure type and climate zone are displayed. A summary table is also provided in Appendix F, Table F.4.)

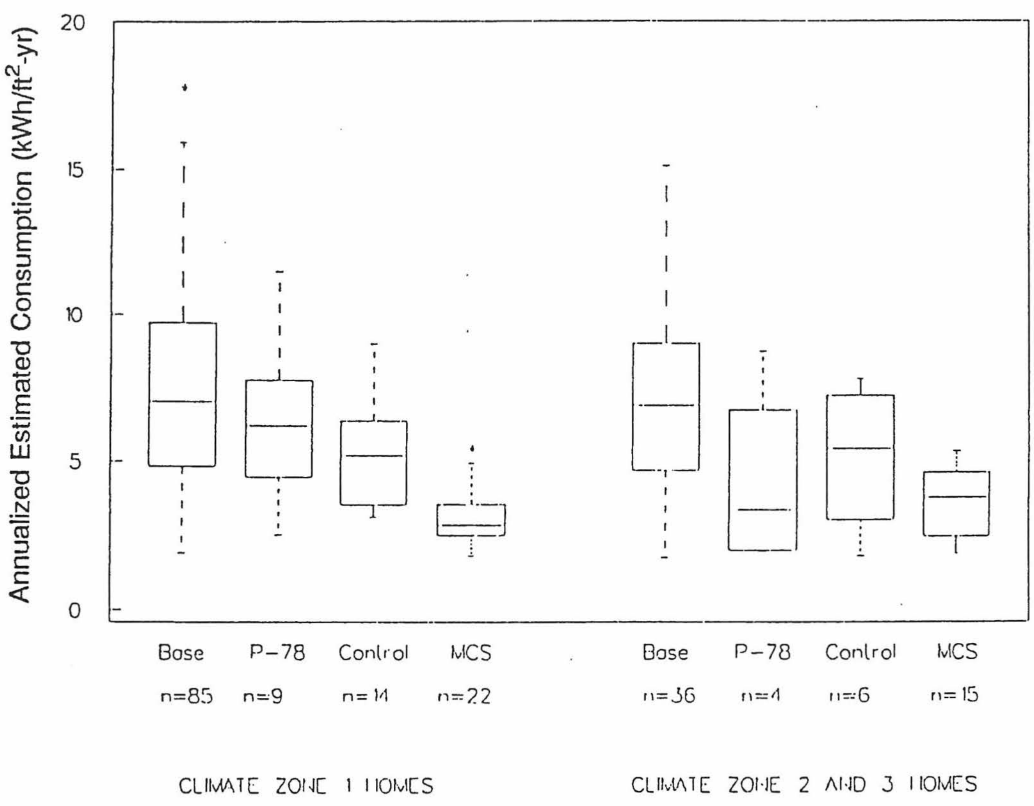

FIGURE 2.5. 1986-1987 ELCAP Residential Sample Characterization Annualized Estimated Consumption Mean Heating Season and Selected Typical Meteorological Year Weather

The distributions for AEC_{oat}/ft^2 by climate zone and structure type look very similar to those displayed in Figure 2.5. (AEC_{oat}/ft^2 distributions may be found in Appendix G, Figure G.2. A summary table for these distributions may be found in Appendix F, Table F.5.) General trends observed between structure classes in the AEC_{iat} estimates appear to be consistent with the AEC_{oat} and AEC_{65} estimates as well.

2.4.2 Linear Fit Results

In Section 2.4.2.1, the impact of the two predictor variables is examined by averaging the results of the three fit methods. The slope parameters from the linear fits are examined in some detail in Sections 2.4.2.2 through 2.4.2.4. The impact of the three fit methods on the slope parameter is discussed in Section 2.4.2.2. The slopes, interpreted as as-operated UAs, are compared to nameplate UAs in Section 2.4.2.3. Structure type and climate zone results are presented for the slopes calculated from the midrange temperature difference fits in Section 2.4.2.4. The intercept parameters from the linear fits are the topics of Sections 2.4.2.5 and 2.4.2.6. Section 2.4.2.5 presents the effect of the fit method on the intercepts from the linear fits. Section 2.4.2.6 presents structure type and climate zone results for intercepts from the midrange fits.

2.4.2.1 Impact of Predictor Variable

Selecting the predictor variable as the outside air temperature rather than the inside-outside temperature difference will, in general, impact both the slope and intercept parameters from the linear fit. A systematic comparison is made of these effects in Table 2.4 for both the slopes and the intercepts. The summary values in the table are computed by averaging across the three methods of fit (see Table 2.2) for all inside-outside temperature fits based parameters and then for the outside air temperature fit based parameters. The slopes from the outside air temperature fits have been multiplied by -1 to facilitate comparisons. The intercepts from the outside air temperature fits have been transformed into pseudo balance temperature differences. This transform is applied because the intercept from the outside air temperature fit is a building balance point and not directly comparable to the building balance temperature difference. This pseudo balance temperature

TABLE 2.4. Comparison of Mean Parameters from the Linear Fits Split by Predictor Variable and Averaged Across Three Methods

Air Temperature	Slope: Normalized kWh/(day-°F-ft^2)	Slope: As-Operated UA Btu/(°F-hr)	Intercept: Balance Temp. Diff (°F)
Inside-Outside	0.001698	387.28	11.04
Outside	0.001514	346.25	9.77[a]

(a) Pseudo balance temperature difference.

difference is computed by subtracting the building balance point (or intercept value from the outside temperature based fit) from the mean heating season inside air temperature for the days used in that fit.

Slopes from linear fits of the heater data to outside air temperature tend to produce lower slope estimates than linear fits to inside-outside temperature differences. The decrease represents about 11% of the slope computed from the inside-outside temperature difference. Because smaller slopes imply greater thermal integrity, the outside air temperature based slopes imply an average improved performance of 11%. This trend is reversed in the intercepts. A higher balance temperature difference would imply greater thermal integrity. The average decrease observed for the outside air temperature pseudo intercepts is about 11.5% of inside-outside temperature difference intercepts. The apparent efficiency gain in the outside air temperature slopes is negated by an almost equal amount in the intercept when comparisons are made to inside-outside temperature difference based parameters. (A graphic comparison of as-operated UAs for the two types of predictor variables within each fit category - standard, robust with cutoff, and midrange - may be found in the Appendix G, Figures G.3 through G.5.)

2.4.2.2 Impact of the Three Fit Methods on Slopes

On the average, for both sets of predictor variables, the slopes from the three linear fit methods follow a similar trend. The mean slopes from the midrange fits are largest, followed by those from the standard fits, which are followed by those from the modified robust slopes. The size of effects between fit categories are not equal across predictor variables as an examination of Table 2.5 indicates. The absolute differences between mean or median as-operated UAs and the modified robust and standard fits are greater when the predictor variable selected is the outside air temperature.

The robust slopes with cutoff are, on the average, 5% to 6% lower than the midrange fits, depending on the choice of predictor variable. The standard fits are 7% to 10% lower than the midrange fits for the temperature difference fits and outside air temperature fits, respectively. As a general rule, homes will appear to have the highest as-operated UAs (and lowest thermal efficiency) using a midrange fit; homes will appear to have the lowest as-operated UAs (and best thermal efficiency) using a standard least squares fit. (Scatter plot comparisons of as-operated UAs for pairs of methods are found in Appendix G. Figures G.6 through G.8 make pairwise comparisons for the as-operated UAs from the fit categories when temperature difference is the predictor variable; Figures G.9 through G.11 are analogous, but calculations are based on outside air temperature difference as the predictor variable.)

This ordering of slopes from the linear fits (Middle > Robust > Standard) reflects the existence of slope changes at both ends of the heating characterization curve, which, in general, drag the slope calculation down. In a more ambitious linear model where the intent is to remove heating system and zoning effects from the as-operated UA and thus come closer to the conductive UA, it may be useful to fit slopes piecewise over the heating characterization curve. The as-operated UA could then be selected from that region deemed most reasonable for the type of heating system installed and probable

TABLE 2.5. Comparison of As-Operated Effective Conductances (Slopes) Split by Fit Methods and Predictor Variable (Btu/hr-°F)

	Means			Medians		
Air Temperature	Middle	Robust	Standard	Middle	Robust	Standard
Inside-Outside	403.57	383.29	374.99	356.17	336.22	329.63
Outside	364.41	344.83	329.51	315.20	297.33	284.63

zoning habits. For example, the conductive UA for a baseboard heated home might best be computed from a midrange fit to dodge the coldest temperatures where many space heating characterization curves begin to experience scatter and/or a concave downward bend. This midrange fit would also avoid the potentially nonlinear low consumption region where the average outside temperature is near the balance point of the structure with substantial diurnal variation about that average. For a heat pump home, a fit to the region of outside air temperature where the efficiency of the system is closest to one is best suited for a pure calculation of the shell's conductive UA.

2.4.2.3 Comparison of As-Operated Effective Conductances and Nameplate Effective Conductances

The as-operated UAs taken from any of the six fits summarized from Table 2.2 are lower, on the average, than the nameplate UAs calculated from audit data. For information on nameplate UA calculations, see Conner, Lortz, and Pratt (1990). Using the largest slopes (those from the midrange temperature difference fits), the as-operated UAs are roughly 90% of the nameplate UAs--if no infiltration estimate is added to the nameplate UAs. A scatter plot of nameplate UA versus the as-operated UAs from the midrange fits is displayed in Figure 2.6 (note x and y axis are reversed compared to Figure 1.9). After adding in an assumed infiltration rate of 0.4 air exchanges per hour, mean as-operated UAs are 76% of the mean nameplate UAs. Figure 2.7 illustrates the increased disagreement between the nameplate and as-operated UA calculations when infiltration is added to nameplate UA calculations. This result is not dependent on the goodness of a linear fit. When the ratio of as-operated UAs to nameplate UAs is binned on R-squares, the same result follows within each quartile grouping. As-operated UAs from the other fits only lower the agreement to the nameplate UA. The same result is noted in Section 1.4.

2.4.2.4 Case Study and Climate Zone Results for Slopes

Averaged across climate zones, the floor area-normalized slopes from the middle range fit to the inside-outside temperature difference for the MCS homes is 64% of the mean base slope. Very little difference is noted between the mean slopes for the post-78 and control homes, although the control homes

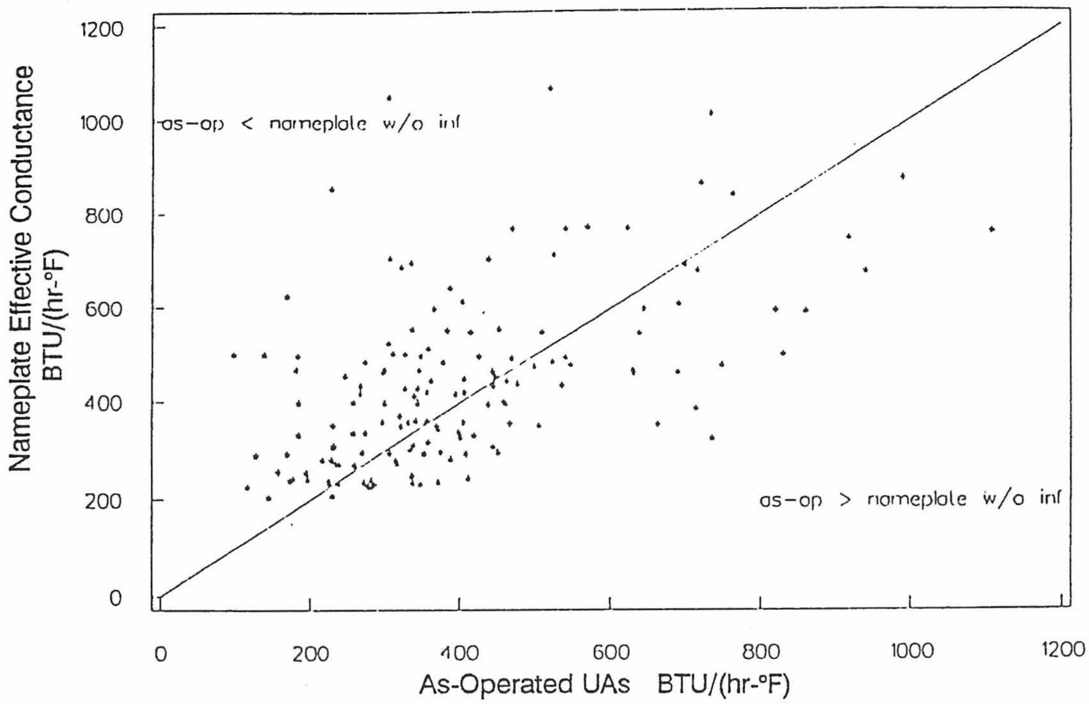

FIGURE 2.6. 1986-1987 ELCAP Residential Sample Characterization Nameplate Effective Conductances Without Infiltration Versus As-Operated Effective Conductances. As operated UAs shown are from the slopes of the midrange fit of the heater-to-temperature difference.

have a slightly lower mean slope. Because the larger the slope the greater the envelope heat loss, these slopes order the thermal integrity of the structures as base < post-78 ≤ control < MCS. Figure 2.8 displays these slopes split by structure type and climate zone. (See Appendix F, Table F.6. for summary statistics.) Some climate zone differences exist. Slopes for the climate zone 2 and 3 homes tend to be lower than the climate zone 1 homes by one-half to one-third, depending on study type. Given the more extreme weather conditions in climate zones 2 and 3, this is expected.

2.4.2.5 Impact of the Three Fit Methods on Intercept Parameters

Table 2.6 displays the mean and median intercepts for each of the six linear fits described earlier in Table 2.2. Pseudo balance points are displayed to facilitate comparisons along with the mean and median balance points

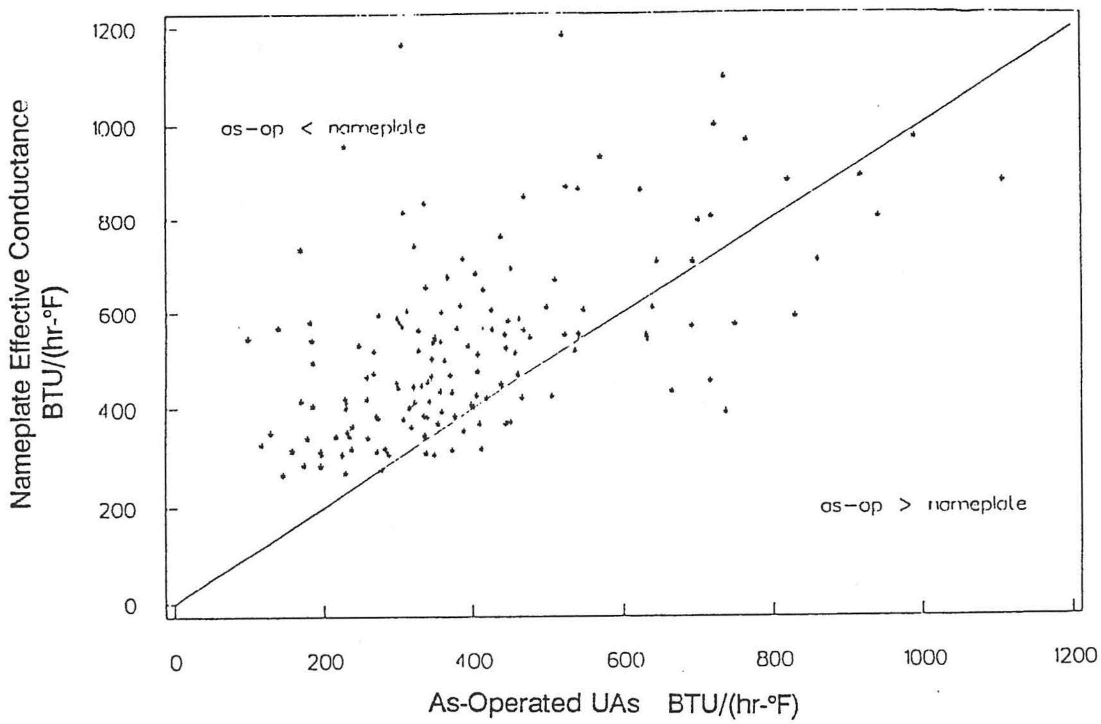

FIGURE 2.7. 1986-1987 ELCAP Residential Sample Characterization Nameplate Effective Conductances Plus Infiltration Versus As-Operated Effective Conductances. As-operated UAs shown are from the slopes of the midrange fit of the water-to-temperature difference.

for those intercepts calculated from outside air temperature. The mean and median intercepts from the outside air temperature fits are also indicated. In general, the midrange fits produce intercepts that are greater than those produced by the other fit methods by one or 1.5°F, thus making the home appear to be more efficient. This is the opposite (but expected) conclusion reached from the slopes for the midrange fits. The nonlinearities in the heating characterization curve tend to drag the intercept toward lower values on temperature difference fits and toward higher values on outside air temperature fits. The midrange fit is affected much less by this effect. Little difference is noted between the modified robust method and the standard method, for the inside-outside temperature difference fits. This is not the case when outside air temperature is selected as the predictor variable. The intercepts from the robust and standard methods calculated with outside air

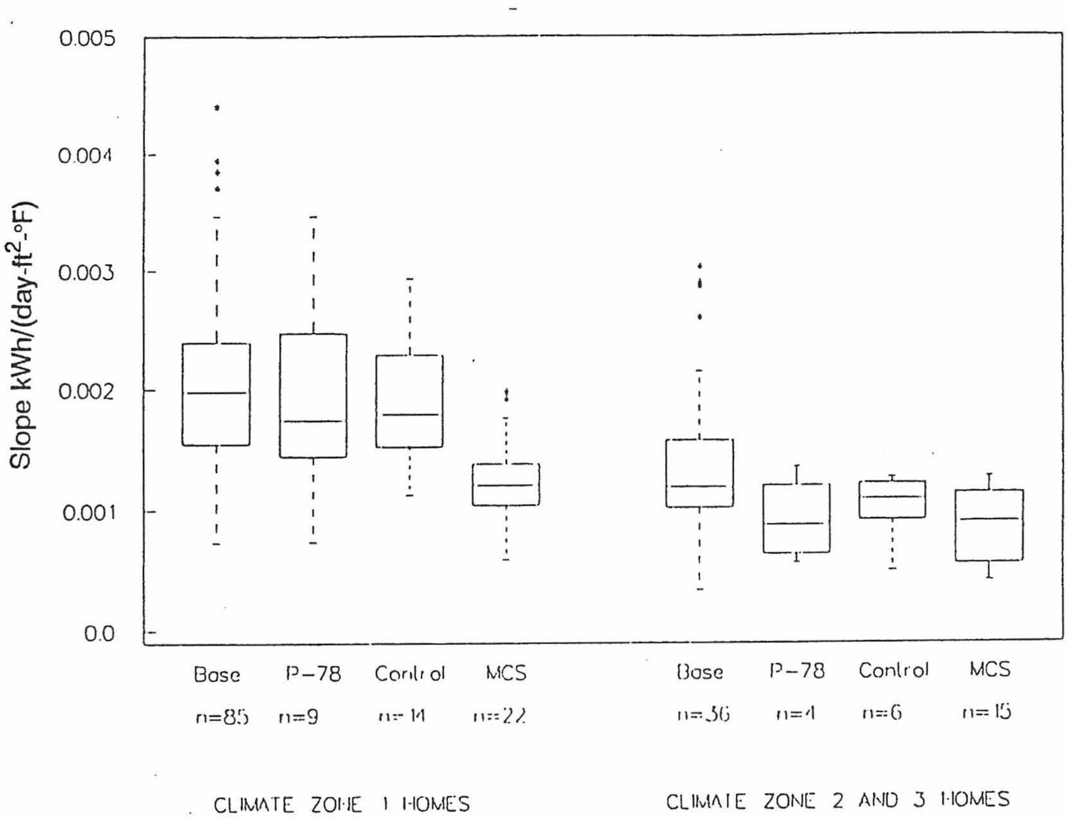

FIGURE 2.8. 1986-1987 ELCAP Residential Sample Characterization Slopes from Middle Linear Delta Temperature Fit

TABLE 2.6. Intercept Comparison by Fit Methods and Predictor Variable (°F)

	Means			Medians		
Air Temperature	Middle	Robust	Standard	Middle	Robust	Standard
Inside-Outside	11.67	10.73	10.72	12.03	10.59	10.65
Outside[(a)]	10.85	9.49	8.97	11.57	9.90	9.23
	↑	↑	↑	↑	↑	↑
Balance Temperature	(58.35)	(59.71)	(60.23)	(57.93)	(59.13)	(60.22)

(a) These are pseudo balance temperature differences. The actual intercept or building balance point is noted directly below the pseudo estimate.

temperature as the predictor variable are more readily distinguished than those based on temperature difference.

The balance points differ little between the standard and robust fits, yet they differ substantially more between those fits and the midrange fit. The change in slope at the high end of consumption appears to be exerting a stronger influence on the intercept calculation for the temperature difference fits (at least in the current form that the modified robust technique is being applied [see Volume I, Miller et al. 1990]) than the curvature at the low-consumption region.

2.4.2.6 Structure Type and Climate Zone Results for Intercepts

Building balance points aggregated within structure types indicate the same ordering of thermal integrity for the structure types and the slopes. The balance point distributions from the midrange fit of heater to outside air temperature is displayed by structure type and climate zone splits in Figure 2.9. From the corresponding summary (see Appendix F, Table F.7), the mean balance temperature difference for base homes is observed to be about 75% that for the MCS homes, or 4°F across climate zones. Post-78 and control homes remain as poorly distinguished for balance points as they are for the slopes from the linear fits. The climate zone 1 balance points tend to be higher, on the average, than the others two zones - a result consistent with higher thermal integrity associated with homes in climate zones 2 and 3.

The distributions for the balance temperature differences computed from the midrange linear fit of heater inside-outside temperature difference are displayed by structure type and climate zone in Figure 2.10 (also see Appendix F, Table F.8). The cross-climate zone means differentiate performance of all four classes of structures. The balance temperature difference for the MCS homes is 3.6°F higher in the mean than the balance temperature difference for the base homes, or 37% higher than the mean-base estimate. Within climate zones, the mean relation for the balance temperature differences for the post-78 and control homes reverses, although the base-to-MCS relation remains ordered as noted.

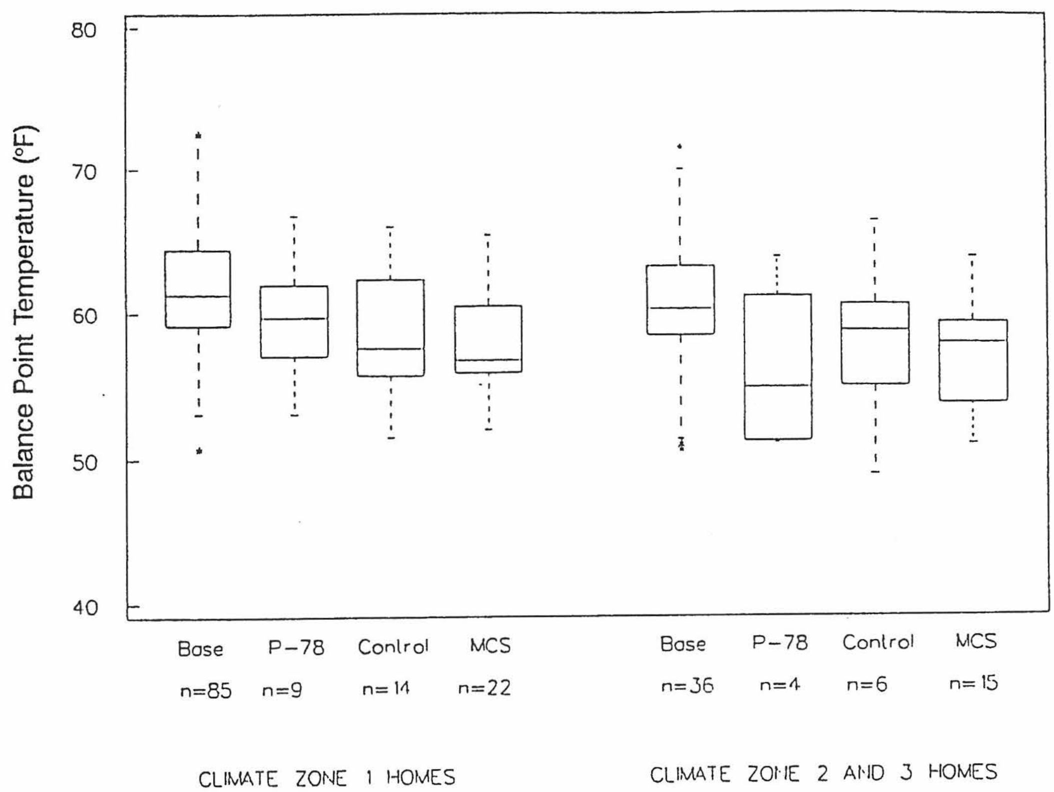

FIGURE 2.9. 1986-1987 ELCAP Residential Sample Characterization Balance Point from Midrange Outside Air Temperature Fit

2.4.3 Tabular Summary for Performance Statistics by Structure Type

Table 2.7 summarizes several derived parameters and performance statistics from the 1986-1987 heating season characterization analysis. It provides a quick inventory of results for cross structure comparisons. The summary values for the base homes also include the post-78 homes. The various AEC computations and enhancements are summarized in Table 2.7.

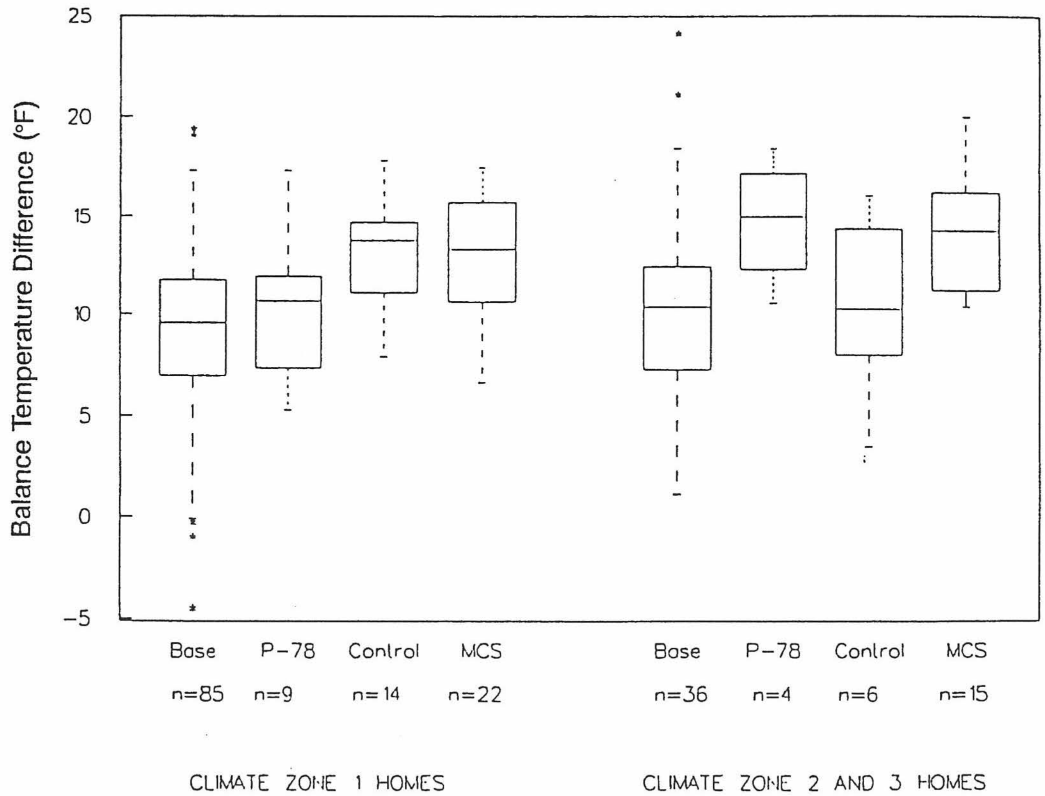

FIGURE 2.10. 1986-1987 ELCAP Residential Sample Characterization Balance Delta Temperature from Middle Linear Delta Temperature Fit

TABLE 2.7. Averaged Results by Study Type Across Climate Zones

Home Quantity	Base Homes	Post-78	Control	MCS
General				
Total Homes	121	13	20	37
Climate Zone 1 (%)	70	69	70	59
Floor Area (ft^2)	1,729	1,911	1,497	1,748
AEC[a] Computations				
Inside Air Temperature used in AEC_{iat} (°F)	69.8	68.7	68.9	69.1
Normalized AEC_{iat} [kWh/(ft^2-yr)]	7.62	5.72	5.25	3.32
Normalized AEC_{oat} [kWh/(ft^2-yr)]	7.39	5.40	4.97	3.20
Normalized AEC_{65} [kWh/(ft^2-yr)]	5.32	4.30	3.74	2.34
AEC_{iat} (kWh/yr)	12,066	10,076	7,628	5,677
Linear Fit Related				
As-operated UA Middle ΔT Fit [Btu/(hr-°F)]	445	441	356	292
Slopes Middle ΔT Fit [kWh/(day-°F-ft^2)]	0.00183	0.00167	0.00164	0.00109
Balance ΔT Middle ΔT fit (°F)	9.7	11.6	12.3	13.3
Balance Point Middle OAT fit (°F)	61.4	58.5	58.4	57.5

(a) AEC represents the annualized estimated consumption.

3.0 FIRST- AND SECOND-YEAR COMPARISONS

3.1 INTRODUCTION

This section presents an analysis of the contrasts between the thermal performance characterizations for the 1985-1986 and 1986-1987 heating seasons. Although gross comparisons are certainly possible from the previous characterization work, the analysis presented here examines the systematic and quantitative change in thermal parameters derived for the set of homes common to both heating seasons. This comparison is of great value for at least two reasons. First, the unavoidable changes in weather between any two heating seasons provide a natural experiment to test the sensitivity of the simple empirical methodology used to calculate the indices of thermal performance. And second, a study of the significant changes in the derived parameters can suggest improvements in methodology for future characterization work. The methodological enhancements described in Section 2.0 were applied to the metered data from the first year, the 1985-1986 heating season, before the comparisons reported here were made.

Characterization analyses based on metered data are becoming an informational tool for regional load forecasters. Understanding the stability of these characterizations over time is a crucial step in legitimizing empirical approaches such as those previously described in this document. The current work addresses the question of how stable the ELCAP characterizations are for the set of analyzed homes and concludes with recommendations for future thermal analyses.

3.1.1 ELCAP Thermal Analysis Methodology

Effectively, the AEC is the estimated space-heating consumption of the home as it is actually operated, but as if exposed to annual patterns of outdoor temperature for the standard weather year. The AEC includes no standardization for solar differences or levels of internal gains. Thus the AEC reflects solar and internal gains implicit in the metered data for the given heating season. A comparison of AECs across years can help delimit the impact of omitting such factors.

Three types of AEC estimates are calculated in units of total kWh/yr, AEC_{iat}, AEC_{65}, and AEC_{oat} (see Section 2.0).

In addition to the AEC calculations, a linear fit to a selected portion of the data provides a slope and intercept for each residence. Three types of linear fits are computed for each of the two independent variable choices: a standard linear fit, a robust linear fit with cutoff, and a midrange linear fit. Table 3.1 provides a summary of the various parameters of thermal performance that are calculated for the ELCAP residences. A home that is characterized has all the parameters of thermal performance listed in Table 3.1.

3.1.2 Site Selection

An ELCAP residence is included in this comparison study where a characterization is available for both the 1985-1986 and 1986-1987 heating seasons. A variety of conditions force a characterization to be unavailable. To obtain a characterization, adequate coverage of the dynamic range of specific climate zone temperatures must be present. Inadequate coverage may be from occupant-dependent behaviors such as negligible use of electricity for space heating or occupant-independent logistic problems such as bad or missing data. In addition to adequate range coverage, the data must display fairly uniform heater usage; i.e., a trend of increasing heater load with decreasing outside air temperature without excessive scatter.

TABLE 3.1. Thermal Characterization Parameters Available for Comparisons

Air Temperature	Space-Heating Estimates	Linear Fits: As-Operated UAs	Linear Fits: Balance Δ Temperature	Linear Fits: Balance Point
Inside-Outside	AEC_{iat}, AEC_{65}	S,R,M[a]	S,R,M	
Outside	AEC_{oat}	S,R,M		S,R,M
Variable	n = 3	n = 6	n = 3	n = 3

(a) S, R, and M represent the standard, robust with cutoff, and midrange fits, respectively.

The 187 residences not characterized for either heating season are three times more likely to fall into the inadequate coverage category than the non-uniform usage category. Most of these inadequacies are occupant driven, and usually involve heavy wood use. Residences with no characterization for either heating season typically fall out of the thermal analyses for the same reason each year. Heavy wood burners tend to remain heavy wood burners.

Sites available for one heating season but not the other are typically borderline sites with just enough days of nonsupplemental heater usage present to be kept in the analysis for one year but not for the other year. These 85 sites are disjointly divided into two groups of homes depending on which year is not characterized. Approximately one-fifth of the homes in each of these two groups appears to have drastically cut back on wood burning in the characterized year. Thus, a small migratory heavy wood burning population exists, but the relative proportions of migrating sites is about the same in the two years studied.

Table 3.2 displays the climate zone and building class distributions for the homes with characterizations available for both heating seasons. Because the performance of each home is compared to itself, climate zone designation variables are not incorporated in this analysis. The analyses presented here attempt only to distinguish differing levels of change for the two heating

TABLE 3.2. Distribution of Homes in Climate Zone and Building Type Comparisons

Parameter	Climate Zone 1	Climate Zone 2	Climate Zone 3
Heating Degree Days Based on 65°F	< 6000	6000-8000	> 8000
Number of Homes by Study			
All homes	88	29	10
Base	61	18	4 (n = 83)
MCS[a]	18	8	3 (n = 29)
Control	9	3	3 (n = 15)6

(a) MCS represents Model Conservation Standards.

seasons according to case study. The initial sample of 127 homes is partitioned into 83 base homes, 29 MCS homes, and 15 control homes, with the majority of homes falling in the mildest climate zone.

3.1.3 Analysis Methodology for Year-to-Year Comparisons

In the discussions that follow, several simple statistical measures are used to determine how significant the observed mean differences are for the various quantities of interest from one heating season to the next. These quantities include the three types of AEC estimates, two parameters from the various linear fits, and other metered quantities such as mean heating season inside air temperatures. For testing purposes, the combined sample of homes is divided into four subsamples: all, base, MCS, and control homes. For each site, a difference is calculated as a second-year value minus the corresponding first-year value. Relative comparisons are used for the pairwise population means where a systematic difference in magnitude can be expected for the various case studies, such as in AEC comparisons for base and RSDP homes. The scaling used is to divide each observation by the overall sample mean for the first year. Several questions are then posed for each quantity of interest:

- Given a specific subsample, how significant are the estimated mean differences across years?
- Given a specific subsample, how does the within-year variation (across sites) for each of the two heating seasons compare to the variation of site-by-site differences across years?
- How significantly different are the estimated mean differences for each pair of subsamples?

One method for quantifying the significance of these comparisons is to compute the minimum level alpha (α) for which the hypothesis of no difference is rejected. For an α level test, the probability of rejecting a true hypothesis (of no difference) is no larger than α. Under this definition, a small significance level represents strong sample evidence of a real difference in the underlying population, while a large significance level denotes weak evidence of any such difference. In the interpretation of results for this report, significance levels less than 0.01 are deemed highly significant, levels between 0.05 and 0.01 are termed significant, levels between 0.10 and

0.05 are considered marginally significant, and those greater than 0.10 are reported as nonsignificant. As in all hypothesis testing, there may be a difference between a statistically significant result and one that is practically significant. For example, given a large sample, very small changes may prove to be highly significant in a statistical sense, yet the magnitude of change may be so small as to be negligible from a practical standpoint.

An example of the first type of question would be to determine the significance of the average first-year/second-year difference in AEC_{iats} across the base case homes common to both years. Answering the second question provides a measure of spread for the 1985-1986 and 1986-1987 AEC_{iat} distributions, as well as for the distribution of differences across the years. The latter quantities could be used to determine how well the first-year estimates correlate with the second-year estimates. If AEC_{iat} is a property of the structure, as desired, a fairly high positive correlation should result.

The last test determines whether the estimated average first-year/second-year differences for two different subsamples of home types are significantly different. For example, what is the minimum α level at which the mean estimated difference in AEC_{oat} for the base homes can be judged as significantly different from the mean estimated difference for the MCS homes? Absolute or relative comparisons are made depending on the quantity analyzed.

3.2 GROSS DIFFERENCES BETWEEN THE HEATING SEASONS

In Section 3.2.1, average inside air temperatures and solar availability (global horizontal radiation) are compared for the two heating seasons. The second year is observed to be quite a bit warmer and sunnier than the first. In Section 3.2.2, differences in the measured space-heating data, inside air temperature data, and coverage of the dynamic temperature ranges are also observed to be consistent with the change in weather patterns. A poorly understood increase in appliance internal gains is also noted.

3.2.1 Weather

The 1985-1986 and 1986-1987 heating seasons were ideal for carrying out the first-year/second-year comparisons. Nature cooperated by delivering two very different heating seasons. Table 3.3 presents averaged outdoor air temperatures during the full heating season (September through May) as well as the coldest portion of the heating season (November through February) for a selection of cities in the Pacific Northwest. Although a detailed weather comparison is not within the scope of this work, Table 3.3 indicates that it was approximately 2.5°F to 5°F warmer for the region in the second heating season when compared to the averaged temperatures from the first heating season.

Table 3.4 facilitates gross comparisons of solar availability. Averaged global horizontal radiation is displayed for the same cities and time periods as for those found in Table 3.3. While the differences are not constant across the region, these data indicate a greater potential for solar gains in the second year. For the cities represented in Table 3.4, the average increase in mean solar radiation is about 3%.

TABLE 3.3. Summary of Mean NWS[a] Outside Air Temperature Data (°F)

September through May	Seattle	Portland	Spokane	Yakima	Richland	Boise	Missoula
1985-1986	46.3	47.0	37.9	39.9	43.0	40.7	35.2
1986-1987	48.6	49.6	41.3	43.7	48.1	44.4	37.5
Change	2.3	2.6	3.4	3.8	5.1	3.7	2.3
December through February							
1985-1986	40.5	38.7	26.6	26.9	30.4	26.0	22.5
1986-1987	42.1	40.8	28.9	30.4	33.4	29.8	23.3
Change	1.6	2.1	2.3	3.5	3.0	3.8	0.8

(a) Data Source: National Weather Service.

TABLE 3.4. Mean NWS[a] Horizontal Solar Radiation (W/m^2)

September through May	Seattle	Portland	Spokane	Yakima	Richland	Boise	Missoula
1985-1986	101.8	108.8	109.2	125.9	119.1	145.1	115.7
1986-1987	108.7	109.0	114.5	129.6	123.6	148.9	119.2
Change, %	7	0.2	5	3	4	3	3
November through February							
1985-1986	47.0	51.8	40.0	48.1	52.0	67.3	49.1
1986-1987	47.4	52.8	45.7	50.1	50.8	69.4	50.4
Change, %	1	2	14	4	-2	3	3

(a) Data Source: National Weather Service.

3.2.2 Differences in Metered Data

The first-year/second-year analysis focuses on the stability of derived estimates of thermal performance from one year to another. The weather-driven changes implicit in the metered data provide an opportunity for testing the sensitivities of the derived parameters. In this section, several across-year comparisons are made for the metered data, including space heating and inside air temperature data.

3.2.2.1 Heating Data

The average daily measured space-heating load is about 15% lower in the 1986-1987 heating season than in the 1985-1986 heating season for the combined sample of homes and within each study sample. No significant differences are found between classes of structures. After removal of wood use days, extended vacancy days, and adjustment for substitute outside air temperature data, this difference in mean daily load drops to about 10% for the combined sample of homes. Similarly, no significant differences between classes of structures are noted. Thus, for all home types, the average consumption in the second-year analysis is about 10% lower than that in the first-year analysis for the days used to calculate AEC estimates.

3.2.2.2 Mean Heating Season Inside Air Temperatures

The increases observed in the average internal temperatures in the second heating season play an important role in the stability of AEC estimates (see Section 3.3). Simple statistical summaries for mean measured inside air temperatures are displayed in Table 3.5 for the combined and case study samples. These temperature data include only those days used in the analysis; thus, days of extended vacancy and wood-stove use are removed. The temperature data for each base home is summarized by averaging a single temperature sensor in the main living area. Inside air temperatures for the MCS and control homes are summarized by averaging readings from three temperature sensors: one in the main living area and, typically, two in bedrooms. (The scatter plots comparing mean internal temperatures for the combined, base, MCS, and control homes may be found in Appendix H, Figures H.1 through H.4.)

For the combined sample, mean estimates for averaged inside air temperatures show a highly significant average increase of 0.6°F. This increase is likely to be the result of the warmer second heating season, rather than increased thermostat setpoints. A single parameter, such as a mean heating

TABLE 3.5. Mean Heating Season Inside Air Temperatures (°F)
(Y1) = 1985-1986, (Y2) = 1986-1987

Sample	Combined	Base	MCS	Control
Size	127	83	29	15
Mean (Y2)	69.6	69.9	69.1	68.8
Mean (Y1)	68.9	69.5	68.2	67.2
Mean (Y2-Y1)	0.6	0.4	0.9	1.6
Significant level	0.00018	0.02	0.01	0.09
SD[a] (Y2)	3.35	3.48	2.43	4.02
SD (Y1)	3.74	3.57	2.73	5.51
SD (Y2-Y1)	1.80	1.38	1.76	3.47
Correlation (Y1,Y2)	0.88	0.92	0.77	0.78

(a) SD = standard deviation.

season inside air temperature, does not completely summarize the patterns actually observed when inside air temperate is plotted versus outside air temperature. In Appendix H, Figure H.5, two separate strategies are apparent in this data taken from a single-heating season. Once days are cold enough, the daily internal temperature values approach a common value, probably a degree or two above that of the thermostat setpoint. During the spring and fall months, however, the internal temperature is highly correlated to outside air temperature and may rise above the setpoint. In a milder heating season, the effect of the spring and fall months on the mean heating season internal air temperature is more pronounced, producing a noticeably higher value.

The largest increases in mean internal air temperatures for the second heating season over the first are found in the RSDP homes. The changes in the mean internal air temperatures for the base, RSDP, and control samples are 0.4°F, 0.9°F, and 1.6°F, respectively. These mean changes are statistically significant, but only marginally so for the control homes. The standard deviations in Table 3.5 indicate that the variation of internal air temperatures across sites within a given year is greater than the variation of the year-two/year-one differences. As a result, the correlations of inside air temperatures are relatively high. The control homes have the greatest amount of variation and the least clearly defined trend. This is observed by comparing the magnitude of the standard deviations to those values for the other groups of homes. In a tighter home, the inside air temperatures take longer to decay. Additionally, averaging multiple sensors from a home that closes rooms off (or zones) amplifies the indoor temperature drift in the thermostat dead band that would be apparent from averaging a single sensor in the main living area. Given multiple sensors in the tighter RSDP homes, it is not surprising to see larger changes in the mean heating season internal temperatures as compared to those for the base homes.

Table 3.6 indicates the minimum α level at which the changes in mean heating season internal temperatures for pairs of case study homes differ significantly. Restricting the comparisons only to days used in the original thermal analysis, no significant results are noted. If, however, all days in

TABLE 3.6. Significance Level for Pairwise Comparison of Mean Metered Heating Season Inside Air Temperatures by Case Study (°F)

Sample	Base and MCS	MCS and Control	Base and Control
Days Used	0.17	0.44	0.17
All Days	0.09	0.62	0.18

the heating season are used, the difference between base and MCS becomes marginally significant (α = 0.09). Using all days for which inside air temperature readings are present, the difference from the second year to the first year is 0.8°F, 0.5°F, 1.1°F, and 1.3°F for the combined, base, MCS, and control homes, respectively.

3.2.2.3 Data Availability and Miscellaneous Observations

For the combined set of homes, approximately 2.5 more weeks of space-heating data are available in the second year. This is essentially a difference in data capture rates as the ELCAP project matured. No notable differences exist across the case studies. However, when actual days used in the analysis are compared, this discrepancy drops to about 4 days, presumably because of fewer overall days of heater usage in the warmer second year. Thus the data sets for the two heating seasons are roughly equivalent in terms of the number of data points available.

As a consequence of warmer and sunnier weather in the 1986-1987 heating season, some differences in the coverage of the dynamic range of inside-outside temperature differences are easily observed. Table 3.7 displays the difference between the heating seasons for the minimum and maximum temperature difference at which a positive heater load occurs. The milder outside air temperatures in the second year significantly decrease the average maximum inside-outside temperature difference by 4.5°F (α = 1.4e-8). The base homes display the greatest temperature drop, followed by the control homes and then the MCS homes. Table 3.7 also displays the minimum temperature difference for a positive heater load. The RSDP homes experience the first positive heating load 3°F to 4°F later in the second year. This phenomenon is not generally observed for the base homes, although when all homes are combined, a significant (α = 0.04) trend in the same direction of 1°F is noted. This overall

TABLE 3.7. Difference in Maximum and Minimum Delta Temperatures when the Heater Load is Positive by Study Type 1985-1986 Value - 1986-1987 Value (°F)

Difference	Combined	Base	MCS	Control
Maximum ΔT	-4.5	-5.2	-2.7	-4.4
Significance Level for Maximum ΔT	1.4E-8	7.1E-7	0.07	0.04
Mean Difference Minimum ΔT	1.0	-0.2	3.1	4.0
Significance Level for Minimum ΔT	0.04	0.58	0.005	0.11

apparent delayed use of space heating for a fixed temperature difference is most likely from increased solar availability in the second year. The greater sensitivity for the RSDP homes is likely to be from a greater tendency for indoor temperature drifting in the thermostat dead band to occurring in tighter homes during the spring and fall heating months. The greater prevalence of solar gains during spring and fall months could cause an apparent shift upward in building balance points.

3.2.2.4 Internal Gains

Internal gains are defined as heat given off by appliances, people, plants, and animals in the home. In the computation of AECs, no accommodation for variations in internal gains are made. There is no reason to expect internal gains to change between the two heating seasons. From the ELCAP data, a rough appliance-only internal gain is calculated. This number is computed by adding up the all nonspace-heating data and subtracting half of the hot water load data, 0.8 of the dryer load (if monitored), and any outside lighting data. These rough internal gains (for the days used in the analysis) for the combined set of homes display a marginally significant increase in the second year (~3%; $\alpha = 0.06$) over the first year. The MCS homes display the greatest increase at 7% ($\alpha = 0.09$) when compared to 1985-1986 heating season levels. The change in control homes is ~2%, but it is not statistically significant ($\alpha = 0.87$). A pairwise comparison of the difference between years for the MCS and base homes displays the strongest change between classes, but the difference is insignificant (α = 0.24).

How closely trends in actual, utilized internal gains follow those observed trends in the rough appliance internal gains is highly speculative. These rough data indicate that appliance gains most likely did not decrease in the second year and may have gone up a few percentages, overall. If solar availability and outside weather temperature were constant over both years, increased availability of internal gains from appliances would decrease all AEC estimates in the second year.

3.3 DIFFERENCES IN ANNUALIZED ESTIMATED CONSUMPTION FOR SPACE HEATING

Empirical construction of a standardized estimate for space-heating consumption is an ambitious task, given that the AEC is preferably a property of the structure independent of occupancy behaviors and weather conditions. To the extent that the various AEC estimates are stable from one heating season to the next, this goal has been achieved. In this section, the changes in the AEC_{iat}, AEC_{oat}, and AEC_{65} estimates are explored first for the combined set of homes and then for the individual case studies. Recommendations for enhancements to future work are suggested where weaknesses were observed.

3.3.1 General Trends for the Combined Set of Homes

Various annual space-heating consumption estimates for the combined set of homes are compared across the two heating seasons in Table 3.8. The mean population AECs are given for both total annual consumption and annual consumption divided by conditioned floor area for the two heating seasons, as well as the mean of the differences between years. The most obvious conclusions from Table 3.8 are as follows.

- Small, nonsignificant differences are observed across years for the total sample of homes whether AEC_{iat} or AEC_{iat}/ft^2 is considered. Mean AEC_{iat} changes -39 kWh/yr in the second year, which is -0.4% of the mean AEC_{iat} in the first heating season. The analogous difference for AEC_{iat}/ft^2 is 0.02 kWh/yr-ft^2.
- Significant differences are noted across years for the total population of homes if AEC_{oat} (α = 0.03) or AEC_{oat}/ft^2 (α = 0.05) is considered. A 354-kWh/yr drop occurs in the second year for

TABLE 3.8. Annualized Consumption for First-Year Estimates (1985-1986) and Second-Year Estimates (1986-1987). For both years, 127 homes were analyzed.

Sample	AEC_{iat}	AEC_{iat}/ft^2 (a)	AEC_{oat}	AEC_{oat}/ft^2	AEC_{65}	AEC_{65}/ft^2
Mean (Y2)	9940	6.30	9691	6.12	6989	4.38
Mean (Y1)	9979	6.28	10044	6.33	7396	4.62
Mean (Y2-Y1)	-39	0.02	-354	-0.21	-407	-0.23
100*Mean(Y2-Y1) / Mean (Y1)	-0.4%	0.4%	-3.5%	-3.3%	-5.5%	-5.0%
Significance	0.82	0.84	0.03	0.05	0.002	0.01
Standard Deviation Within Years						
AEC Y2	5506	3.41	5513	3.37	4520	2.62
AEC Y1	5338	3.21	5511	3.37	4340	2.52
Differences AEC Y2-AEC Y1	1955	1.26	1814	1.17	1442	1.01
Correlation (Y1,Y2)	0.94	0.93	0.95	0.94	0.95	0.92

(a) Units for AEC are in kWh/yr; units for AEC/ft^2 are in $kWh/yr\text{-}ft^2$.

AEC_{oat} (this drop represents a -3.5% change relative to the mean first-year level for AEC_{oat}). The drop in AEC_{oat}/ft^2 is -0.21 $kWh/yr\text{-}ft^2$ or -3.3% of the mean value for the first year.

- A highly significant difference is noted between years for the total population of homes when AEC_{65} (α = 0.002) or AEC_{65}/ft^2 (α = 0.01) is compared. A drop of 5.5% is noted when mean AEC_{65} is compared to the first-year level.

- Less variation is observed for the differences across years than for the measures within years (across sites). Correlations of the first- and second-year estimates are quite high, ranging from 0.92 to 0.95.

Scatter plots displaying the AEC_{iat}, AEC_{oat}, and AEC_{65} estimates for the combined sample of homes may be found in the Appendix H, Figures H.8 through H.10.

It appears that for the combined set of homes, the effects of increased solar availability and higher mean heating season inside air temperatures on AEC_{iat} do a good job of negating each other. (This is graphically depicted in Appendix H, Figure H.11. Increased solar availability in the second year is depicted as a downward shift in the LOWESS curve, while the increase in inside air temperatures can be viewed as a shift of the translated curve to the left. The net effect is little or no change in the curves.) When AEC_{oat} is considered, the impact of solar availability can be observed in isolation. Here, the overall effect is a drop in consumption of 3% to 5% depending on choice of AEC_{oat} or AEC_{oat}/ft^2 for the second year. The AEC_{65} is the estimate most strongly affected by the weather changes. Here the changes in solar availability bring the second-year estimate down, but with no compensating tendency for the mean inside air temperature to drift in the thermostat dead band.

3.3.2 Case Study Comparisons

In this section, comparisons are made within the base, MCS, and control case studies for the AEC_{iat}, AEC_{oat}, and AEC_{65} estimates. Pairwise population comparisons are also made to determine the minimum α level at which mean differences between the heating seasons are distinguished from one another.

3.3.2.1 General Comparison Performed for Base Study

Table 3.9 presents information, analogous to that found in Table 3.8, for 83 base homes. An insignificant increase in mean AEC_{iat} ($\alpha = 0.69$) and AEC_{iat}/ft^2 ($\alpha = 0.56$) of roughly 1% occurs in the second year. A decrease of roughly 2.5% is observed for the mean AEC_{oat} estimates in the second year. The α levels for accepting means as different from one another is quite high ($\alpha = 0.14$ and $\alpha = 0.12$) and is considered nonsignificant. The α levels are much lower, however, for the AEC_{oat} tests than for those associated with the AEC_{iat} estimates. The AEC_{65} estimates display the largest decrease for the base homes in the second year. Mean decreases in the second year, of 3.3% and 3.1%, are found for AEC_{65} and AEC_{65}/ft^2, respectively. The greatest significance is associated with the AEC_{65} change, but even this decrease is only marginally significant for the base homes.

The base homes do not show the strength of trends that the combined sample of homes indicates in Table 3.8. The magnitude of percentage for the trends observed in AEC_{iat}, AEC_{oat}, and AEC_{65} do, however, match those observed for the combined set of homes. From Table 3.9, the standard deviations within years are observed to be much larger than those computed for differences across years. As a result, the correlations of the first- and second-year estimates are quite high, ranging from 0.93 to 0.96. Scatter plots displaying the AEC_{iat}, AEC_{oat}, and AEC_{65} estimates for the base homes may be found in Appendix H, Figures H.12 through H.14.

TABLE 3.9. General Trends in Annualized Consumption for First-Year Estimates (1985-1986) and Second-Year Estimates (1986-1987) - 83 Base Homes Analyzed

Sample	AEC_{iat}	AEC_{iat}/ft^2 (a)	AEC_{oat}	AEC_{oat}/ft^2	AEC_{65}	AEC_{65}/ft^2
Mean (Y2)	11909	7.53	11670	7.35	8323	5.19
Mean (Y1)	11827	7.45	11958	7.55	8604	5.36
Mean (Y2-Y1)	82	0.08	-288	-0.19	-282	-0.17
100*Mean(Y2-Y1) / Mean (Y1)	0.7%	1.0%	-2.4%	-2.6%	-3.3%	-3.1%
Significance	0.69	0.56	0.14	0.12	0.07	0.13
Standard Deviation Within Years						
AEC Y2	5632	3.42	5633	3.37	4800	2.68
AEC Y1	5447	3.22	5631	3.40	4609	2.62
Differences AEC Y2-AEC Y1	1905	1.20	1769	1.13	1398	1.01
Correlation (Y1,Y2)	0.94	0.94	0.95	0.94	0.96	0.93

(a) Units for AEC are in kWh/yr; units for AEC/ft^2 are in $kWh/yr\text{-}ft^2$.

3.3.2.2 General Comparison Performed for Model Conservation Standards Study

In Table 3.10, the mean AEC estimates are displayed for the two heating seasons for the MCS homes. Roughly, an 8% change in AEC_{iat} is marginally significant (α = 0.10), an 11% change in AEC_{oat} is considered to be significant (α = 0.03), and a 17% change is considered to be a highly significant change in AEC_{65} (α = 0.004). The standard deviations found in Table 3.10 indicate less variation for differences across years than across sites within years. Correlations of the first- and second-year estimates remain reasonably high (0.75 to 0.82) but are somewhat less than those in the base case. Scatter plots displaying the AEC_{iat}, AEC_{oat}, and AEC_{65} estimates for the MCS homes may be found in Appendix H, Figures H.15 through H.17. The MCS homes appear to be very sensitive to changes in the weather, especially to available solar effects.

TABLE 3.10. General Trends in Annualized Consumption for First-Year Estimates (1985-1986) and Second-Year Estimates (1986-1987) - 29 Residential Standards Demonstration Program MCS Homes Analyzed

Sample	AEC_{iat}	AEC_{iat}/ft^2	AEC_{oat}	AEC_{oat}/ft^2	AEC_{65}	AEC_{65}/ft^2
Mean (Y2)	5340	3.24	5118	3.09	3761	2.28
Mean (Y1)	5816	3.50	5742	3.46	4539	2.73
Mean (Y2-Y1)	-476	-.26	-624	-0.36	-779	-0.44
100*Mean(Y2-Y1) / Mean (Y1)	-8.2%	-7.4%	-10.9%	-10.5%	-17.2%	-16.5%
Significance	0.10	0.12	0.03	0.03	0.004	0.003
Standard Deviation Within Years						
AEC Y2	1992	1.12	2062	1.13	1978	1.14
AEC Y1	2368	1.27	2407	1.32	2264	1.28
Differences AEC Y2-AEC Y1	1486	0.86	1445	0.86	1316	0.75
Correlation (Y1,Y2)	0.78	0.75	0.80	0.76	0.82	0.81

3.3.2.3 General Comparison Performed for Control Study

In Table 3.11, the mean AEC estimates are displayed for the two heating seasons for the control homes. It is difficult to draw many conclusions from this set of homes; it has a small sample size, high variation of the differences across years, and a sensitivity to floor area not observed in the previous AEC tables. None of the mean differences are even marginally significant. Furthermore, the percentage change varies considerably when floor area normalization is applied to the AEC estimates. The percentage decrease in the second year for AEC_{65} is -6.1%, which is relative to the first year, but drops to only -3.5% for AEC_{65}/ft^2.

Correlations of the estimates for the two years are moderate, ranging from 0.46 to 0.78. Most of the correlations are somewhat smaller than their counterparts for the base and MCS studies. Perhaps the big differences in operating strategies between the two years for this small set of homes is

TABLE 3.11. General Trends in Annualized Consumption for First-Year Estimates (1985-1986) and Second-Year Estimates (1986-1987) - 15 Residential Standards Demonstration Program Control Homes Analyzed

Sample	AEC_{iat}	AEC_{iat}/ft^2	AEC_{oat}	AEC_{oat}/ft^2	AEC_{65}	AEC_{65}/ft^2
Mean (Y2)	7935	5.42	7582	5.16	5850	3.99
Mean (Y1)	7802	5.15	7776	5.13	6232	4.14
Mean (Y2-Y1)	133	0.27	-194	0.03	-382	-0.15
100*Mean(Y2-Y1) / Mean (Y1)	1.7%	5.2%	-2.5%	0.6 of 1%	-6.1%	-3.5%
Significance	0.86	0.62	0.78	0.95	0.44	0.68
Standard Deviation Within Years						
AEC Y2	2831	2.11	2807	2.03	2748	2.00
AEC Y1	3203	1.79	3227	1.83	2796	1.63
Differences						
AEC Y2-AEC Y1	2863	2.05	2627	1.83	1852	1.35
Correlation (Y1,Y2)	0.56	0.46	0.63	0.55	0.74	0.78

responsible for the variation implied in Table 3.11. Comparing standard deviations for the AEC_{65} estimates to those for AEC_{iat} and AEC_{oat} provides some indication that part of the problem with these homes could be large swings in mean inside air temperatures for the heating seasons. This hypothesis is supported by Table 3.5, where the standard deviations of the differences in mean heating season inside air temperature are as high as the across site standard deviations for the other sample of homes. The causes of these temperature swings are not known, although it has been speculated that occupancy changes and/or sampling error could be at fault.

Scatter plots displaying the AEC_{iat}, AEC_{oat}, and AEC_{65} estimates for the control homes may be found in Appendix H, Figures H.18 through H.20.

3.3.3 Pairwise Comparisons

In Table 3.12, α levels are computed for pairwise comparisons of the percentage changes found in Tables 3.9 through 3.11. For these tests, scaling is employed to compensate for large absolute differences in total AEC for three sets of homes. Marginally significant differences are found for the scaled differences for both AEC_{65} (and AEC_{65}/ft^2) and AEC_{iat} (and AEC_{iat}/ft^2) when MCS and base homes are compared to one another. A significant change is found for AEC_{65} (and AEC_{65}/ft^2) for the MCS and base homes. The mean scaled change in AEC_{iat} for base homes of 0.7% is distinguished from the -8.2% mean change of the MCS homes at the α level 0.08. The mean scaled change in AEC_{oat} for base homes of -2.4% is distinguished from the -10.9% mean change of the MCS homes at the α level 0.09. The largest and most significant pairwise change is for the AEC_{65} estimates. The decrease in the base homes of 3.3% and the decrease by 17.2% for the MCS homes are distinguished at $\alpha = 0.05$. No significance is associated with a test involving the control homes.

3.3.4 Errors in Annualized Estimated Consumption Calculations

A measure of discrepancy between a local AEC_{iat} and the metered heating data is computed at each site for each heating season. This measure of discrepancy or error helps illustrate why the AEC_{iat} values are closer to one another for the combined set of homes and the base homes, than for the MCS

TABLE 3.12. Significance Level for 100*(AEC Y2-AEC Y1)/Mean(AEC Y1) for Pairs of Studies by Annualized Estimated Consumption Type

Sample	Base and MCS	MCS and Control	Base and Control
AEC_{iat}	0.08	0.36	0.92
AEC_{iat}/ft^2	0.09	0.27	0.69
AEC_{oat}	0.09	0.40	0.99
AEC_{oat}/ft^2	0.11	0.29	0.74
AEC_{65}	0.05	0.25	0.72
AEC_{65}/ft^2	0.02	0.20	0.96

homes over the two heating seasons. The local AEC_{iat} is computed exactly as the AEC_{iat} except the outside locally measured weather data at the site is used. Table 3.13 displays the median and mean percentage discrepancies.

In most cases, the local AEC_{iat} overestimates the metered space-heating data. The mean errors are quite a bit larger than the median errors. This is because the mean is sensitive to the impact of a few homes with large over-estimation problems, whereas the median is not. Errors clearly occur more frequently in the 1986-1987 season. This is probably because of a greater tendency for the internal temperature to drift in the thermostat dead band during the second year. The mean difference between years is highly significant (α = 0.009) for the combined set of homes. When the α level is computed for the difference between the two heating seasons for the base, MCS, and control homes, the only significant case study result that can be established is for the base homes (α = 0.04). No other significant differences between pairs of case studies can be established.

The average overestimation for the base homes in the second heating season was almost twice that for the first year. This overestimation is large enough to cover a big part of the decrease in consumption that the AEC_{iat} would predict because of increased solar availability in the second year. The overestimation in the MCS homes, although larger than the base homes, certainly did not double in the second year. If it had, the overestimation would

TABLE 3.13. Discrepancy Between Local AEC_{iat} and Metered Data (%)

Season	Combined Homes		Base Homes	
	Median	Mean	Median	Mean
1986-1987	1.84	4.26	1.72	3.51
1985-1986	1.19	2.50	0.70	1.83
Change	0.65	1.76	0.92	1.69

Season	MCS Homes		Control Homes	
	Median	Mean	Median	Mean
1986-1987	2.87	5.68	1.84	5.68
1985-1986	2.93	4.08	3.22	3.19
Change	0.56	1.60	0.77	2.49

have come closer to compensating for the lower space-heating requirements from increased solar availability in the second year.

An important question concerns the propagation of errors for a given site over the years. If AECs are to be computed over more than one year, it is desirable that errors in local AEC_{iat} not be highly correlated from year to year. Table 3.14 indicates that while the errors are not highly correlated from year to year (except for the control homes), some moderate positive correlation does exist. This may indicate some bias in the technique--or it may be that not enough years have been sampled.

3.4 DIFFERENCES IN PARAMETERS FROM THE LINEAR FIT

In this section, mean differences between heating seasons for the slope and intercept parameters, derived from the various linear fits of daily space-heating data to the inside-outside air temperature and outside air temperature, are summarized. The mean differences for the slope parameter are typically nonsignificant and small in absolute magnitude. The mean differences between years for intercepts are statistically significant only if inside-outside temperature difference is the predictor variable and the MCS homes are included in the sample of homes analyzed. For the combined set of homes, the

TABLE 3.14. Comparison of Standard Deviations for Local AEC_{iat} Errors Within Years and Across Years for All Common Sites by Case Study

Sample	Combined	Base	MCS	Control
Standard Deviation Within Years				
1985-1986	7.58	7.02	7.78	9.91
1986-1987	4.78	4.89	4.80	3.28
Differences				
ErrY2-ErrY1	7.47	7.38	7.69	8.06
Correlation (Y2,Y1)	0.34	0.27	0.33	0.68

relative differences observed in the AEC estimates closely match the cumulative relative differences associated with parameters from the linear fits.

3.4.1 Changes in As-Operated Effective Conductances

The slopes from the linear fits of heater to inside-outside temperature difference can be interpreted as the heat loss coefficient for the home divided by the heating system efficiency. This as-operated UA implicitly contains rough adjustments from room closures as well. Since UAs can be interpreted as a measure of thermal integrity, stability across years is an important consideration. Table 3.15 displays the slopes (or as-operated UAs) from the standard, robust with cutoff and midrange fits of heater loads to inside-outside temperature difference. Very small absolute changes are noted, which are insignificant for the combined set of homes and the case study homes. Normalizing the slopes by floor area similarly produces negligible, nonsignificant changes. (Appendix H, Figures H.21 through H.24 compares the as-operated UAs from the standard temperature difference linear fits over the two heating seasons for the four collections of homes.)

In Table 3.16, the slopes (or as-operated UAs) from the standard, robust with cutoff, and midrange fits of heater load to outside air temperature are displayed. Again, little significance is associated with the changes in mean slopes for the combined set of homes or the case study homes. The one exception is the MCS robust slope, which displays a marginally significant drop in the mean of 10% (or -26 Btu/hr-°F) in the second year.

TABLE 3.15. First-Year and Second-Year Comparison of Mean Differences in As-Operated Effective Conductances. The various first-year second-year fits of heater-to-temperature differences are study type (BTU/hr-°F).

Sample	Combined	Base	MCS	Control
Size	127	83	29	15
Standard Fit				
Mean (Y1)	369.4	418.0	253.8	323.8
Mean (Y2-Y1)	-2.9	-3.1	-4.3	1.4
Significance	0.67	0.70	0.73	0.96
Robust Fit				
Mean (Y1)	371.6	420.1	257.0	321.0
Mean (Y2-Y1)	-1.2	2.3	-9.0	13.3
Significance	0.88	0.79	0.46	0.63
Middle Fit				
Mean (Y1)	393.0	438.5	281.6	356.8
Mean (Y2-Y1)	-6.7	-7.2	0.5	-17.8
Significance	0.48	0.52	0.98	0.57

As noted in Section 2.0, Second-Year Analysis, slopes from linear fits based on outside air temperature give lower estimates for as-operated UAs than do slopes from linear fits to inside-outside temperature differences. Also, the midrange fits give the maximum as-operated UAs, regardless of the choice of predictor variable. These relations hold true in the mean for both heating seasons.

When pairwise comparisons are made, no significant differences are found between the base, MCS, or control homes for the as-operated UA from any of the delta temperature-based (ΔT) fits. For the outside air temperature-based fits, marginally significant levels ($\alpha = 0.09$) of change are noted in comparing the mean robust slopes of the base and MCS homes. Other pairwise comparisons are insignificant.

3.4.2 Balance Points and Intercepts from the Linear Fits

The changes in the intercepts from the various linear fits of heater load to inside-outside temperature difference indicate some significant changes over the two heating seasons. This is in contrast to the slopes from

TABLE 3.16. First-Year and Second-Year Comparison of Mean Differences in As-Operated Effective Conductances. The various fits of heater-to-outside air temperature are study type (BTU/hr-°F).

Sample	Combined	Base	MCS	Control
Size	127	83	29	15
Standard Fit				
Mean (Y1)	332.5	380.7	224.9	272.9
Mean (Y2-Y1)	-6.4	-5.4	-9.9	-5.4
Significance	0.37	0.56	0.39	0.83
Robust Fit				
Mean (Y1)	345.1	392.5	246.0	274.3
Mean (Y2-Y1)	-8.2	-3.1	-26.4	-1.3
Significance	0.26	0.74	0.05	0.96
Middle Fit				
Mean (Y1)	362.6	408.6	261.9	302.9
Mean (Y2-Y1)	0.35	3.9	-13.2	6.9
Significance	0.97	0.76	0.42	0.85

the same fits which, on the average, show small, nonsignificant changes. The intercept or balance temperature difference can be interpreted as the inside-outside temperature difference that the structure can support without use of the space-heating equipment. Table 3.17 summarizes the changes for the intercepts from the standard fits of heater load to temperature difference. These intercepts experience the most significant overall change. Table 3.17 indicates a trend for the intercepts to be larger in the second year. The largest and most significant changes are associated with the MCS homes. The increase in intercepts is a response to the weather rather than increased thermal integrity of the structures. Higher inside air temperatures in the second year would have a tendency to move the intercepts in the direction observed. Scatter plots comparing these temperature-difference based intercepts from standard fits are located in Appendix H, Figures H.25 through H.28.

In Table 3.18, changes in intercepts from the standard fit of heater load to outside air temperature are displayed. These intercepts are interpreted as building balance points. A building balance point is the outside air temperature below which space heating is normally required. The mean

TABLE 3.17. Differences for the Intercepts from the Standard Delta Temperature Fits by Study Type (°F)

Sample	Combined	Base	MCS	Control
Mean (Y1)	10.2	9.5	12.0	10.6
Mean (Y2-Y1) (°F)	0.75	0.41	1.5	1.2
Significance Level	0.003	0.18	0.008	0.14
Standard Deviation Within Years				
Y2	4.207	4.203	3.052	3.959
Y1	4.330	4.626	3.059	3.802
Differences	2.827	2.743	2.863	3.053
Correlation (Y1,Y2)	0.78	0.81	0.56	0.69

downward change in the intercepts for the second year implies added thermal integrity as did the upward shift in balance ΔTs. However, the α levels associated with these changes indicate that they are insignificant.

In Table 3.19, pairwise population comparisons are made for the changes in the intercepts from the standard ΔT-based fits and the standard outside air temperature-based fits. In general, when outside air temperature is the predictor variable, smaller, less significant changes are observed in the intercepts. The differences between change levels for the MCS and base homes are marginally significant (α = 0.07).

3.4.3 Comparison of Changes in Annualized Estimated Consumption and Parameters from Linear Fits

The AEC_{iat} estimate is implicitly related to the parameters derived from the linear fit of space heating to inside-outside temperature difference. Similarly, the AEC_{oat} estimate is implicitly related to the parameters derived from the linear fit of space heating to outside air temperature. The line, parameterized by its slope and intercept, is more or less embedded in the LOWESS relation that is used along with the standard weather year to calculate the AEC estimates. Thus, in some sense, the changes in the AEC estimate incorporate changes in the slope and intercept simultaneously thus providing greater change amplification and statistical significance than either linear fit parameter could produce singly.

TABLE 3.18. Differences for the Intercepts from the Standard Outside Air Temperature Fits by Study Type (°F)

Sample	Combined	Base	MCS	Control
Mean (Y1)	60.3	61.5	57.6	58.6
Mean (Y2-Y1) (°F)	-0.32	-0.42	-0.44	0.46
Significance Level	0.35	0.27	0.50	0.78

TABLE 3.19. Significance Level for Differences in Intercepts from Standard Fits by Predictor Variable for Pairs of Studies

Sample	Base and MCS	MCS and Control	Base and Control
Delta Temperature	0.07	0.77	0.33
OAT	0.98	0.61	0.60

The relation between AEC and the linear fit parameters may be made more explicit by an analogy to standard engineering methods for computing annual heating loads. In the standard HDD method, annual heating requirements, E, are predicted by multiplying building UA by HDDs computed to some base temperature, such as 65°F (E = UA * HDD). The empirical version of this standard engineering equation is produced by three substitutions:

- The AEC is substituted for the engineering space-heating estimate, E.
- The standard fit as-operated UA is substituted for building UA, although the as-operated UA includes factors not contained in the building UA.
- The HDD is replaced by effective HDDs calculated using the standard linear fit intercept.

The intercept from the outside air temperature-based fit may be used as the base temperature along with the standard outside weather year data to compute an effective HDD value. The intercept from the inside-outside air temperature-based fit (once subtracted from the mean heating season inside air temperature) may also be used as the base temperature. Table 3.20 summarizes the changes in effective HDDs between the heating seasons for the combined set

TABLE 3.20. Differences in Effective Heating-Degree Days Using Intercepts from the Standard Fits to Both Predictor Variables

Predictor Variables	Combined	Base	MCS	Control
Delta Temperature (HDD)				
Mean (Y2-Y1)	-35	-18	-166	-128
Difference scaled by Y1	-0.8%	-0.5%	-5%	-3%
Significance level	0.64	0.84	0.18	0.70
OAT-Based (HDD)				
Mean (Y2-Y1)	-93	-133	-134	168
Difference scaled by Y1	-2%	-3%	-3%	4%
Significance level	0.36	0.26	0.53	0.72

of homes from two HDD computations. The intercepts used in the calculation are both from the standard fits to inside-outside air temperature and outside air temperature. The absolute magnitude of changes are all less than 5% of the first-year level for the two types of HDD calculations. The mean differences in effective HDDs are insignificant. Absolute changes are greater and more consistent for the MCS homes. The effective HDDs computed from the outside air temperature balance points tend to be larger by 200- to 400-degree days for these homes. The direction of the change switches, for the control homes, depends on the choice of predictor variable in the original linear model. Although neither of the changes for the control homes is statistically significant, the switch indicates the need for further study of the inside air temperature strategies being used in the control homes.

Table 3.21 illustrates that mean estimates for the combined set of homes closely satisfy the relation where AEC equals the product of as-operated UAs and effective HDDs. This is true for both types of predictor variables and for each heating season. The AECs tend to be 1% to 2% lower than the product of as-operated UAs and effective HDDs.

In Table 3.22, steps 2 through 5 illustrate how changes in the as-operated UA and effective HDDs both contribute to the changes in AEC (as expected). If the first year is selected as the reference year, then the percentage change in AEC should be roughly equal to the percentage change in as-operated UAs plus the percentage change in effective HDDs.

TABLE 3.21. Comparison of Annualized Estimated Consumptions and the Product of As-Operated Effective Conductance and Effective Heating Degree Days by Year and Predictor Variable, Means for 127 Homes

Predictor Variables	AEC	As-Operated UA * HDD
Delta Temperature		
1986-1987	9,940	10,140
1985-1986	9,979	10,130
Outside Air Temperature		
1986-1987	9,691	9,932
1985-1986	10,044	10,109

In Table 3.23, AEC_{iat} and AEC_{oat}, along with their respective (standard) linear fit-based parameters, are substituted into the last expression of Table 3.22. The mean changes for both inside-outside temperature based analyses and outside temperature based analyses indicate the changes in AEC_{oat} and AEC_{iat} are within half a percent of the sum of mean changes for the slope and intercept-based HDD parameters. This exercise displays a general agreement for the relative changes averaged over the combined group of homes for the AEC estimate and the parameters from the linear fit.

TABLE 3.22. Method for Reconciling Changes in the Derived Thermal Parameters

Step Number	Calculation
1	$AEC = asopUA * HDD$
2	$\Delta AEC = \Delta(asopUA * HDD)$
3	$d(AEC) = HDD*d(asopUA) + asopUA*d(HDD)$
4	$\frac{d(AEC)}{AEC} = \frac{d(asopUA)}{asopUA} + \frac{d(HDD)}{HDD}$
5	$Error = \frac{d(AEC)}{AEC} - \left[\frac{d(asopUA)}{asopUA} + \frac{d(HDD)}{HDD} \right]$

TABLE 3.23. Change Over the Combined Set of Homes for the Two Predictor Variables with Percentage Changes Relative to the 1985-1986 Season

Sample	Error	=	AEC	-	[Slopes (S)	+	HDD (S)]
OAT	0.4%		-3.5%		-1.9%		-2%
Delta Temperature	0.4%		-0.4%		-0.007%		-0.8%

4.0 PHYSICAL MODELS FOR ASSESSING HEATING SYSTEM PERFORMANCE

4.1 INTRODUCTION

This section describes the results of analyses designed to assess the impact of heating system and foundation type on the thermal performance of residential structures. The analyses are based on a widely used model that expresses electrical energy usage for space heating as a function of HDDs, the heat loss coefficient for the structure, and the efficiency of the heating system. In theory, the influence of foundation type is accounted for by the heat loss coefficient or nameplate UA; hence, in its usual formulation, the model mentioned above does not explicitly include terms for foundation effects. Heating system efficiency, on the other hand, is an explicit component of the model.

Given that the primary objectives of these analyses are to assess the relative performances of various electrical heating systems as well as to quantify any foundation effects not captured by the nameplate UA, an expanded empirical model is used to test for both types of effects. The empirical model also allows the determination of power transformations of the nameplate UA and HDDs which are optimal with respect to the prediction of electrical consumption for space heating.

Previous analyses (see Section 1.0, First-Year Analysis, and Section 2.0, Second-Year Analysis) have displayed a marked tendency for as-operated UAs to be lower than nameplate UAs (indicating that actual heat loss tends to be less than predicted by nameplate UAs), even before correcting the nameplate UAs for infiltration. It has been postulated that these differences may be from differences in heating system types or foundation types. Preliminary analyses reported in Section 1.4 suggest that such differences do exist and indicate a need for further study.

4.2 DIFFERENCES THAT COINCIDE

In this study, differences that appear to coincide with differences in heating systems and/or foundation types are examined in greater detail. Where possible, the factors which may account for such differences are speculated.

In theory, only differences related to heating system choice would be expected, since a correction for foundation type is included in the computation of the nameplate UA. In fact, it is noted that residual effects still appear to be related to both heating system and foundation type.

The objectives of the analyses described below are as follows:

- Investigate the existence of any heating system and foundation interactive effects on residential thermal performance.
- Assess the relative performances of various electrical heating systems on residential thermal performance.
- Quantify any foundation effects not captured by the foundation component of nameplate UA.
- Investigate the empirical relation of nameplate UA and HDD balance temperature to AEC.

The results of these analyses are useful for quantifying the average energy savings that might be achieved by changing the penetration rate for a particular heating system. Results also suggest refinements for estimating the annual heating load at a given residence.

4.3 SAMPLE CHARACTERISTICS

The sample of homes used to fit the models described in this document was drawn from that subset of the ELCAP RSDP and residential base samples used in the 1986-1987 heating season thermal characterizations (see Section 2.0, Second-Year Analysis). A site was included in the analysis only if all data relevant to the models described in this document were available (i.e., AEC, nameplate UA, HDD temperature balance, electric heating system most used, and foundation type), and the foundation was from a pure rather than mixed category type. This selection process resulted in a total sample of 107 sites. The partitioning of this sample by heating system and foundation type is given in Table 4.1.

As noted below, heating system and foundation type are not the only factors which may be related to AEC. Factors such as climate zone or study group (i.e., base or RSDP; both types of homes are included in the analyzed sample) may be important correlates of AEC as well. As is evident from

TABLE 4.1. Sample Partition

Sample	Forced Air	Baseboard	Radiant	Heat Pump
Crawlspace	14	31	6	10
Heated Basement	6	18	1	0
Unheated Basement	3	3	1	0
Slab	3	10	1	0

Table 4.1, the limited sample available for the present study precludes the assessment of all factors which might be relevant to the analysis.

4.4 METHODOLOGY

The analyses described below are motivated by the following relation, which is derived from the fundamental heat balance equation:

$$AEC = \frac{C \cdot UA(np) \cdot HDD(Tb)}{COP(hs)} \tag{4.1}$$

where AEC = annualized estimated consumption
C = constant product of a unit conversion factor (0.007)
COP = coefficient of performance
HDD = heating degree days
UA = heat loss coefficient
hs = heating system
np = nameplate
Tb = balance temperature

Of these quantities, AEC, UA(np), and HDD(Tb) have been estimated in prior analyses (see Section 2.0, Second-Year Analysis). Equation (4.1) is the same as that used by BPA in its Standard Heat Loss Methodology (see Volume I, Miller et al. 1990).

For a given residence, the AEC may be interpreted as an estimate of the annual heating load under standardized weather and operating conditions without nonelectric supplemental space heat. While a first-order setback adjustment has been incorporated into the AEC, no correction has been attempted for zoning. Internal and solar gains are not explicitly treated, even though they are reflected in the measured load data. Computation of the AEC for a given residence is based on an empirical, nonparametric LOWESS fit of the daily metered space-heating loads to corresponding daily inside-outside temperature differences (see Volume I, Miller et al. 1990). Applying the results to temperature differences generated by TMY data and an average measured inside air temperature over the heating season yields the AEC. The HDDs are based on the nonnegative differences between an empirically derived balance temperature and observed TMY temperatures (see Section 2.0, Second-Year Analysis). The building balance point is estimated by subtracting the temperature difference intercept of a least squares fit to the metered load and temperature difference data from the average heating season inside air temperature.

As defined above, Equation (4.1) presupposes the separability of foundation and heating system effects; that is, the improvement or degradation in thermal performance associated with a particular heating system is assumed to be constant across foundation types. Conversely, the improvement or degradation in thermal performance associated with a particular foundation type is assumed to be constant across heating systems. In order to test these assumptions, an expanded model was employed:

$$\mathrm{AEC} = \frac{C \bullet \mathrm{UA(np)} \bullet \mathrm{HDD(Tb)}}{\mathrm{COP(hs)} \bullet \mathrm{EFF(fd)} \bullet \mathrm{EFF(hs,fd)}} \qquad (4.2)$$

Here EFF(fd) is the effect of the foundation type and EFF(hs,fd) is the interactive effect of hs and fd. Note that Equation (4.1) is obtained by setting the additional parameters equal to 1. Dividing through by UA(np) and HDD(Tb), and taking the natural logarithm of both sides yields the linear (mean) model:

$$\begin{aligned}\ln[\mathrm{AEC/UA(np)} \bullet \mathrm{HDD(Tb)}] = {} & \ln(C) - \ln[\mathrm{COP(hs)}] - \ln[\mathrm{EFF(fd)}] \\ & - \ln[\mathrm{EFF(hs,fd)}]\end{aligned} \qquad (4.3)$$

Upon choosing a heating system and foundation as a standard for comparison, the latter model has the form of a two-way analysis of variance (ANOVA), including interaction terms. This allows for the testing of whether or not the heating system and foundation effects are separable (i.e., additive in the linear model), in which case EFF(hs,fd) = 1 for all heating systems and foundation types. In the present application, the following standardizations

$$COP(FA) = EFF(CS) = EFF(FA,fd) = EFF(hs,CS) = 1 \qquad (4.4)$$

occur where FA denotes forced air and CS denotes crawlspace. Referring to Table 4.1, it is clear that the EFF(HP,fd), interactions are not estimable, because of the absence of sites in three of the four HP cells. A test of the estimable interactions was significant at the 0.0007 level, indicating that the interactions cannot be ignored, hence, the heating system and foundation effects are not separable in the proposed model.

4.5 A SIMPLIFIED INTERACTIVE MODEL

Because of the difficulty of interpreting the results of a standard ANOVA with significant interactions, a simpler (but equivalent) analysis was performed in which the denominator

$$COP(hs) \cdot EFF(fd) \cdot EFF(hs,fd) \qquad (4.5)$$

of Equation (4.2) was replaced by the single parameter COP(hs,fd). This approach is simply estimating the joint efficiency of each heating system and foundation combination without attempting to separate the heating system and foundation contributions. This model is constrained by COP(FA,CS) = 1; that is, forced air homes with crawlspace foundations are taken as the basis for comparison, and are arbitrarily assigned an efficiency rating of 1.

The results of fitting the simplified interactive model are displayed in Table 4.2. Column one displays the heating system and foundation combination, column two displays the associated coefficient of performance (relative to forced air [FA], crawlspace [CS]), and column three provides the associated sample size. The remaining columns indicate the results of performing pairwise significance tests for the various joint COPs. The Xs in a given column identify a set of heating system and foundation combinations for which no two combinations were judged to be significantly different at the 0.1 level. In

TABLE 4.2. Heating System and Foundation Regression Results

Heating System[a] Foundation Type	COP	n	Pairwise Groupings (level = 0.1)						
FA.UB	0.976	3	X						
FA.CS	1.000	14	X						
BB.SLAB	1.133	10	X						
RAD.CS	1.145	6	X	X					
FA.SLAB	1.290	3	X	X	X				
BB.UB	1.367	3	X	X	X	X			
BB.CS	1.435	31		X	X		X		
HP.CS	1.637	10			X			X	
BB.HB	1.802	18				X		X	
FA.HB	1.958	6				X		X	
RAD.SLAB	2.006	1			X	X	X	X	
RAD.HB	2.107	1			X	X	X	X	X
RAD.UB	4.276	1							X

C = .00413
R-square = .410
eR-square = .365

(a) FA = Forced Air
BB = Baseboard
RAD = Radiant
HP = Heat Pump
UB = Unheated Basement
HB = Heated Basement
CS = Crawlspace
SLAB = Slab-on-grade

any study involving as many comparisons as made here, the ideal approach is to set a simultaneous level of significance against which all comparisons will be tested. This level of significance asserts that among all comparisons made, the probability of one or more Type-1 errors is controlled at the 0.1 level. In the present case, however, the relatively small sample sizes preclude a simultaneous approach, and the reader is cautioned that the

0.1 level refers only to the individual pairwise tests; the simultaneous level for all such tests has not been controlled.

4.6 HEATING SYSTEM AND FOUNDATION COMBINATIONS

Table 4.2 is designed to display the estimated COPs for the various heating system and foundation combinations and to indicate where significant differences occur. Each column of Xs represents a maximal subgroup of the heating system and foundation combinations for which no pair is significantly different. To determine the set of all other combinations, which are not significantly different for a fixed combination, one must look across columns. The union of all columns containing an X for the combination of interest will form this set. To indicate how the table can be used, consider the heat pump and crawlspace combination (HP.CS). The HP.CS is included in the third and sixth pairwise groupings, as indicated by the Xs appearing in the HP.CS row beneath the groupings. The HP.CS COP is not significantly different from the COP for any combination occurring in either grouping but is significantly different from the COP for each combination not occurring in either grouping. For example, FA.SLAB, BB.UB, and BB.CS are all members of the third grouping. Thus, their estimated COPs are not significantly different from the estimated COP for the HP.CS. In fact, no two members of the third group have significantly different COPs. Similarly, BB.HB, FA.HB, RAD.SLAB, and RAD.HB are all members of the sixth grouping, so their estimated COPs do not differ significantly from those for HP.CS (nor do they differ from each other). All remaining combinations (FA.UB, FA.CS, BB.SLAB, RAD.CS, RAD.UB) have estimated COPs, which do differ significantly from that for HP.CS.

Table 4.2 represents the proportion of variance explained in the log-linear version of Equation (4.2) with the denominator replaced by COP(hs,fd). The fact that the relatively low value of the R-square statistic is not truly reflective of the strength of the relation among the variables in the model is discussed in Section 4.7, An Empirical Model. Because the COPs are reported in the original scale (i.e., COPs are found by exponentiating the estimated coefficients from the log-linear model), an empirical R-square (denoted eR-square) has been computed for that scale as well.

The most obvious trend suggested by Table 4.2 is that heated basements appear to be associated with the higher COPs. More subtle trends can be noted by fixing either heating system type or foundation type and observing the ordering of COPs associated with the other factor. Accordingly, considered below is the ordering of COPs by foundation type when the heating system is fixed as forced air or baseboard heat, and the ordering of COPs is fixed by heating system when the foundation is fixed as a crawlspace or heated basement. Because of the imprecision inherent in small sample sizes, cases have been restricted to those where n > 6.

4.6.1 Crawlspace Foundations

For crawlspace foundations, the ordering, with respect to heating systems, can be depicted as follows:

$$\text{CS:}\quad \underset{n = 14}{\text{FA }(1.000)} < \underset{n = 6}{\text{RAD }(1.145)} < \underset{n = 31}{\text{BB }(1.435)} < \underset{n = 10}{\text{HP }(1.637)} \tag{4.6}$$

Because electric forced air homes with crawlspace foundations were taken as the basis for comparison, their relative efficiency is, by definition, 1. To illustrate the interpretation of the remaining efficiencies, note that the efficiency of radiant heating, relative to electric forced air, is 1.145. Accordingly, radiant systems are estimated to be 14.5% more efficient than forced air systems. The underlining identifies groups of heating systems for which all pairwise COPs are not significantly different; thus, the only significant difference noted is FA < HP. The superior performance of heat pump systems is consistent with the mild nature of the 1986-1987 heating season upon which these results are based, as well as the design efficiencies in the heat pump systems themselves. The poor performance of forced air systems relative to radiant and baseboard heating systems may be from heating duct losses combined with a reduced zoning potential.

4.6.2 Heated Basement Foundations

The heating system ordering is for heated basement foundations

$$\text{HB:}\quad \underset{n\,=\,18}{\text{BB }(1.802)} < \underset{n\,=\,6}{\text{FA }(1.958)} \qquad (4.7)$$

Although the COP estimates differ, the difference is not statistically significant. If the difference were significant, it would be difficult to explain, given that a baseboard heating system is generally easier to zone. (Heating duct loss is probably not an important factor here, as heated basements tend to recapture such losses.) This suggests that the observed difference may be from sampling error or the influence of some uncontrolled factor such as the climate zone.

4.6.3 Forced Air Heating Systems

Forced air heating systems impose the following ordering of COPs by foundation type

$$\text{FA:}\quad \underset{n\,=\,14}{\text{CS }(1.000)} < \underset{n\,=\,6}{\text{HB }(1.958)} \qquad (4.8)$$

The absence of underlining indicates that the difference in COPs is statistically significant. The difference can perhaps be attributed to the potential for zoning off the basement and for the recovery of heating duct losses in the basement.

4.6.4 Baseboard Heating Systems

For baseboard heating systems, the ordering of COPs by foundation type is

$$\text{BB:}\quad \underset{n\,=\,10}{\text{SLAB }(1.133)} < \underset{n\,=\,31}{\text{CS }(1.435)} < \underset{n\,=\,18}{\text{HB }(1.802)} \qquad (4.9)$$

Again, the absence of underlining indicates that each pair of COPs is significantly different. The superior performance of heated-basement homes is possibly explained by the ability to zone off the basement, while the inferior performance of slab homes may be from a greater potential for heat loss through the foundation.

4.7 AN EMPIRICAL MODEL

The generalization of Equation (4.2), which we will refer to as an empirical model, is given by

$$AEC = \frac{C\ [UA(np)]^{a}[HDD(Tb)]^{b}}{COP(hs)\cdot EFF(fd)\cdot EFF(hs,fd)} \qquad (4.10)$$

The difference between the two models lies in the assumptions regarding exponents a and b. In Equation (4.2), the assumption is made that a = b = 1. In the above model, a and b are included as unknown parameters. Taking the natural logarithm of both sides yields

$$\ln(AEC) = \ln(C) + a\ \ln[UA(np)] + b\ \ln[HDD(Tb)] - \ln[COP(hs)] - \ln[EFF(fd)] - \ln[EFF(hs,fd)] \qquad (4.11)$$

The latter equation has the form of a standard analysis of covariance (mean) model. Thus the unknown parameters, including a and b, can be estimated using least squares techniques. As in the analysis described above, the interaction effects are found to be highly significant ($p = 0.0009$), and the simpler (but equivalent) model

$$\ln(AEC) = \ln(C) + a\ \ln[UA(np)] + b\ \ln[HDD(Tb)] - \ln[COP(hs,fd)] \qquad (4.12)$$

is fit to facilitate interpretation. The results of this analysis are given in Table 4.3.

Comparing the COPs from Table 4.2 with those of Table 4.3 indicates general agreement for combinations with sample sizes greater than 5. Although the COPs for the pairs RAD.CS and BB.SLAB and BB.HB and HP.CS are interchanged, this is of little consequence because neither pair is significantly

TABLE 4.3. Heating System and Foundation Coefficients of Performance, Empirical Model

Heating System Foundation Type	COP	n	Pairwise Groupings (level = .1)					
FA.UB	0.972	3	X	X				
FA.CS	1.000	14	X					
RAD.CS	1.053	6	X	X				
BB.UB	1.281	3	X	X	X			
BB.SLAB	1.299	10		X		X		
FA.SLAB	1.438	3		X	X	X	X	
BB.CS	1.440	31			X	X		
RAD.SLAB	1.621	1	X	X	X	X	X	
BB.HB	1.638	18			X		X	
HP.CS	1.648	10			X		X	
FA.HB	1.810	6					X	
RAD.HB	1.922	1			X	X	X	X
RAD.UB	3.516	1						X

(a) a = 0.972; b = 0.684; C = 0.065; R-square = 0.749; eR-square = 0.661

different under either model. The instability of the remaining estimates is likely to be from sampling error.

The difference in the R-square statistics (0.410 in Table 4.2 and 0.749 in Table 4.3) at first seems startling. It must be remembered, however, that the dependent variable differs for the two tables. In Table 4.2, the dependent variable in the log-linear model is ln[AEC/UA(np)•HDD(Tb)], whereas in Table 4.3 the dependent variable is simply ln[AEC]. Because the former quantity has already been adjusted for UA(np) and HDD(Tb), there is less variance to explain and fewer predictors with which to explain it. A more equitable comparison focuses on the variance not explained by the two models; i.e., their mean square errors (MSEs). As expected, the MSE for Table 4.2 (0.0858) is less than that for Table 4.3 (0.0965); thus, allowing optimal power transformations of UA(np) and HDD(Tb) to reduce the MSE by about 11%.

It is interesting to examine the estimates for the parameters a and b. At 0.972, the estimate for a is very near the theoretically predicted value of 1. On the other hand, the estimated value of b = 0.648 is much lower than 1, reflecting a substantial downweighting of the influence of HDD(Tb) on AEC. Both estimates are highly significant. The physical interpretation of b is not clear because of the obvious unit conversion problem.

5.0 REFERENCES

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APPENDIX A

FIRST-YEAR ANALYSIS - ACCEPTANCE AND REJECTION OF SITES

APPENDIX A

FIRST-YEAR ANALYSIS - ACCEPTANCE AND REJECTION OF SITES

Of the roughly 440 End-Use Lead and Consumer Assessment Program (ELCAP) residential studies homes, 339 homes were tracked for data availability and suitability for the thermal analysis workups. These 339 homes include case study homes but not Residential Standards Demonstration Program (RSDP) homes. This section makes an accounting for those 339 homes. The different analysis categories that the homes were partitioned into are explained below. The percentage of sites falling into each category is given to provide several ways of aggregating the 339 sites. Several scatter plots of space-heating data versus indoor-outdoor temperature difference are displayed from the different analysis categories.

Tracking the 339 homes was made manageable by defining several categories and awarding homes with the appropriate number of points. These 10 analytical categories relate the analysis constraints applicable for a given site. The 10 categories are explained below.

CATEGORY ONE

Sites in category 1 are included in the reporting of final results. After removal of vacation and wood-burning days (if possible), these homes had enough points to continue with the analysis. The scatter plots of daily heater versus inside-outside temperature difference had a fairly linear shape, as opposed to a wedge or an upside down V-shape. Sites without an ELCAP woodstove sensor that report the use of wood-burning equipment in the house are placed in this category if the distortion in the scatter plot of space heating versus inside-outside temperature difference appears to be small. These sites are also placed in this category if the scatter plot exhibited a linear rather than a wedge-like shape (typical on many such scatter plots where the heating load in the residence has been supplemented with wood). Figure A.1 displays the scatter plot of a category-1 site. This site was selected at random from

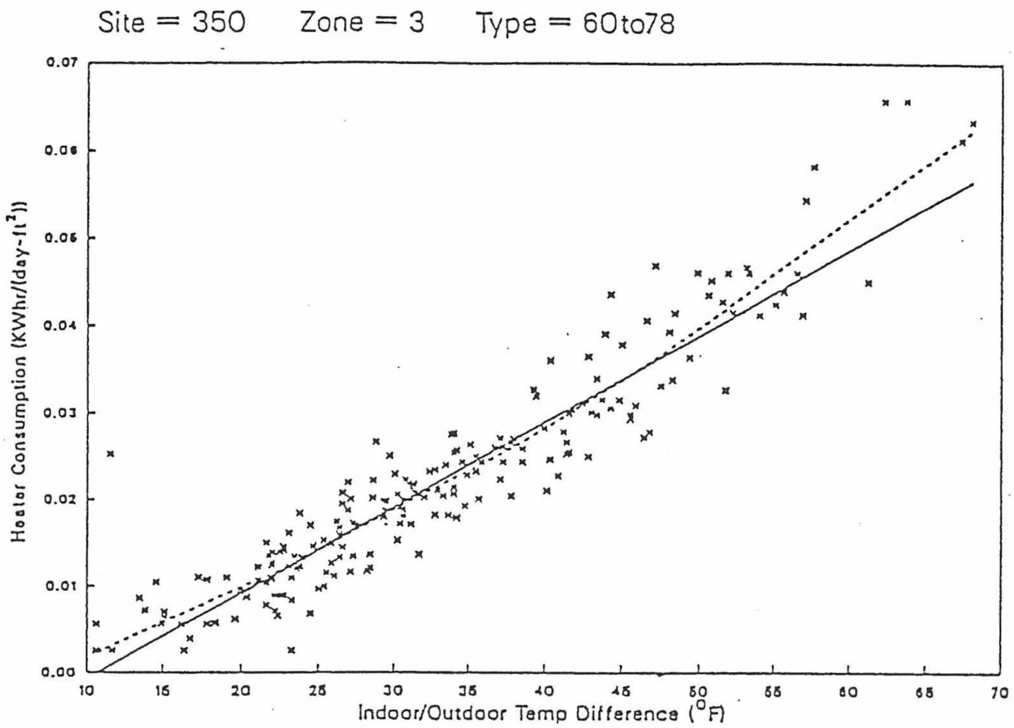

FIGURE A.1. Category-1 Site

all the residential base sites included in the final results. Here the daily floor area normalized space-heating consumption is plotted versus the measured inside-outside temperature. Note the linear relation of the data points. The robust regression line is solidly drawn; the smooth-curve fit to the points is dashed.

CATEGORY TWO

Included in this category are sites that were analyzed but excluded from final results because of nonuniform use of electric space-heating equipment, a substantial reduction in data points available to model the sites after removal of wood-burning days (making the thermal characterization clearly inadequate), or some other unidentified source of apparent secondary heat contamination in the scatter plot of space heat versus inside-outside temperature difference. For example, sites with wood-burning equipment and without a functioning ELCAP wood-stove sensor, which exhibit significant wedge-like scatter in the plot of space heat versus inside-outside temperature difference would be placed in this category. Figure A.2 displays a randomly selected category-2 site selected from all the residential base sites in this category. Again, daily floor area normalized space-heating consumption is plotted versus the measured inside-outside temperature at the site. Observe the wedge-like shape displayed by the scatter plot. This particular home had wood-burning equipment in place and a functioning wood-stove sensor. Figure A.3 displays the same data after removal of days identified as wood-burning days. Note the absence of a high delta temperature (ΔT) in Figure A.3. This site appears to have wood use supplementing the heating system rather than providing the entire heat source. After the removal of wood-burning days, not enough data remains to adequately characterize the thermal performance of the structure.

CATEGORY THREE

Category-3 sites are differentiated from those of category 2 in that typically the heater-versus-temperature-difference plot displays even more

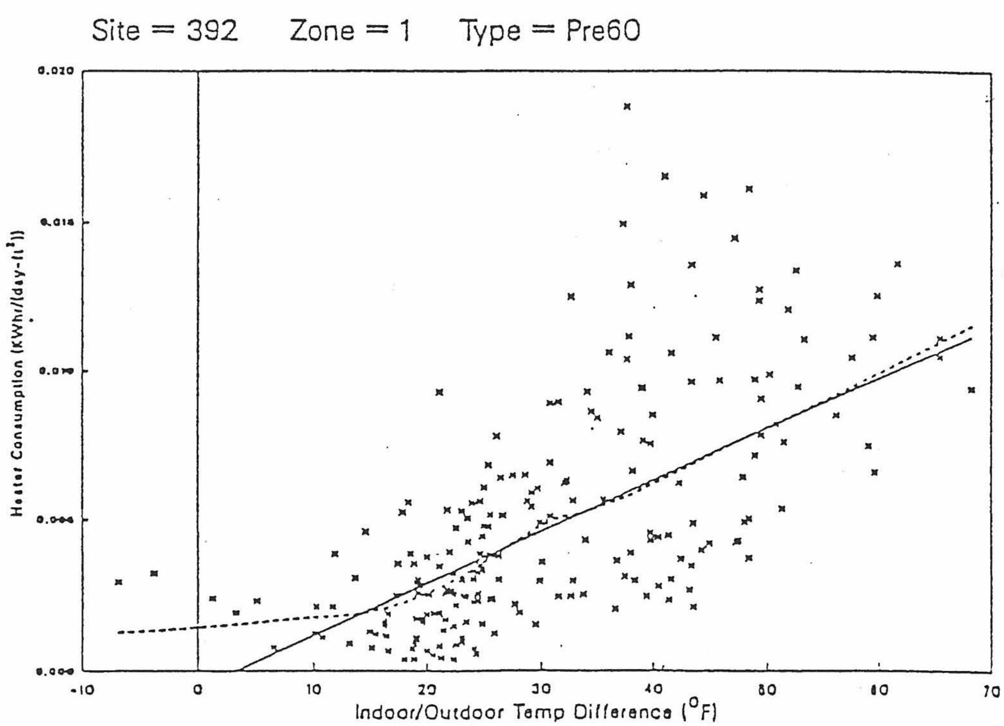

FIGURE A.2. Category-2 Site, Before Wood-Use Removal

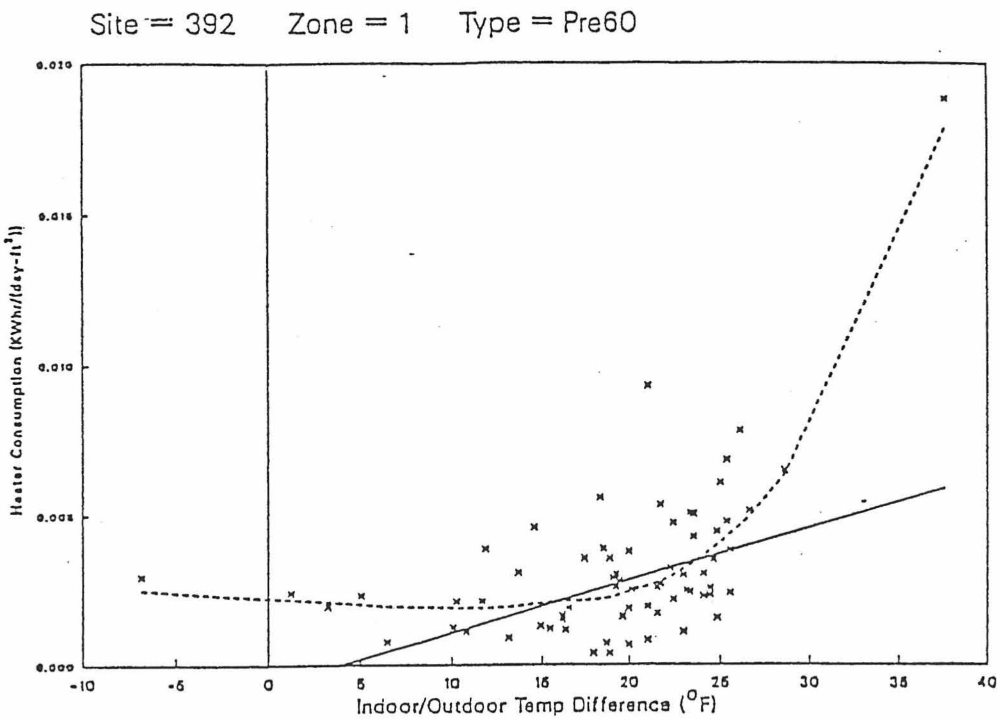

FIGURE A.3. Category-2 Site, After Wood-Use Removal

scatter. The heater is often a nonincreasing function of temperature difference. After removal of wood-use days, little data is often left. Figure A.4 displays a randomly selected category-3 site. Note that these points display much less of a linear trend than do those in Figure A.2. Note the increased number of points lying on the horizontal axis denoting zero heating load for high levels of ΔT as compared to Figures A.1 and A.2. After the removal of wood-burning days, the scatter plot in Figure A.5, displays the virtual absence of points. The scatter plots of category-3 sites tend to display greater dependence on wood or some other secondary heat source.

CATEGORY FOUR

These sites, although having permanent electrical equipment installed, depended entirely on another source of heat. The metered data for electrical energy consumption is entirely zero. From a study of the survey data, it appears that the bulk of these sites are substituting electrical consumption with wood and, in a few cases, kerosene.

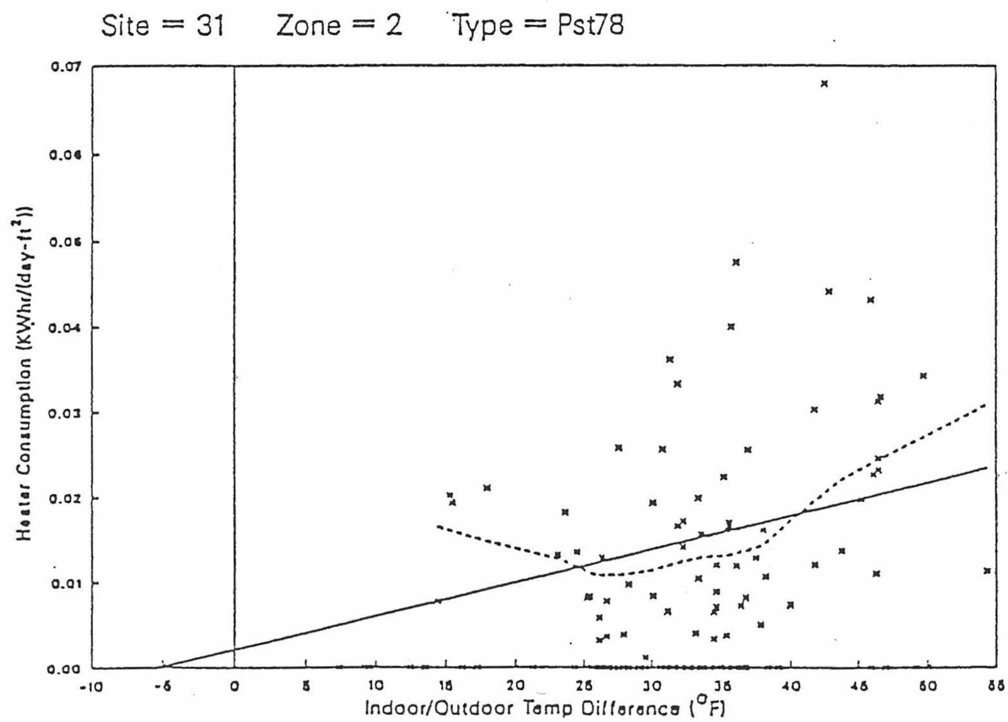

FIGURE A.4. Category-3 Site, Before Wood-Use Removal

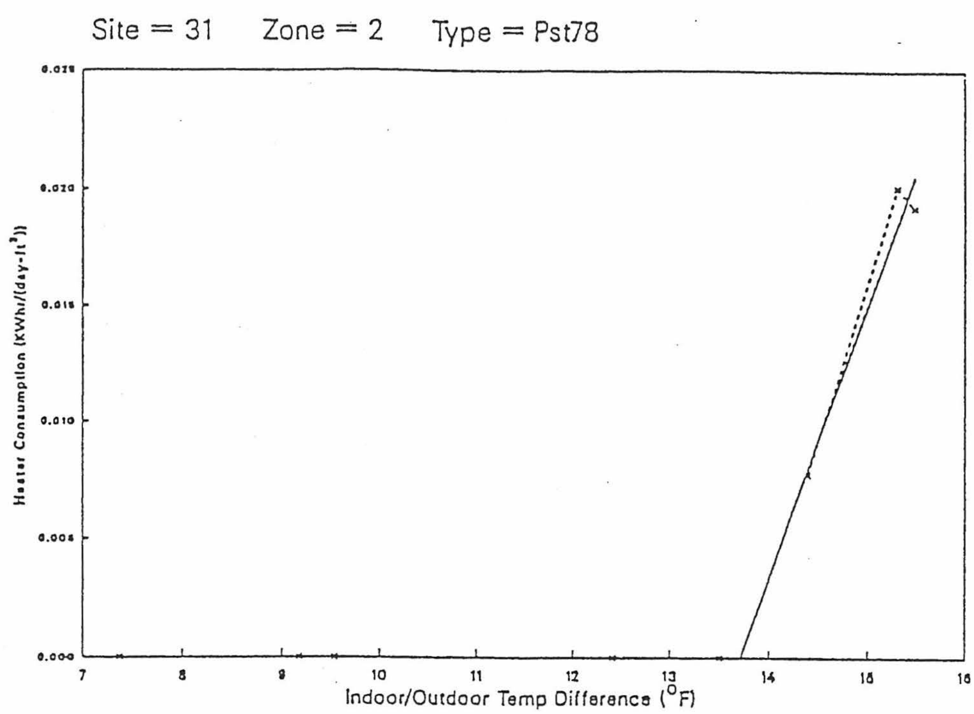

FIGURE A.5. Category-3 Site, After Wood-Use Removal

CATEGORY FIVE

These sites, although having permanent electrical equipment installed, also have other nonelectric permanent equipment in place. What separates these sites from other categories of sites is that they appear to be using the nonelectric heating predominantly. This is noted by the study of survey data. The metered data for electrical space heating is essentially zero for this category of sites.

CATEGORY SIX

These sites are gas or oil case study homes, and therefore, were not suitable for a thermal analysis based on electrical space-heating consumption.

CATEGORY SEVEN

These sites either have no heating season data at all, or insufficient heating season data to attempt a characterization of the thermal performance of the home.

CATEGORY EIGHT

These sites have a data-quality problem that typically relates to the installation of the metering equipment or the function of the metering equipment. These problems were discovered during the thermal analysis workups. The problems with the data necessitated that the site not be included in further analyses.

CATEGORY NINE

These sites failed the initial data-quality test performed at Pacific Northwest Laboratory (PNL) on the metered data. These failures typically point to incorrect installation of the metering equipment or the incorrect functioning of the metering equipment.

CATEGORY TEN

These sites have no substitute outside temperature data available to be used with the other metered data for the site. Without outside temperature data, an analysis based on the independent variable of inside-outside temperature difference cannot proceed.

No site was placed in more than one category, although more than one problem was applicable for sites in categories 6 through 10. The problem perceived as most disabling was selected to classify the site in question. For example, if a site having no heating season data and no outside temperature data source had been identified, the site would be classified as a category-7 site--a site with data availability problems. If the site was a gas and oil home with no heating season data, it would be classified as a category-6 site--a gas and oil home not suitable for inclusion in further analysis.

All sites in categories 1 through 5 and 8 have the following common selection characteristics:

- They are not gas and oil sites.
- They have enough metered data during the heating season to attempt a thermal characterization of the structure.
- The metered data for the site have passed the initial data-quality checks at PNL.
- A satisfactory outside temperature substitute is available if an outside temperature sensor has not been installed at the site.

Figure A.6 displays a histogram of the number of sites divided into each of the analysis categories defined above. The number of sites in each category is displayed as a percentage of the ELCAP residential studies in the legend for the figure. Sites from category 1 make up approximately 41% of the residential base sample when the gas and oil homes are excluded. Of interest is how the percentages are redistributed for those sites which were actually available for analysis. For a site to be applicable and available for the thermal analysis characterization, it is necessary that the site possess the four features noted or, that the site be in category 1 through 5 or 8. The

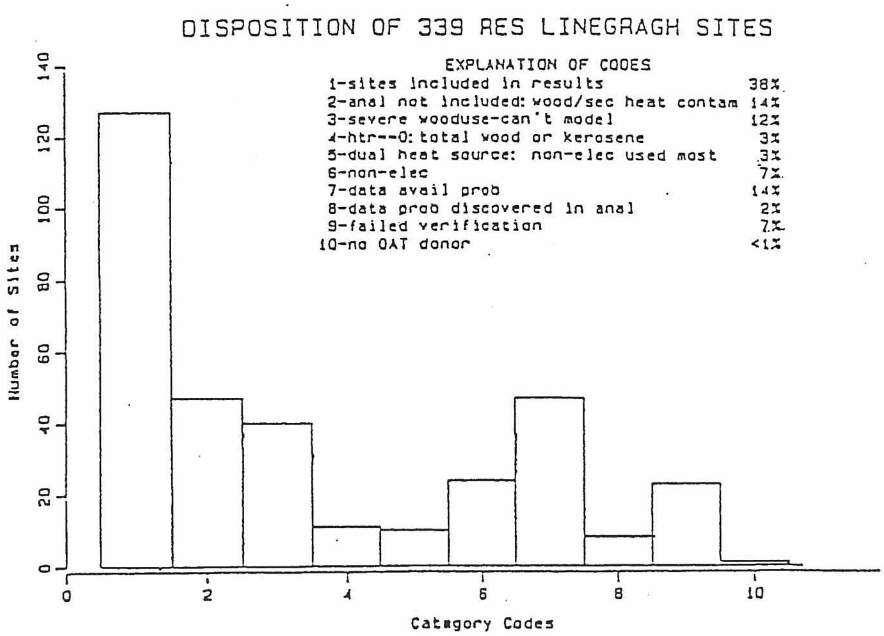

FIGURE A.6. Analysis Category Distributions for Non-Residential Standards Demonstration Program Residential Studies

percentage distributions, displayed in Figure A.6, have been recomputed for the subset of sites that were applicable and available for thermal analysis. These percentages are displayed in Table A.1. Of the sites available for analysis, about 40% could not be thermally characterized because of a partial or complete switching from electricity to wood or a nonelectric supplementary heat source (sum percentages for categories 1 through 5).

The relation of categories 1 through 5 to reported wood-use habits and demographic data from occupant surveys is related in the body of the report.

TABLE A.1. Sites Available for Thermal Analysis

Category 1	53%
Category 2	19%
Category 3	17%
Category 4	4%
Category 5	4%
Category 8	3%

APPENDIX B

THE JACKKNIFE AS APPLIED TO ESTIMATED ANNUAL ELECTRICAL SPACE-HEATING CONSUMPTION

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THE JACKKNIFE AS APPLIED TO ESTIMATED ANNUAL ELECTRICAL SPACE-HEATING CONSUMPTION

To assess the stability of the annualized space-heating estimate for the 127 residential base homes included in the results of this paper (Miller et al. 1990), a statistical procedure called the jackknife was applied to annual electrical space-heating consumption estimates. The majority of the base sample's consumption estimates are seen to be quite stable as measured by the jackknife results. Some graphics are displayed summarizing the jackknife results for the base sample, and the characteristics of those sites that produced the least stable consumption estimates, as measured by the jackknife, are discussed.

Figure B.1 displays the scatter plot of the estimated annual heating consumptions for each of the 127 residential base sites included in the results of this paper versus the jackknifed estimate (Miller et al. 1990). The trend is clearly linear, with the majority of the 127 points falling very close to the identity line where the two estimates would equal one another. There are, however, a few noticeable outlying points.

To assess the stability of the fit, the radius of uncertainty, $s^*|t_{k-1}|\alpha$, may be compared to the jackknife value, y^*. The larger the ratio, the less stable the fit. Figure B.2 displays a histogram of the ratio of the radius of uncertainty to the jackknifed estimate. The majority of the sites have ratios less than 10%, and all but a dozen have ratios under 20%. For those sites with ratios outside 20%, the fits are much less stable.

Sites having the least stable jackknife estimates appear to have several more data features than the sites giving the more stable estimates. For sites with a ratio (of the radius of uncertainly to the jackknife value) above 20%, the number of sites missing high ΔT values are compared to the number of sites with a ratio above 20% not missing high ΔT values. The same comparison was made for sites with ratios under 20%. Those sites with the least stable

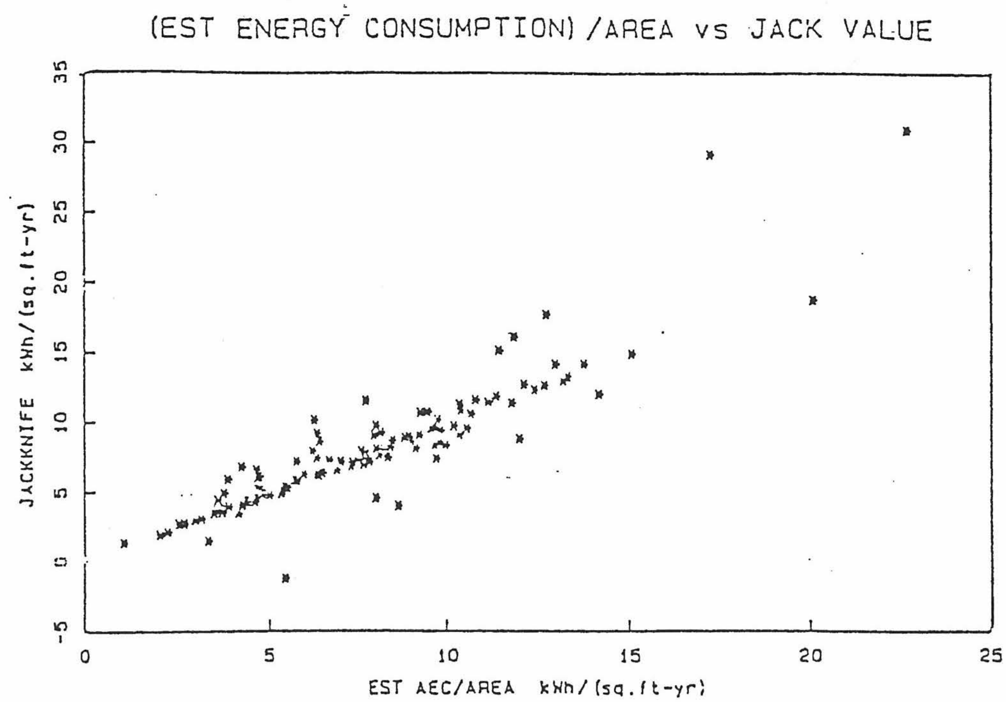

FIGURE B.1. Comparison of Estimated Electrical Consumption to Jackknifed Estimates

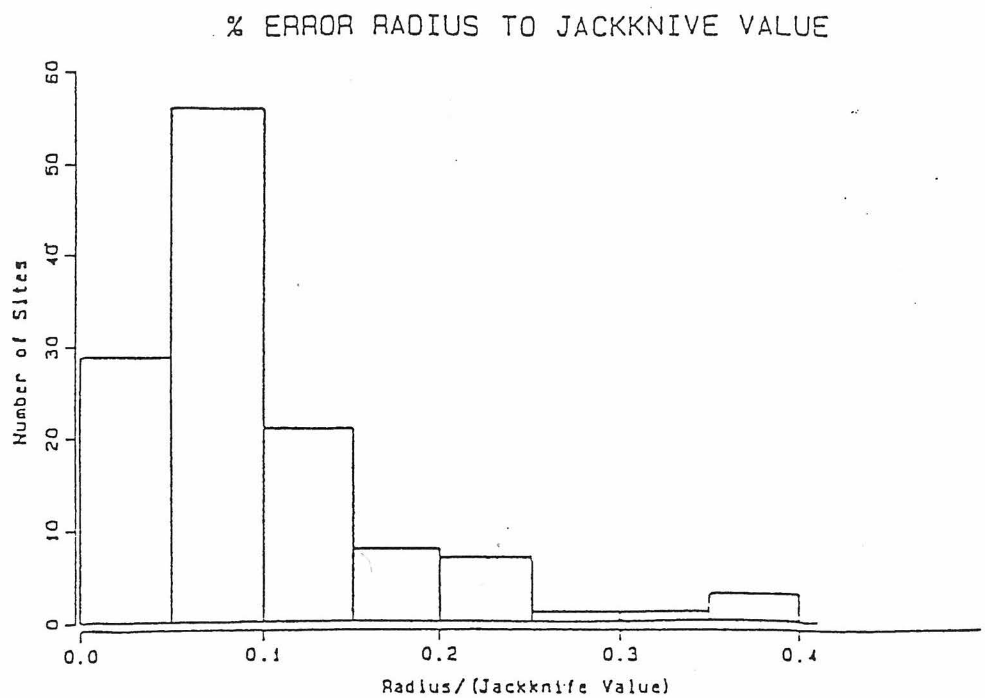

FIGURE B.2. Comparison of Radius of Uncertainty to Jackknifed Estimate estimates were 4.7 times as likely to be missing high ΔT values. Similarly, the overall data density was rated lower three times as often for the sites above the 20% mark. A nonuniform distribution of data points in the initial scatter plot of space-heating energy versus inside-outside temperature difference with large variations in heating values at the upper end of ΔT is more commonly associated with the less stable fits. Removing points where the wood-burning equipment is used can create a nonuniform distribution of data points in the scatter plot.

To assess the effect that inclusion of the dozen less stable jackknife sites may have on results, comparisons are made between derived thermal parameters for the two groups. No significant difference is noted between the median values for estimated annual energy consumption per square foot of floor area, nor is the range of values taken on by the distribution of the energy consumption estimates significantly different for the two groups. Similar results hold for the robust linear slope.

APPENDIX C

TWO-WAY ANALYSIS

APPENDIX C

TWO-WAY ANALYSIS

In this section, the summary tables used to generate the results cited in Section 4.2 are given.

SUMMARY TABLES FOR HEATING SYSTEM DIFFERENCES

The following summary tables are used in the two-way analysis of variance (ANOVA) tests discussed in Sections 4.2 and 4.3. Tables C.1 through C.3 are from the heating system work found in Section 4.2. Tables C.4 and C.5 are from the inside air temperature work found in Section 4.3.

Table C.1 displays the data for the first heating system ANOVA test using climate zone 2 and 3 homes. Here energy consumption estimates from residential base, Model Conservation Standards (MCS), and control homes are binned by heating system type and by effective U-value for the home. Each binned observation value is the estimated annual electrical space heat consumption per square foot of surface area. These energy consumption estimates assume an average inside operating temperature over the heating season of 65°F. The units are in kWh/ft^2. The bold entries in the table represent the median value of all observations categorized into each cell. The italic entries represent the mean value of all observations categorized in the cell. For the simple two-way modeling and two-way analysis of variance tests cited in the body of the text, the median cell values were used. The mean values are included in the table for purposes of comparison, since several cells are sparsely populated.

Table C.2 gives the data associated with the second heating system ANOVA test performed using climate zone 1 homes. Here energy consumption estimates from residential base, MCS, and control-homes in climate zone 1 are binned by heating system type and by effective U-value. This contingency table is constructed similarly to that of Table C.1.

TABLE C.1. Estimated Annual Space Heat and Surface Area at Inside Temperature 65°F for Climate Zone 2 and 3 Homes--**Median** and *Mean* kWh/ft^2-yr Values

Parameters	Forced Air	Baseboard
0.04 < U-value ≤ 0.08	**1.79** (n = 5) *1.90*	**1.31** (n = 15) *1.44*
0.08 < U-value ≤ 0.12	**2.46** (n = 6) *2.84*	**1.42** (n = 9) *1.90*
0.12 < U-value ≤ 0.16	**3.56** (n = 2) *3.56*	**2.48** (n = 5) *3.34*

TABLE C.2. Estimated Annual Space Heat and Surface Area at Inside Temperature 65°F for Climate Zone 1 Homes--**Median** and *Mean* kWh/ft^2-yr Values

Parameters	Forced Air	Baseboard	Heat Pump
0.04 < U-value ≤ 0.08	**0.98** (n = 6) *1.04*	**0.93** (n = 8) *1.12*	**0.80** (n = 6) *0.86*
0.08 < U-value ≤ 0.12	**1.85** (n = 22) *1.85*	**1.72** (n = 12) *1.55*	**1.08** (n = 4) *1.29*
0.12 < U-value ≤ 0.16	**1.71** (n = 3) *2.04*	**1.99** (n = 12) *2.16*	**1.59** (n = 1) *1.59*
0.16 < U-value ≤ 0.22	**2.23** (n = 3) *2.45*	**2.79** (n = 6) *2.69*	**1.35** (n = 3) *1.45*

TABLE C.3. Estimated Annual Space Heat and Surface Area at Inside Temperature 65°F for Climate Zone 1 Homes--Where 0.08 < U-Value ≤ 0.12 **Median** and *Mean* kWh/ft^2 Values

Parameters	Forced Air	Baseboard
Heated Basements	**1.06** (n = 2) *1.06*	**0.72** (n = 1) *0.72*
Slab	**2.04** (n = 1) *2.04*	**1.51** (n = 3) *1.22*
Crawlspace	**2.36** (n = 11) *2.41*	**1.85** (n = 7) *1.79*

TABLE C.4. Climate Zone 1 Baseboard Homes

Parameters	Temp ≤ 68.5	68.5 < Temp ≤ 75
UA/FA ≤ 0.28	3.81 (n = 6)	4.98 (n = 9)
0.28 < UA/FA ≤ 0.80	7.49 (n = 10)	8.54 (n = 14)

TABLE C.5. Climate Zone 2 and 3 Baseboard Homes

Parameters	Temp ≤ 68.5	68.5 < Temp ≤ 75
UA/FA ≤ 0.24	3.69 (n = 7)	5.03 (n = 10)
0.28 UA/FA ≤ 0.60	4.29 (n = 5)	7.48 (n = 4)

Table C.3 provides the data associated with the heating system ANOVA test for climate zone 1 homes, where energy consumption estimates for residential base, MCS, and control homes are binned by heating system type and by pure foundation type. However, only homes with U-values between 0.08 and 0.12 were selected for this analysis. Cell values for this table are constructed similarly to that of the preceding tables.

The next two tables are used in the inside air temperature and effective conductance (UA) work cited in Section 4.3. The factors are nameplate UA divided by conditioned floor area in ft^2 effective conductance/forced air (UA/FA) and mean heating season indoor air temperature in °F. The cell or observation values are median estimated annual electrical space-heating consumption using typical meteorological year (TMY) data and the mean heating season inside air temperature from each site divided by conditioned floor area, AEC_{iat}/ft^2.

Very high levels of significance are associated with both the factor of UA/FA ($\alpha = 0.01$) and mean temperature ($\alpha = 0.03$) in explaining the variation in the cell values of AEC_{iat}/ft^2 for the values in Table C.4.

Low levels of significance are associated with both the factor of UA/FA ($\alpha = 0.35$) and mean temperature ($\alpha = 0.25$) for the purpose of explaining the variation in the cell values of AEC_{iat}/ft^2 for the values in Table C.5.

APPENDIX D

PRELIMINARY EXPLORATION OF LOWESS RESIDUALS

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PRELIMINARY EXPLORATION OF LOWESS RESIDUALS

A total of nine sites from the residential base sample were chosen for the residual investigation. These sites represent a diversity of conditions in that all three climate zones are represented, five major space-heating systems are represented (forced air, radiant, baseboard, heat pump, wood stove), and six geographical areas are represented (Eastern and Western Washington and Oregon, Idaho, and Montana). The specific characteristics of individual sites are illustrated in Table D.1. Despite the diversity, no claim is made that these sites represent the residential base sample or the residential population as a whole. The selections were made for exploratory purposes only.

For each site, a four-stage analysis was performed. The first stage consisted of three graphical examinations of the LOWESS residuals. A plot of the LOWESS predictions (horizontal axis) versus their corresponding residuals (vertical axis) was made. These plots were used to indicate whether the

TABLE D.1. Site Characteristics

Site ID	Heat Type	Heat Most Used	Location	Climate Zone	Wood Use	Foundation Type
044	Forced Air	Forced Air	E. Oregon	2	Minor	Crawlspace
050	Baseboard	Unknown	E. Wash	2	Minor	Heated Basement
056	Radiant	Radiant	E. Wash	1	Major	Crawlspace
062	Forced Air	Forced Air	W. Wash	1	Minor	Crawlspace
191	Baseboard	Baseboard	W. Oregon	1	Minor	Slab and Heated Basement
230	Baseboard	Baseboard	Idaho	2	Minor	Crawlspace
269	Heat Pump	Forced Air	E. Oregon	2	None	Crawlspace and Slab
381	Forced Air	Wood Stove	Montana	3	Major	Crawlspace and Slab Heated Basement
436	Baseboard	Baseboard	W. Wash	1	Minor	Crawlspace

dispersion of the residuals appears to be a function of the magnitude of the predicted values. When such is the case, an inadequacy of the model may be indicated. Because the original temperature and energy consumption data were time ordered, a plot of time (horizontal axis) versus the corresponding residuals (vertical axis) was also made. These plots indicate whether the fit of the model varies in some systematic way across time. Finally, the residuals from each time period were plotted against the residuals from the next available time periods. The latter plots were used to look for a first-order correlation of the residuals across time.

In the second stage of the analysis, the stepwise variable selection procedure was employed to determine which variables best predicted the LOWESS residuals through an ordinary least squares (ols) regression. The full model to which the LOWESS residuals were fit was of the form

$$\begin{aligned} \text{resid}(i,j) = m &+ a(i) + b(i)\cdot\text{pyrometer}(j) + c(i)\cdot\text{int\_gains}(j) \\ &+ d(1)\cdot\text{wind\_speed}(j) + d(2)\cdot\text{humidity}(j) \\ &+ d(3)\cdot\text{wind\_direction}(j) + d(4)\cdot\text{inside\_air\_temp}(j) \\ &+ d(5)\cdot\text{outside\_air\_temp}(j) + e(i,j) \end{aligned}$$

where i denotes a time period within the heating season (1 = August through October, 2 = November through February, 3 = March through May) and j denotes a day during the heating season. The a(i)'s are assumed to sum to zero and thus represent subseasonal adjustments to the overall mean m. The pyrometer and int_gains variables are measures of solar radiation and the internal heat gains generated by other electrical end uses. Since the contributions of these heat sources to space heating were expected to vary considerably by subseason, the model allows for the estimation of subseason-specific slopes. The remaining variables are assumed to be less dependent on subseason, so that a single overall slope is estimated for each.

For each site, a reduced model containing only a subset of the terms in the full model was actually fit. The reductions occurred because of the measurement unavailability and the variable selection procedure. The stepwise procedure builds a best model in a series of steps. At each step, the significant variable exhibiting the highest partial correlation with the dependent variable is added, and one or more of any resulting nonsignificant variables are dropped. The procedure terminates when no more variables can be added or dropped. The model at that step is considered to be best.

In the third stage, the relative importance of the variables included in the model was assessed by comparing their beta weights. A beta weight is formed by multiplying the regression coefficient for a given predictor variable by the quotient of its standard deviation and the standard deviation of the dependent variable. The resulting value indicates the number of standard deviations of change which occur in the dependent variable for a single standard deviation of change in the predictor variable (with all other predictors held constant).

The final stage of the analysis was a graphical examination of the analysis which consisted of a graphical examination of the ols residuals (i.e., the differences between the LOWESS residuals and their ols-predicted values) carried out as in stage one.

RESULTS - EXAMINATION OF LOWESS RESIDUALS

In the fitting of linear or LOWESS models, the assumption is usually made that the deviations of actual observations from the model are independently distributed with mean 0 and common variance. Often the deviations are assumed to be normally, or at least symmetrically distributed as well. When these assumptions can be empirically validated through an examination of residual plots, the analyst feels some confidence that his model has captured the essential structure of the physical relationship being modeled, and that any unexplained variance is truly random in nature.

In examining residuals, the most common practice is to plot the residuals against fitted values in order to detect any dependence of error variance on the level of fitted values. If the model assumptions are met (assuming a uniform density of observations across predicted values), the resulting plot should display a random scattering of points above and below the fitted axis, with the spread remaining nearly uniform across predicted values. Any trends observed in the mean residuals may reflect the omission of important variables or higher-order terms in the basic model. Variation of spread as a function of predicted values may point to model inadequacies or simply nonhomogeneity of the error variances. If the data can be naturally sequenced with respect to time, it is also of interest to plot the residuals in their time ordering. Again, one hopes to find a random scattering of points above and below the time axis, with the spread remaining nearly uniform across time. Departures may suggest the introduction of time-related variables into the model. Correlation of errors across time can be detected by plotting residuals against lagging residuals. If no correlation is present, the plot should have a shotgun appearance. Presence of a positive [negative] correlation will cause the plotted points to appear to be randomly scattered along a line with positive [negative] slope.

While the LOWESS model is nonlinear, the assumptions regarding its deviations are similar. An examination of the plots of LOWESS predictions versus LOWESS residuals (see Figures D.1a through D.1i) reveals potential model inadequacies in sites 269, 381, and 436. Site 269 was the only site to list a heat pump as the most used type of heating system. The predominance of large, positive residuals at high-predicted energy consumption suggests a loss of efficiency at low temperatures which is not adequately explained by a LOWESS model. Site 381 indicates the presence of some skew in the residual distribution; positive residuals tend to be less frequent but of greater magnitude than negative residuals. Because it is known that a forced air system was available, but that wood was considered to be the major heat source, this may reflect frequent wood-stove use combined with infrequent forced air use. Under this scenario, LOWESS would tend to treat the forced air days as outliers, resulting in large residuals. Site 436 also displays somewhat skewed residuals, but without obvious explanation.

Examination of the plots of time versus LOWESS residuals (see Figures D.2a through D.2i) indicates cyclic or overall trends in the residuals, pointing to periods of relatively good or poor fit for sites 191, 69, and 381. Sites 230, 436, 50, and 62 display some increase in variability during certain periods of time. Only the plots for sites 56 and 44 are unremarkable.

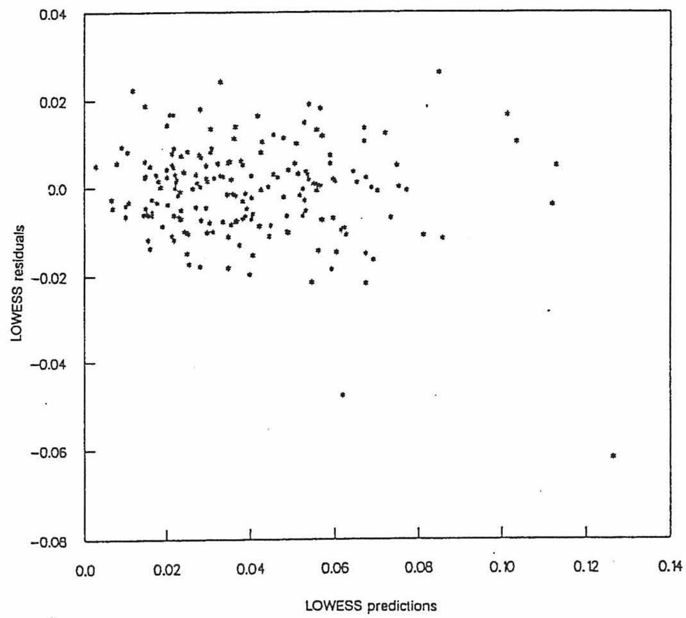


FIGURE D.1a LOWESS Residuals Versus LOWESS Predictions: Site 44

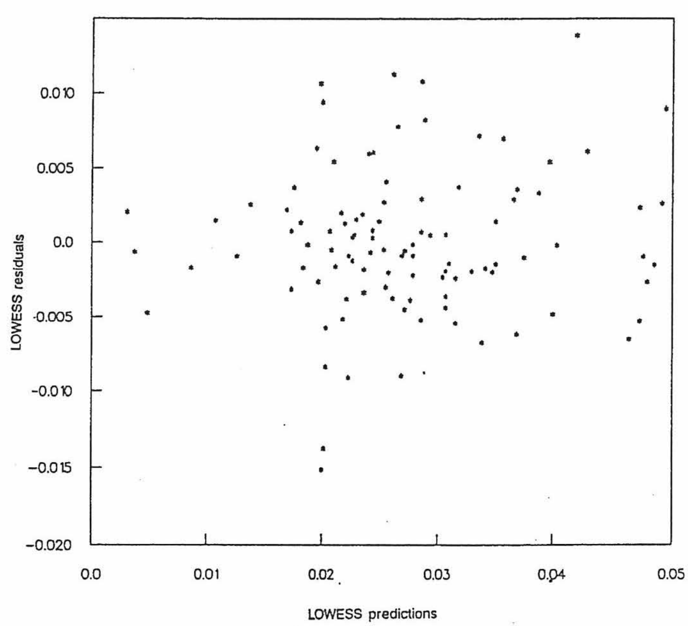


FIGURE D.1b LOWESS Residuals Versus LOWESS Predictions: Site 50

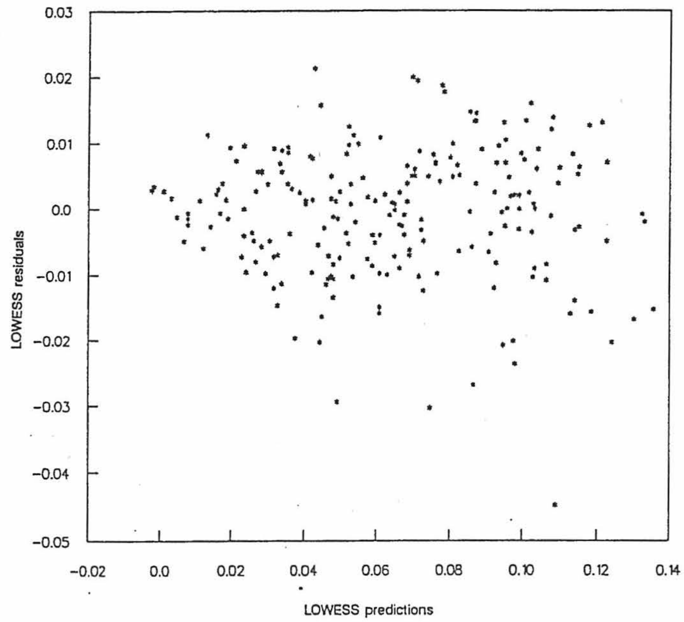


FIGURE D.1c LOWESS Residuals Versus LOWESS Predictions: Site 56

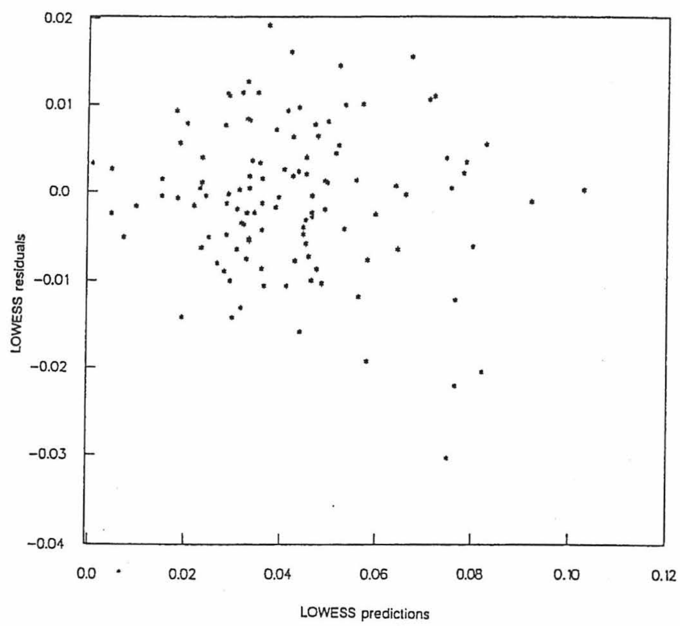


FIGURE D.1d LOWESS Residuals Versus LOWESS Predictions: Site 62

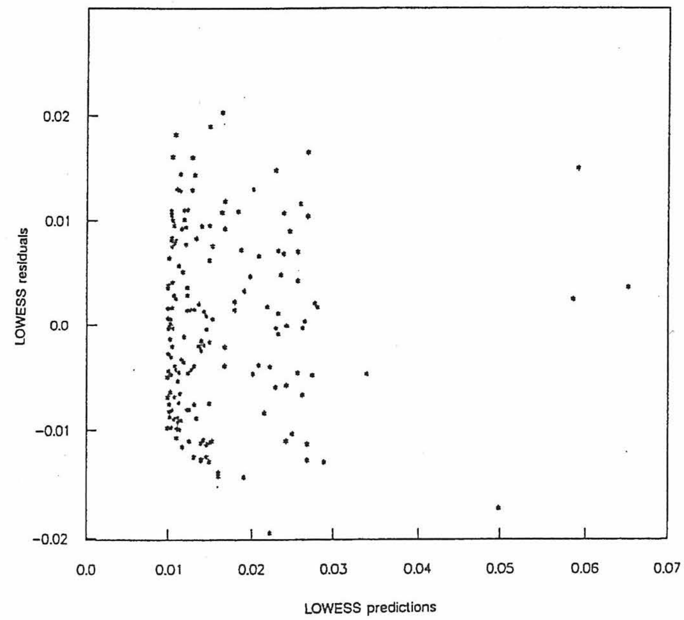


FIGURE D.1e LOWESS Residuals Versus LOWESS Predictions: Site 191

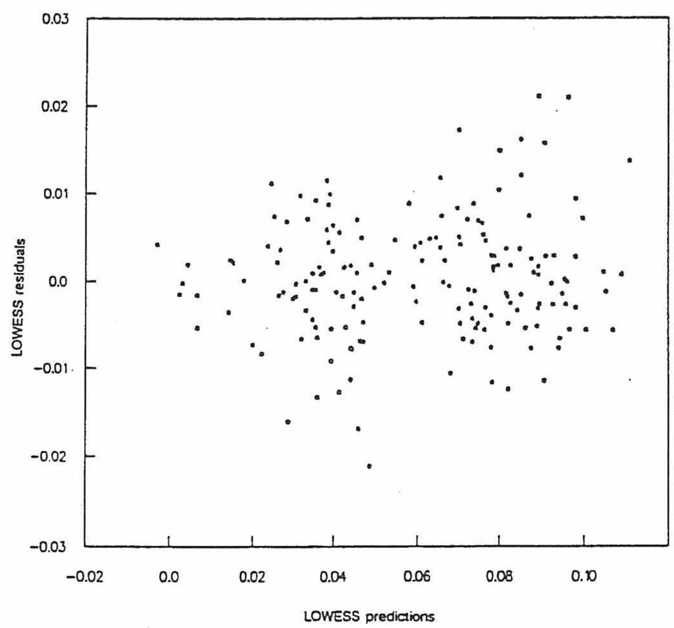


FIGURE D.1f LOWESS Residuals Versus LOWESS Predictions: Site 230

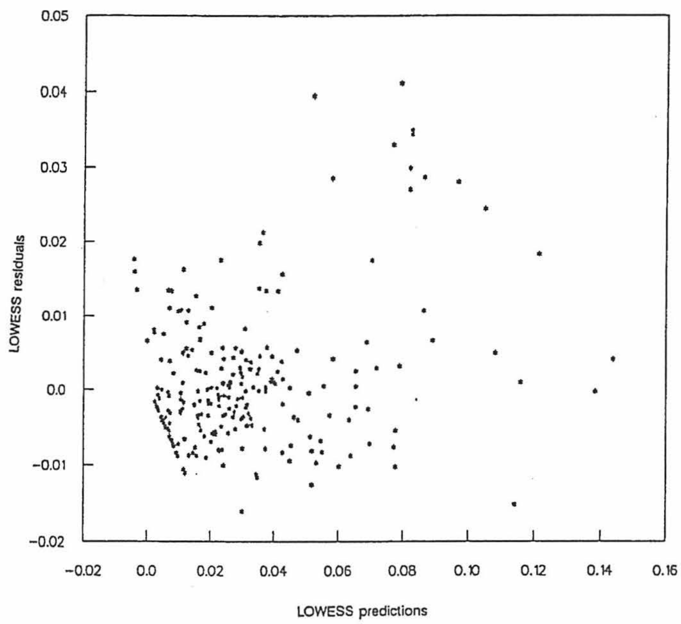


FIGURE D.1g LOWESS Residuals Versus LOWESS Predictions: Site 269

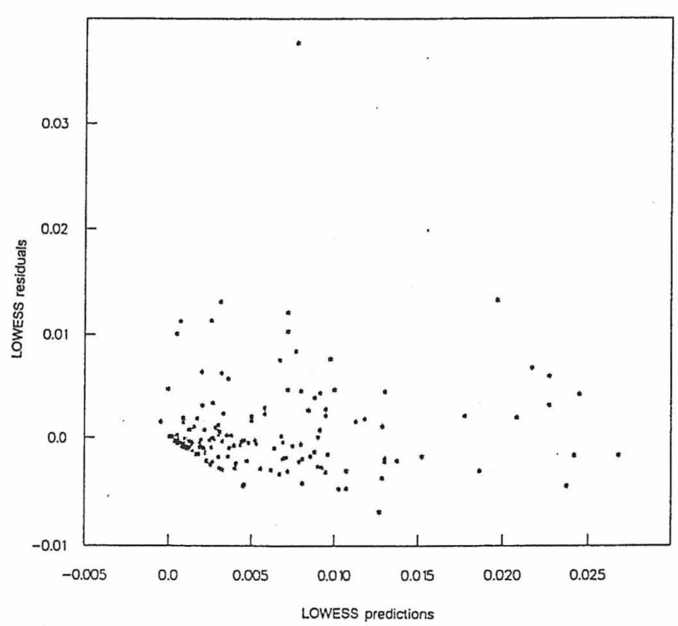


FIGURE D.1h LOWESS Residuals Versus LOWESS Predictions: Site 381

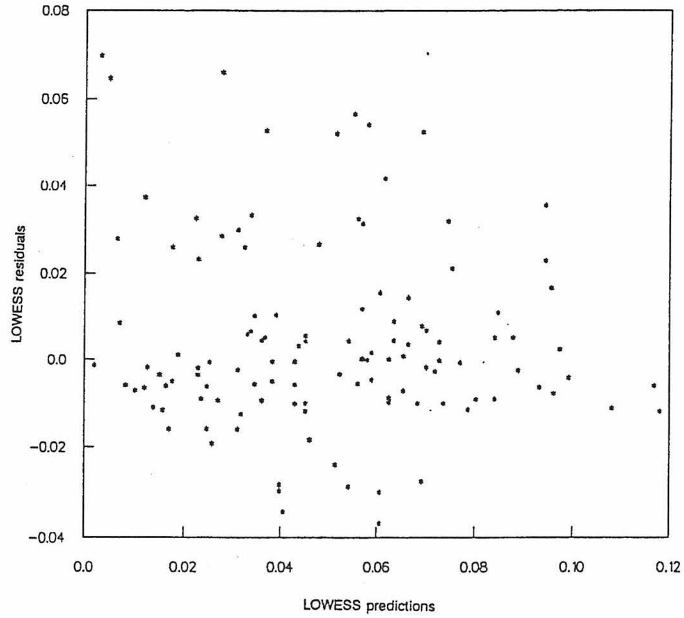


FIGURE D.1i LOWESS Residuals Versus LOWESS Predictions: Site 436

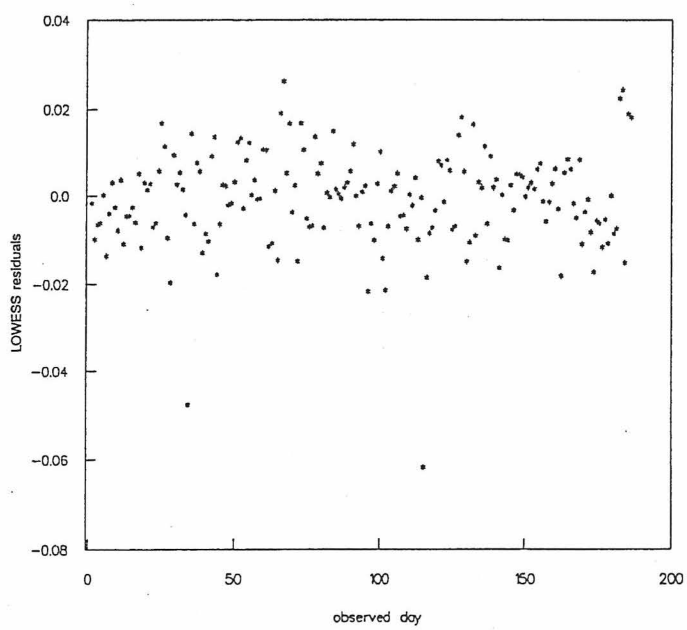
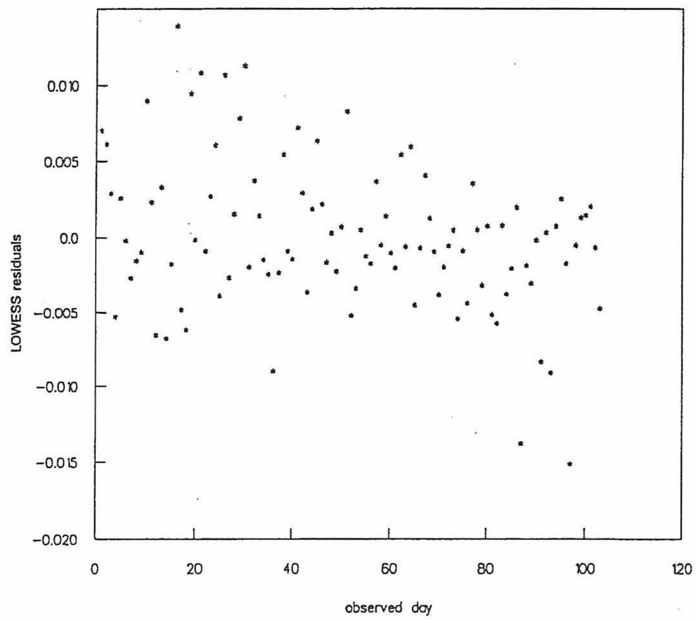
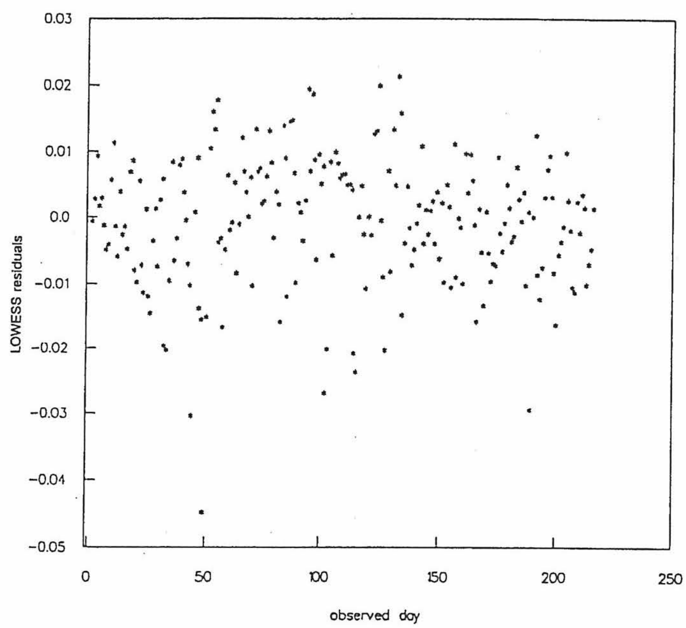


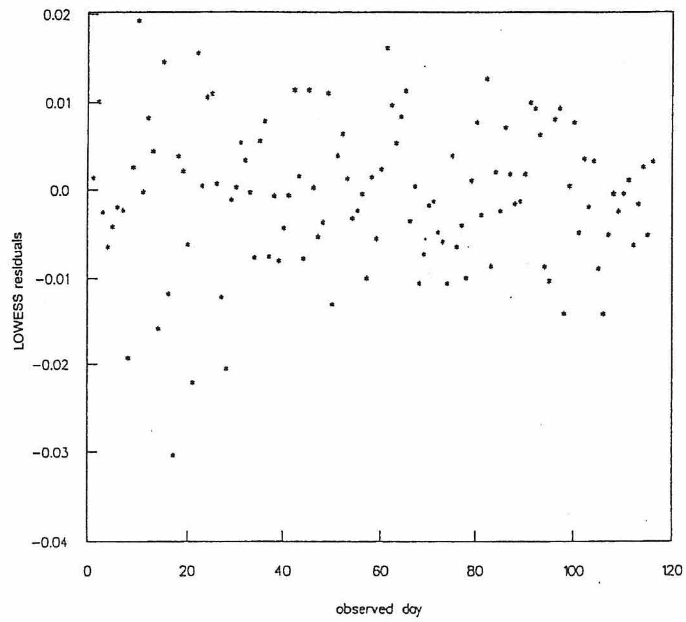
FIGURE D.2a LOWESS Residuals Versus Time: Site 44



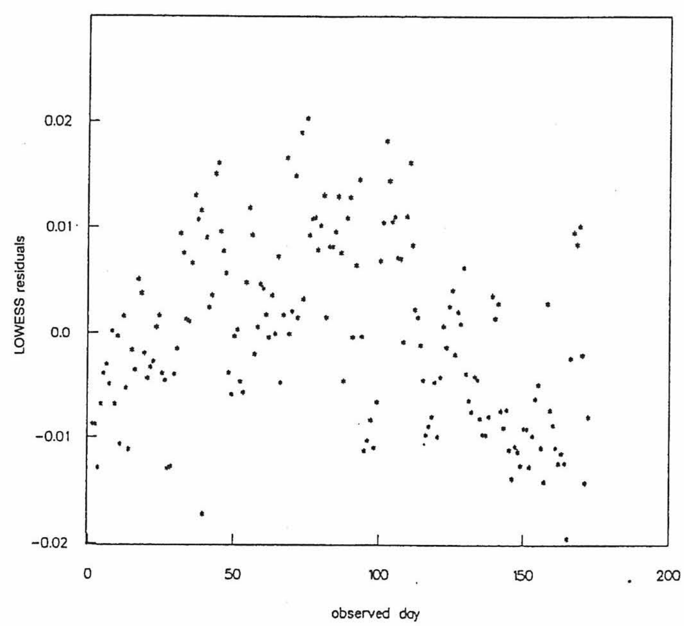
<u>FIGURE D.2b</u> LOWESS Residuals Versus Time: Site 50



<u>FIGURE D.2c</u> LOWESS Residuals Versus Time: Site 56



<u>FIGURE D.2d</u> LOWESS Residuals Versus Time: Site 62



<u>FIGURE D.2e</u> LOWESS Residuals Versus Time: Site 191

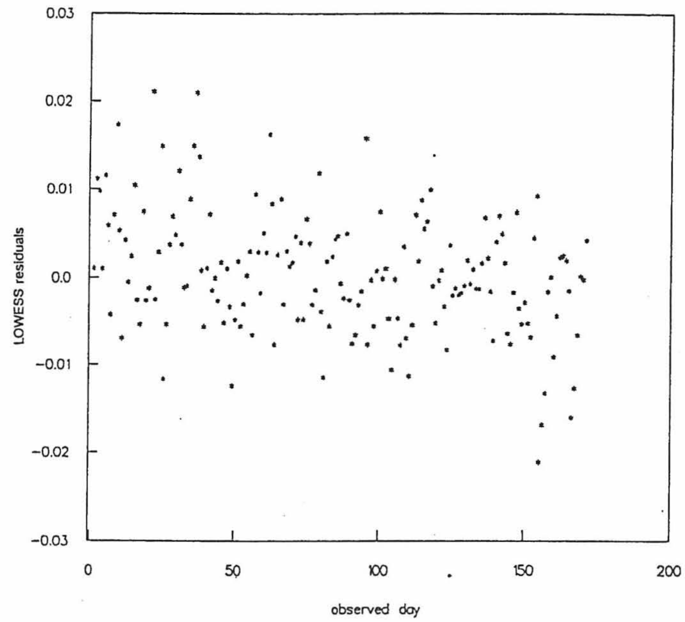


FIGURE D.2f LOWESS Residuals Versus Time: Site 230

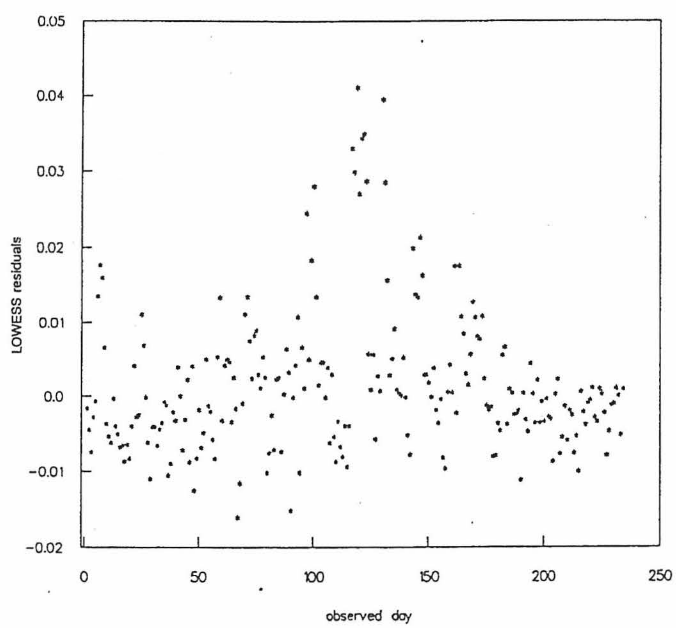


FIGURE D.2g LOWESS Residuals Versus Time: Site 269

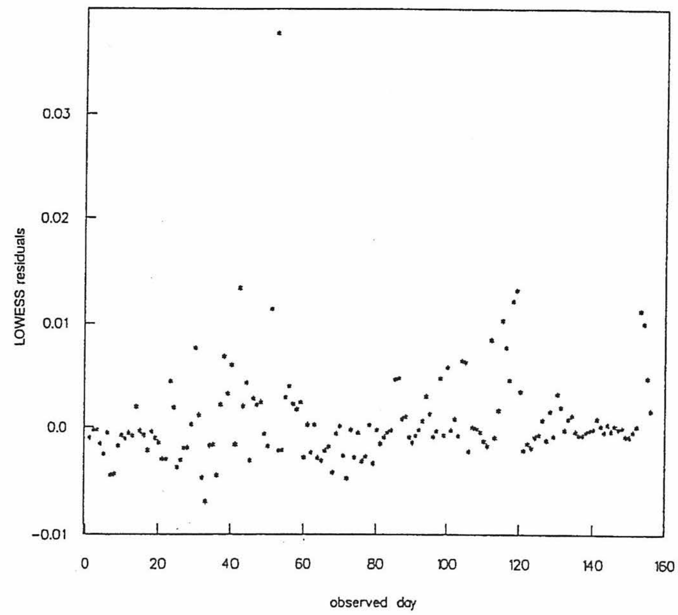


FIGURE D.2h LOWESS Residuals Versus Time: Site 381

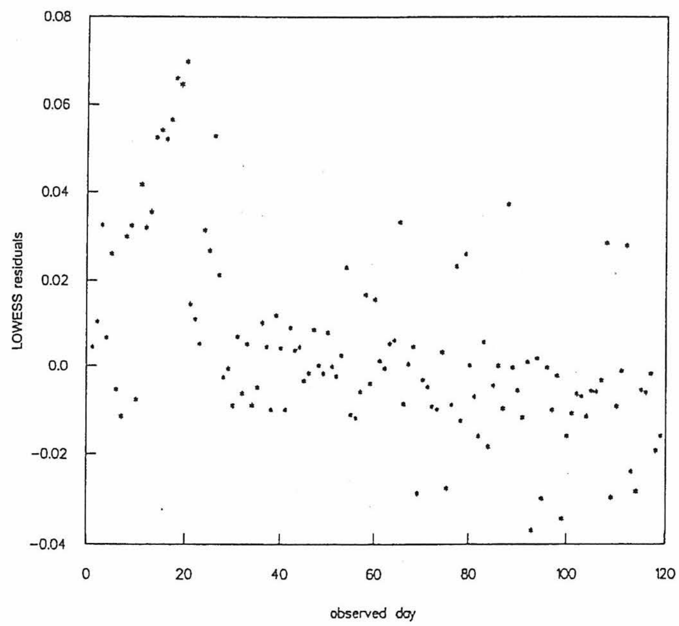


FIGURE D.2i LOWESS Residuals Versus Time: Site 436

The plots of residuals versus residuals from the next available time periods (see Figures D.3a through D.3i) reveal a moderate to strong (0.13 to 0.63) positive first-order correlation for all sites other than 50 and 62. Site 62 has the lowest absolute correlation at 0.0060, but because the inside air temperature variable was missing in the original data, all results for that site are somewhat suspect. Interestingly, the correlation for site 50 is negative (-0.05), with no obvious explanation available.

VARIABLES SELECTED

Table D.2 displays the variables selected for the best ols model for each site. As indicated, no two models were exactly the same. This is from, in part, the fact that not all explanatory variables were available for all sites. Undoubtedly the diversity of conditions represented by the sites played a role as well. It is interesting to note that inside air temperature and/or outside air temperature entered into all but one of the models, even though their difference was included as the independent variable in the LOWESS fit. This suggests that the role of these two factors in predicting energy consumption for space heating is more complex than generally supposed.

Table D.3 provides statistical details of the final best-regression fits. Note that the R squares range from a low of 0.07 to a high of 0.65.

RELATIVE IMPORTANCE OF THE VARIABLES

Beta weights, as previously described, provide a measure of the relative importance of the predictor variables in a multiple-regression fit. Because the sign of a beta weight is the same as that of its corresponding regression coefficient, the relative importance of two variables is best measured by comparing the absolute magnitudes of their respective beta weights. In general, the larger the beta weight (in absolute magnitude, relative to the other beta weights), the more important the variable.

Because a beta weight is meaningful only when the other predictor variables are held constant, it is best viewed as applicable to only small changes in its corresponding variable. Dramatic changes in outside air

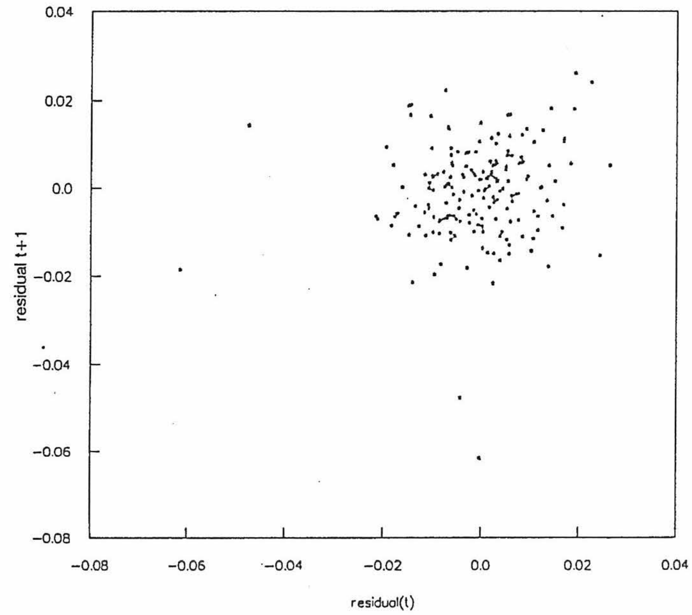


FIGURE D.3a LOWESS Residual(T) Versus LOWESS Residual(T+1): Site 44

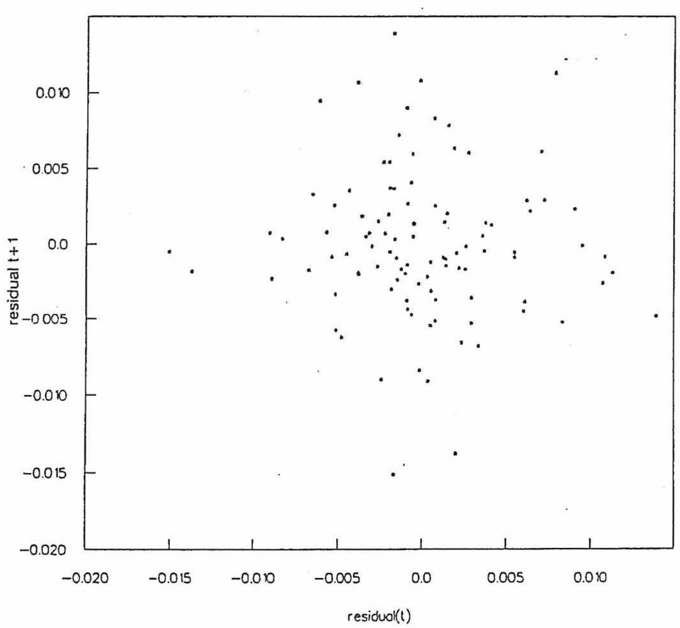


FIGURE D.3b LOWESS Residual(T) Versus LOWESS Residual(T+1): Site 50

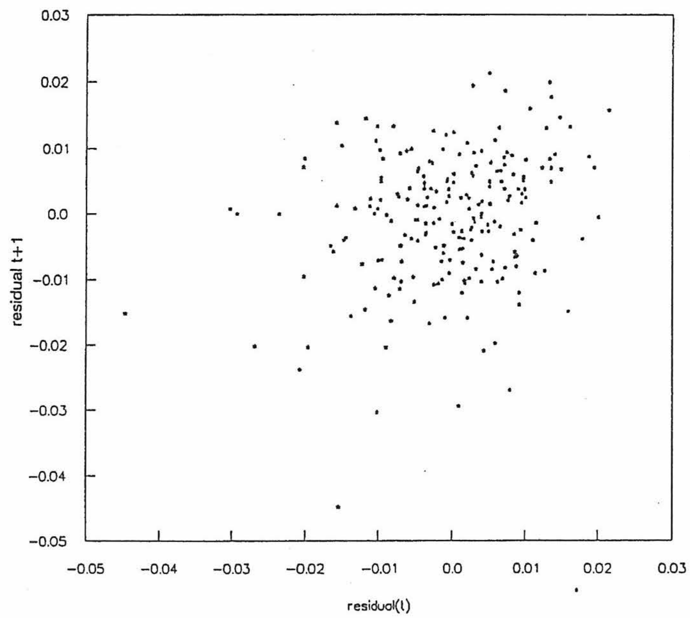


FIGURE D.3c LOWESS Residual(T) Versus LOWESS Residual(T+1): Site 56

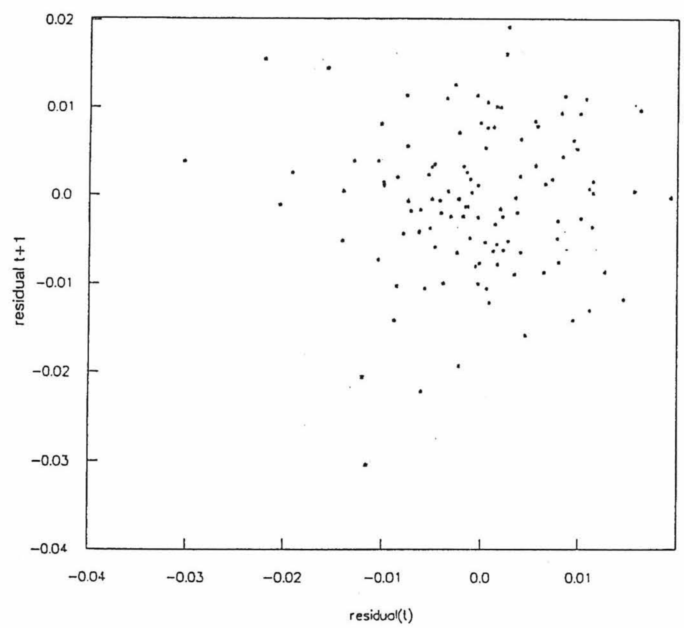


FIGURE D.3d LOWESS Residual(T) Versus LOWESS Residual(T+1): Site 62

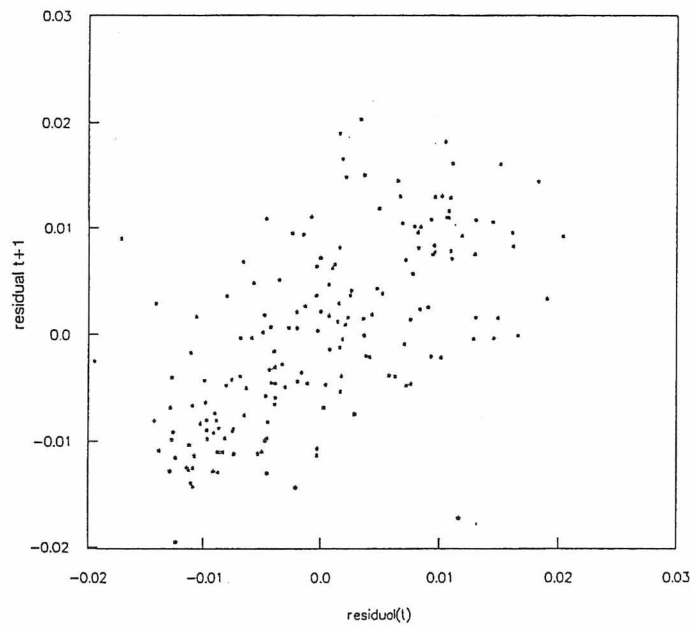


FIGURE D.3e LOWESS Residual(T) Versus LOWESS Residual(T+1): Site 191

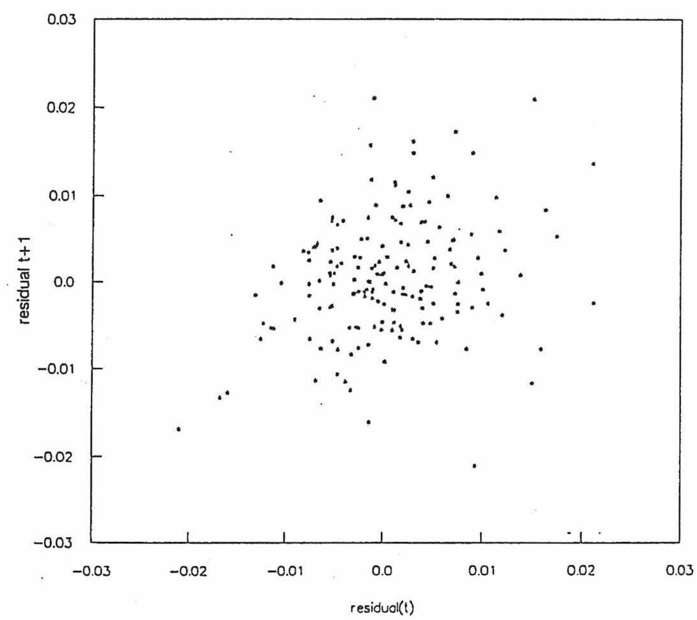
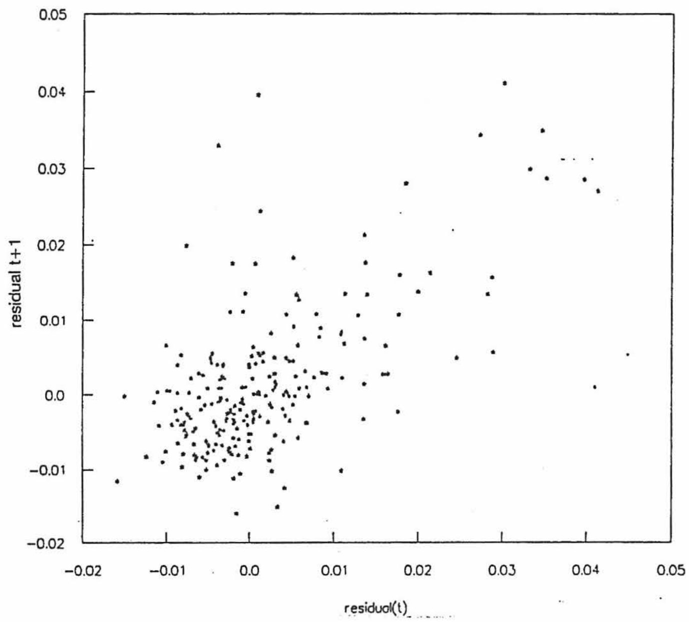
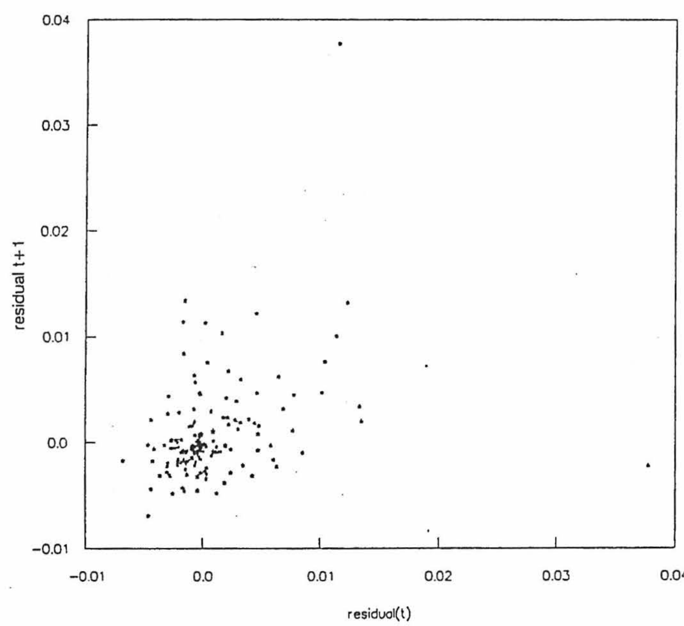


FIGURE D.3f LOWESS Residual(T) Versus LOWESS Residual(T+1): Site 230



<u>FIGURE D.3g</u> LOWESS Residual(T) Versus LOWESS Residual(T+1): Site 269



<u>FIGURE D.3h</u> LOWESS Residual(T) Versus LOWESS Residual(T+1): Site 381

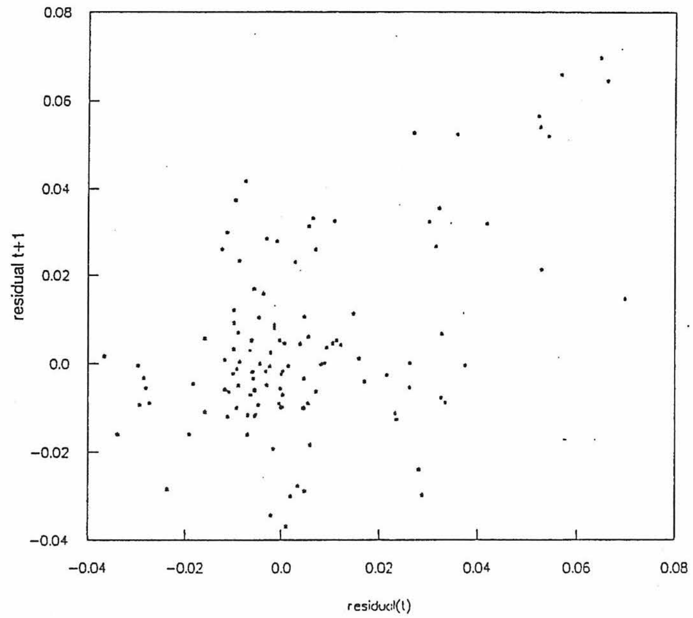


FIGURE D.3i LOWESS Residual(T) Versus LOWESS Residual(T+1): Site 436

TABLE D.2. Availability and Use of Predictors for Least Squares Model for Each Site

SITE ID	PYR	WSP	HUM	WDR	IG	SUBSEASON	IAT	OAT
044	NA	NA	NA	NA			X	
050	NA	NA	NA	X				
056	1,2,3	X	X		2			X
062			NA		2		NA	
191	NA	X		NA		1,2	X	
230		X	X		3			X
269	2					1,2	X	X
381			NA		1		X	X
436		X			2			

NA: Variable Not Available
X: Variable Used In Predicting Residuals
i: Variable Used in Predicting Residuals, Subseason i

TABLE D.3. Final Best Regression Fit

BEST MODEL, SITE 044 — R SQUARE = 0.06872798 — C(P) = 8.06969532

	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	1	0.00149882	0.00149882
ERROR	184	0.02030922	0.00011038
TOTAL	185	0.02180804	

	B VALUE	STD ERROR	TYPE II SS
INTERCEPT	0.39033737		
IAT	-0.00013559	0.00003680	0.00149882

BEST MODEL, SITE 050 — R SQUARE = 0.07378863 — C(P) = -1.48207232

	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	1	0.00018254	0.00018254
ERROR	101	0.00229128	0.00002269
TOTAL	102	0.00247382	

	B VALUE	STD ERROR	TYPE II SS
INTERCEPT	0.00409512		
WDR	-0.00002494	0.00000879	0.00018254

BEST MODEL, SITE 056 — R SQUARE = 0.43170789 — C(P) = 14.79544117

	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	7	0.00892222	0.00127460
ERROR	208	0.01174504	0.00005647
TOTAL	215	0.02066727	

	B VALUE	STD ERROR	TYPE II SS
INTERCEPT	-0.22762429		
PYR1	-0.00011903	0.00001566	0.00326321
PYR2	-0.00018043	0.00002247	0.00364237
PYR3	-0.00008584	0.00001132	0.00324467
IG2	0.00001464	0.00000404	0.00073968
WSP	0.00003621	0.00001566	0.00030190
HUM	0.00020509	0.00007333	0.00044168
OAT	0.00008165	0.00001375	0.00199105

BEST MODEL, SITE 062 — R SQUARE = 0.18024926 — C(P) = 6.86025678

	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	2	0.00145173	0.00072586
ERROR	113	0.00660228	0.00005843
TOTAL	115	0.00805401	

TABLE D.3. (contd)

	B VALUE	STD ERROR	TYPE II SS
INTERCEPT	-0.00463472		
IG2	-0.00000217	0.00000100	0.00027828
WSP	0.00004268	0.00000885	0.00135757

BEST MODEL, SITE 191 R SQUARE = 0.38229146 C(P) = 14.67964533

	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	3	0.00482744	0.00160915
ERROR	168	0.00780021	0.00004643
TOTAL	171	0.01262765	

	B VALUE	STD ERROR	TYPE II SS
INTERCEPT	0.36042819		
WSP	0.00002364	0.00000441	0.00133063
MOSET2	0.00319281	0.00063666	0.00116770
IAT	-0.00012534	0.00005122	0.00027806

BEST MODEL, SITE 230 R SQUARE = 0.29009636 C(P) = 6.42487958

	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	4	0.00235968	0.00058992
ERROR	166	0.00577446	0.00003479
TOTAL	170	0.00813414	

	B VALUE	STD ERROR	TYPE II SS
INTERCEPT	-0.06575973		
IG3	-0.00000674	0.00000213	0.00034730
WSP	0.00001920	0.00000475	0.00056876
HUM	-0.00066276	0.00019665	0.00039513
OAT	0.00002885	0.00001020	0.00027851

BEST MODEL, SITE 269 R SQUARE = 0.36614754 C(P) = 7.69512907

	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	5	0.00781464	0.00156293
ERROR	228	0.01352824	0.00005933
TOTAL	233	0.02134288	

TABLE D.3. (contd)

	B VALUE	STD ERROR	TYPE II SS
INTERCEPT	0.25355823		
PYR2	-0.00022259	0.00002703	0.00402524
MOSET1	-0.00751419	0.00110186	0.00275943
MOSET2	0.01459831	0.00152435	0.00544181
IAT	-0.00010657	0.00003761	0.00047630
OAT	0.00002336	0.00001013	0.00031568

BEST MODEL, SITE 381 R SQUARE = 0.20013280 C(P) = 1.29427740

	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	3	0.00067213	0.00022404
ERROR	152	0.00268629	0.00001767
TOTAL	155	0.00335841	

	B VALUE	STD ERROR	TYPE II SS
INTERCEPT	1.31004159		
IG1	-0.00000111	0.00000035	0.00017408
IAT	-0.00047543	0.00008196	0.00059471
OAT	0.00003275	0.00000773	0.00031720

BEST MODEL, SITE 436 D R SQUARE = 0.65258107 C(P) = 9.37451790

	DF	SUM OF SQUARES	MEAN SQUARE
REGRESSION	3	0.03534961	0.01178320
ERROR	115	0.01881930	0.00016365
TOTAL	118	0.05416891	

	B VALUE	STD ERROR	TYPE II SS
INTERCEPT	1.14576678		
PYR2	-0.00020441	0.00006925	0.00142590
PYR3	-0.00011987	0.00001703	0.00810727
IAT	-0.00038767	0.00003618	0.01878809

temperature, for example, are often accompanied by somewhat predictable changes in other weather variables; hence, it may be of more academic than practical interest to consider a large temperature change during which the other weather variables are held constant.

Care must be taken in interpreting beta weights for a regression coefficient since it is applicable to less than the full set of data. For example, b(i) is applicable only to the ith subseason of the heating season; hence, the scaling of b(i) to obtain its corresponding beta weight must also be based only on the ith subseason. Furthermore, the resulting beta weight can only be compared to other beta weights based on the same subseason. This requires the computation of up to four sets of beta weights for each site: one set for each of the subseasons plus one set which covers the entire season. Clearly, beta weights restricted to a particular subseason can be derived for coefficients applicable to the entire set of data, while only a single beta weight over the appropriate subseason can be obtained for coefficients applicable to a single subseason.

Table D.4 summarizes the meaningful beta weights for the estimated models. To illustrate the interpretation of the tables, consider Table D.4. The wind speed, humidity, and outside air temperature variables were each included in the model for site 56. Because each of these variables was assigned a single weight for the entire heating season, their relative importance can be judged across the entire season. Outside air temperature seems to be most important, since its beta weight is largest, while wind speed is judged to be least important, since its beta weight is smallest. The numerical value of a given weight represents the number of standard deviations of change which will be seen in the dependent variable for a unit standard deviation of change in the predictor variable. Because the pyrometer-1 weight applies only to the first subseason (August through October), it can only be compared to beta weights computed for the same time period. Subseason-specific weights can be computed for variables whose regression coefficients span the entire heating season by multiplying the coefficient by the quotient of the standard deviation of the predictor variable, restricted to the appropriate subseason, the standard deviation of the dependent variable, also so

TABLE D.4. Variables Selected for the Best Least Squares Model for Each Site

4a. Beta Weights: Site 44

VARIABLE	AUG-MAY	AUG-OCT	NOV-FEB	MAR-MAY
Intercept	NA	NA	NA	NA
Inside Air Temp	-.262	NA	NA	NA
Sample Size	186	38	110	38

4b. Beta Weights: Site 50

VARIABLE	AUG-MAY	AUG-OCT	NOV-FEB	MAR-MAY
Intercept	NA	NA	NA	NA
Wind Direction	-.583	NA	NA	NA
Sample Size	103	0	22	81

4c. Beta Weights: Site 56

VARIABLE	AUG-MAY	AUG-OCT	NOV-FEB	MAR-MAY
Intercept	NA	NA	NA	NA
Pyrometer 1	NA	-.793	NA	NA
Pyrometer 2	NA	NA	-.495	NA
Pyrometer 3	NA	NA	NA	-.759
Internal Gains 2	NA	NA	.122	NA
Wind Speed	.134	.153	.104	.164
Humidity	.208	.190	.153	.094
Outside Air Temp	.517	.316	.319	.362
Sample Size	216	36	100	80

TABLE D.4. (contd)

4d. Beta Weights: Site 62

VARIABLE	AUG-MAY	AUG-OCT	NOV-FEB	MAR-MAY
Intercept	NA	NA	NA	NA
Internal Gains 2	NA	-.0595	NA	NA
Wind Speed	.419	.427	NA	NA
Sample Size	116	0	39	77

4e. Beta Weights: Site 191

VARIABLE	AUG-MAY	AUG-OCT	NOV-FEB	MAR-MAY
Intercept	NA	NA	NA	NA
Subseason 1	NA	NA	NA	NA
Subseason 2	NA	NA	NA	NA
Wind Speed	.534	NA	NA	NA
Inside Air Temp	-.191	NA	NA	NA
Sample Size	172	17	100	55

4f. Beta Weights: Site 230

VARIABLE	AUG-MAY	AUG-OCT	NOV-FEB	MAR-MAY
Intercept	NA	NA	NA	NA
Internal Gains 3	NA	NA	NA	-.195
Wind Speed	-.307	NA	NA	-.266
Humidity	.394	NA	NA	.316
Outside Air Temp	.332	NA	NA	.168
Sample Size	171	0	110	61

TABLE D.4. (contd)

4g. Beta Weights: Site 269

VARIABLE	AUG-MAY	AUG-OCT	NOV-FEB	MAR-MAY
Intercept	NA	NA	NA	NA
Pyrometer 2	NA	NA	-.552	NA
Indoor Air Temp	-.173	NA	-.148	NA
Outdoor Air Temp	.179	NA	.135	NA
Sample Size	234	70	106	58

4h. Beta Weights: Site 381

VARIABLE	AUG-MAY	AUG-OCT	NOV-FEB	MAR-MAY
Intercept	NA	NA	NA	NA
Internal Gains 1	NA	-.404	NA	NA
Indoor Air Temp	-.673	-1.43	NA	NA
Outdoor Air Temp	.514	.884	NA	NA
Sample Size	156	18	113	25

4i. Beta Weights: Site 436

VARIABLE	AUG-MAY	AUG-OCT	NOV-FEB	MAR-MAY
Intercept	NA	NA	NA	NA
Pyrometer 2	NA	NA	-1.77	NA
Pyrometer 3	NA	NA	NA	-.553
Indoor Air Temp	-.609	NA	-.694	-.542
Sample Size	186	38	110	38

restricted. A study of the tables reveals no clear patterns regarding the relative importance of the variables in predicting LOWESS residuals. This may be because of the diversity of characteristics of the studied sites. A study of sites with similar characteristics may prove more conclusive.

EXAMINATION OF THE LEAST SQUARES RESIDUALS

The ols residuals represent the differences between the actual LOWESS residuals and the LOWESS residuals as predicted by the ols models defined above. These sets of residuals were examined graphically in exactly the same ways as were the LOWESS residuals. The ols residual plots (Figures D.4a through D.4i, D.5a through D.5i, and D.6a through D.6i) usually display the general characteristics of their corresponding LOWESS residual plots. While the correlation between time-adjacent residuals was reduced slightly for most sites, the reduction was not generally substantial. Only for site 191 did the other residual plots display satisfactory improvement.

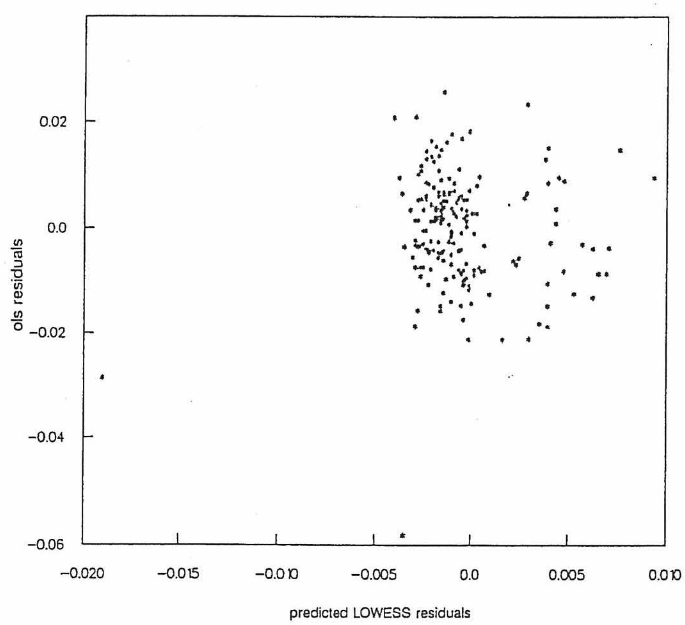


FIGURE D.4a OLS Residuals Versus Predicted LOWESS Residuals: Site 44

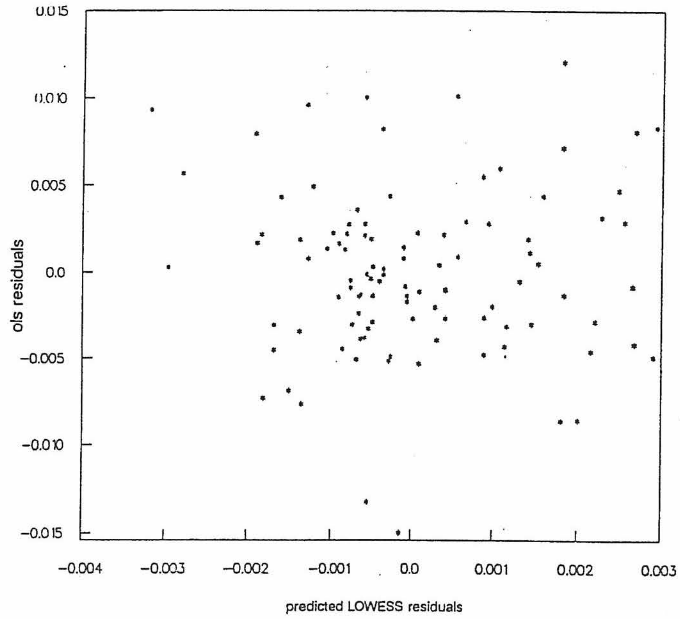


FIGURE D.4b OLS Residuals Versus Predicted LOWESS Residuals: Site 50

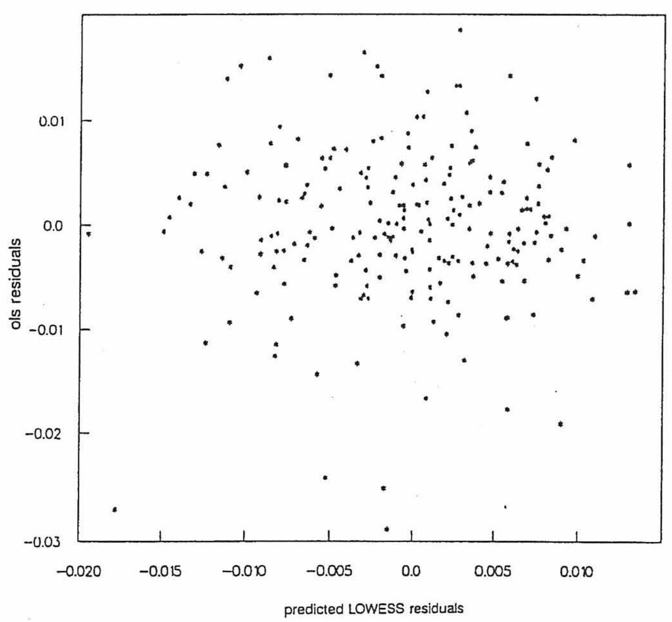


FIGURE D.4c OLS Residuals Versus Predicted LOWESS Residuals: Site 56

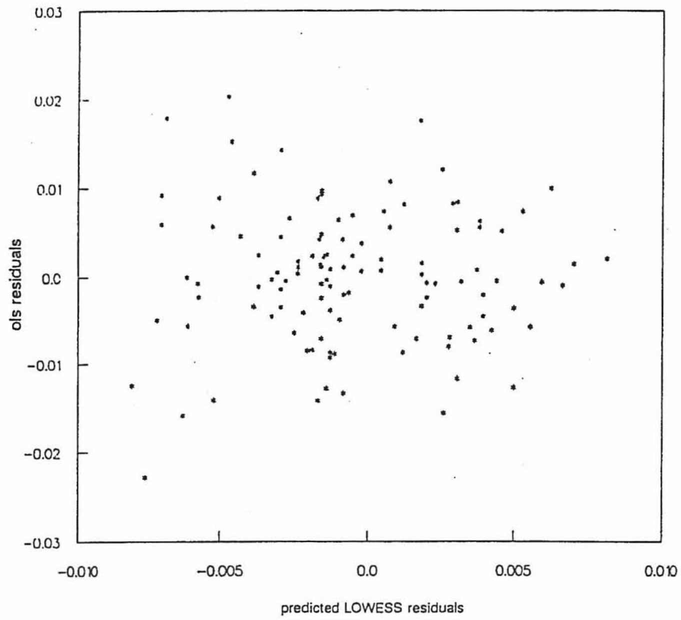


FIGURE D.4d OLS Residuals Versus Predicted LOWESS Residuals: Site 62

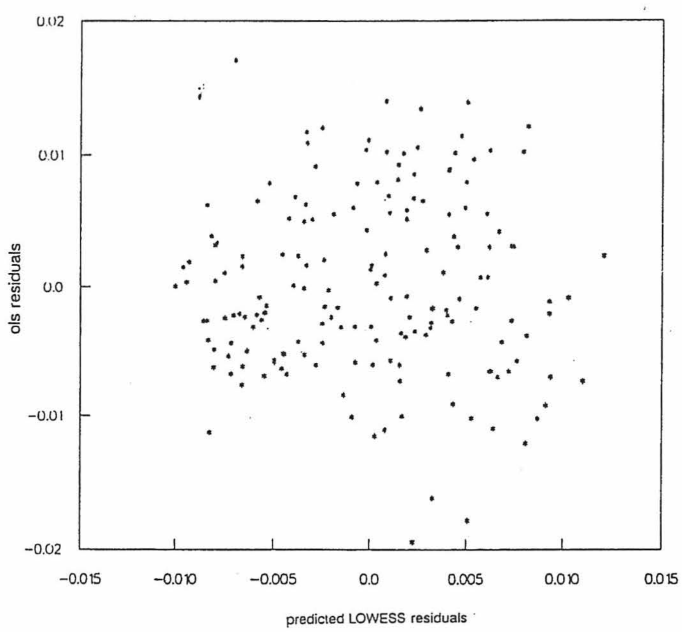


FIGURE D.4e OLS Residuals Versus Predicted LOWESS Residuals: Site 191

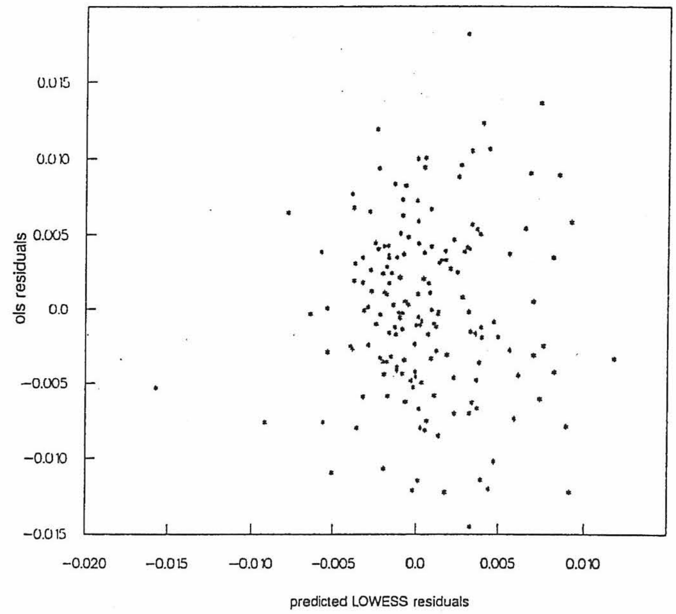


FIGURE D.4f OLS Residuals Versus Predicted LOWESS Residuals: Site 230

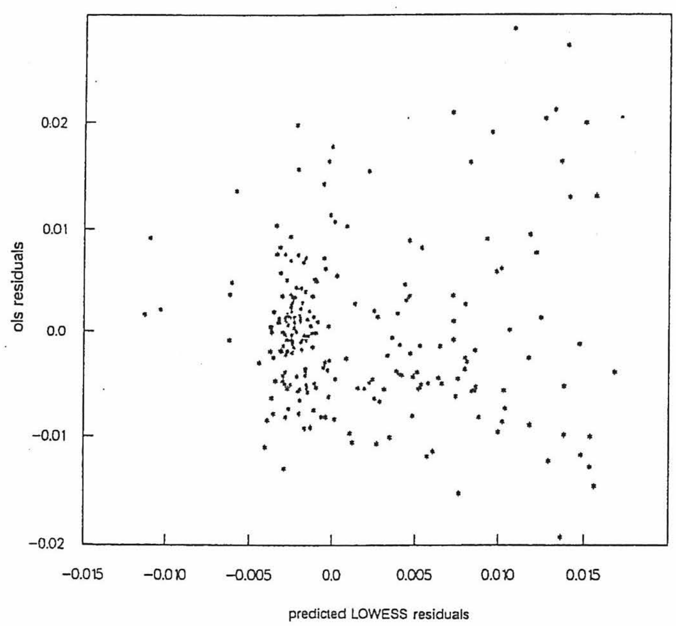


FIGURE D.4g OLS Residuals Versus Predicted LOWESS Residuals: Site 269

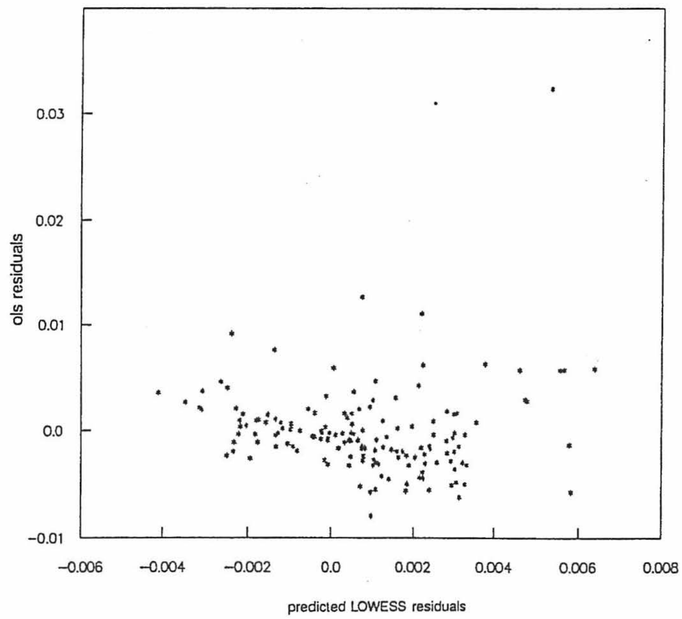


FIGURE D.4h OLS Residuals Versus Predicted LOWESS Residuals: Site 381

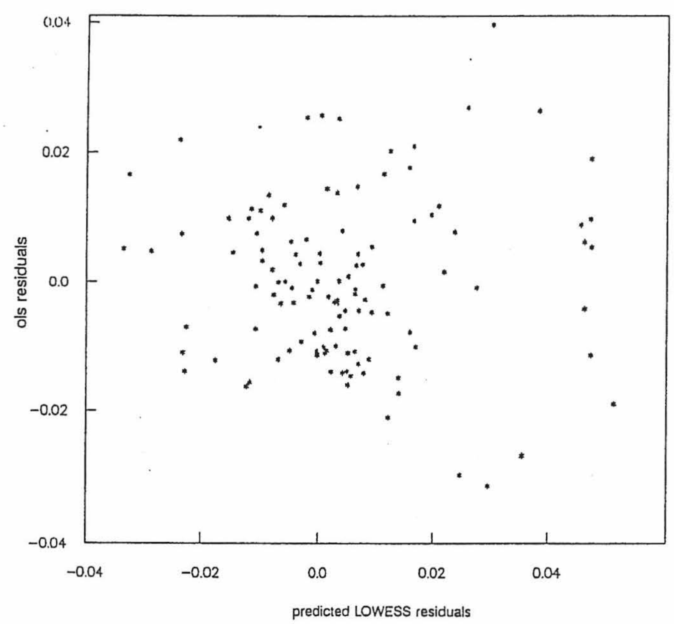


FIGURE D.4i OLS Residuals Versus Predicted LOWESS Residuals: Site 436

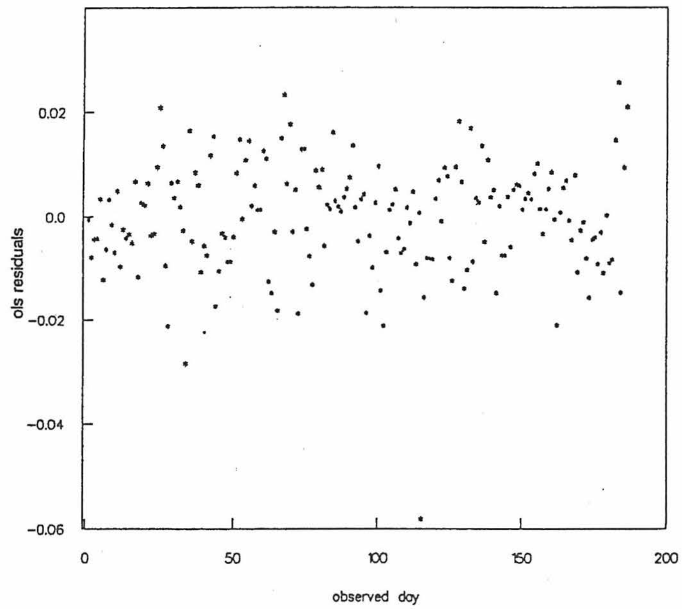


FIGURE D.5a OLS Residuals Versus Time: Site 44

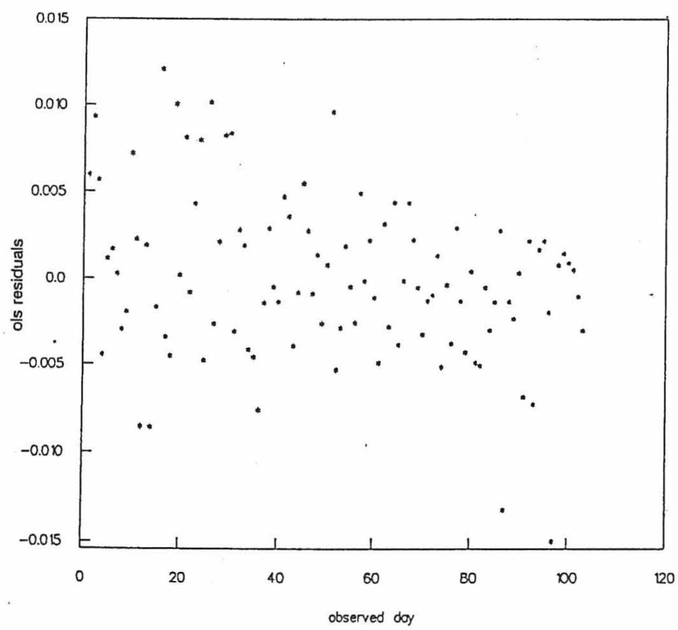


FIGURE D.5b OLS Residuals Versus Time: Site 50

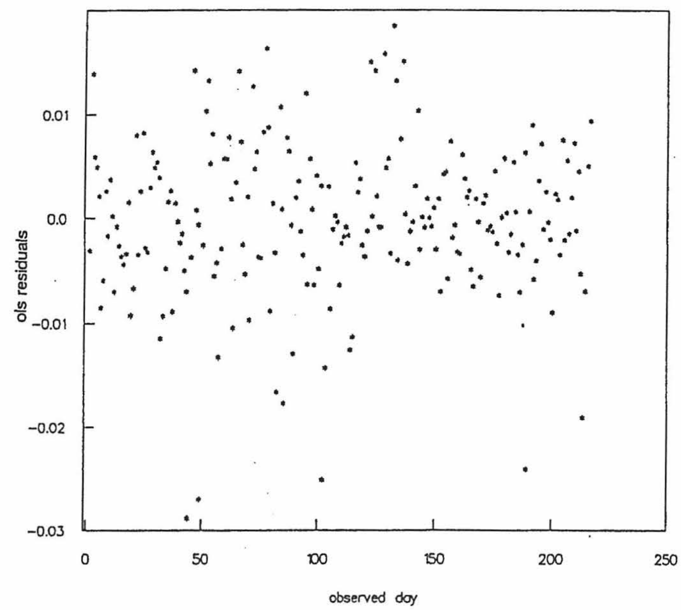


FIGURE D.5c OLS Residuals Versus Time: Site 56

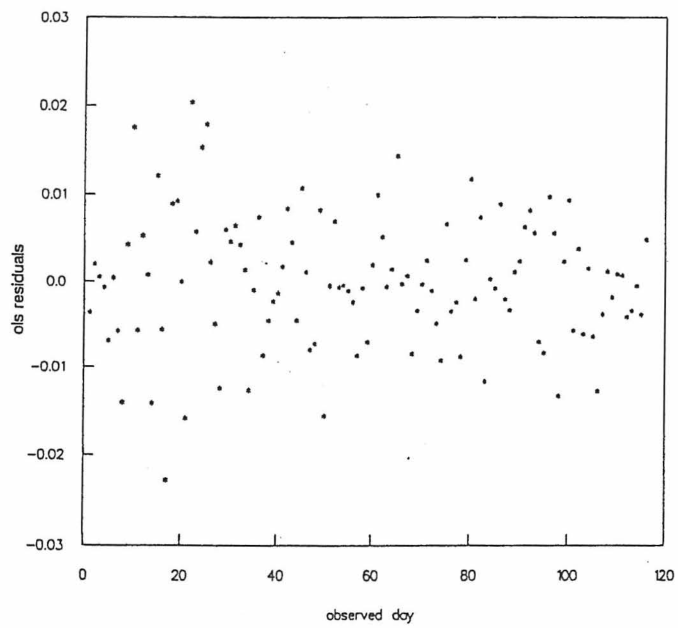


FIGURE D.5d OLS Residuals Versus Time: Site 62

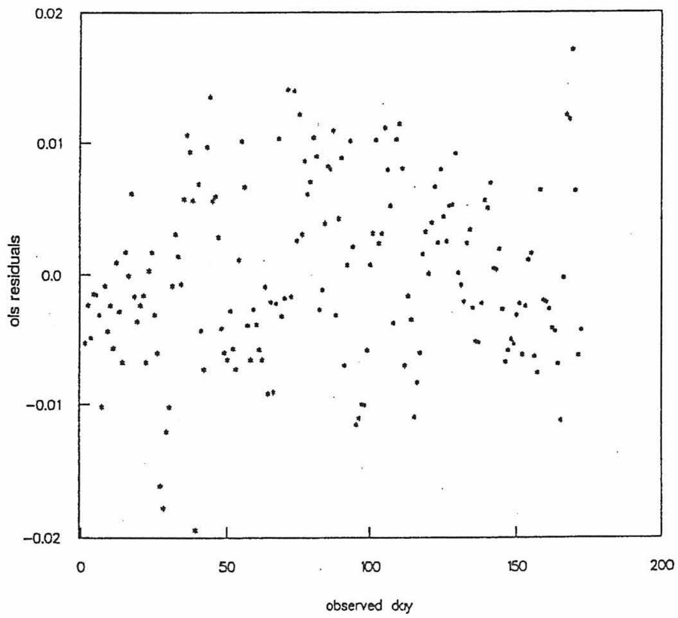


FIGURE D.5e OLS Residuals Versus Time: Site 191

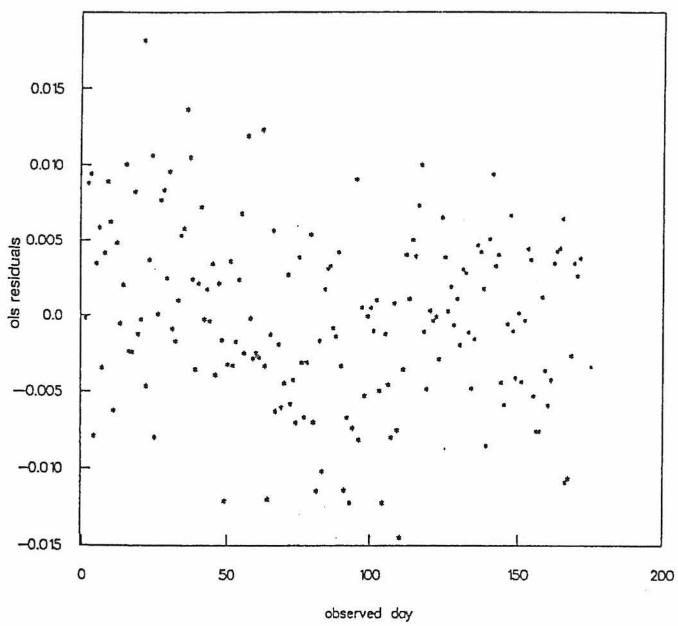


FIGURE D.5f OLS Residuals Versus Time: Site 230

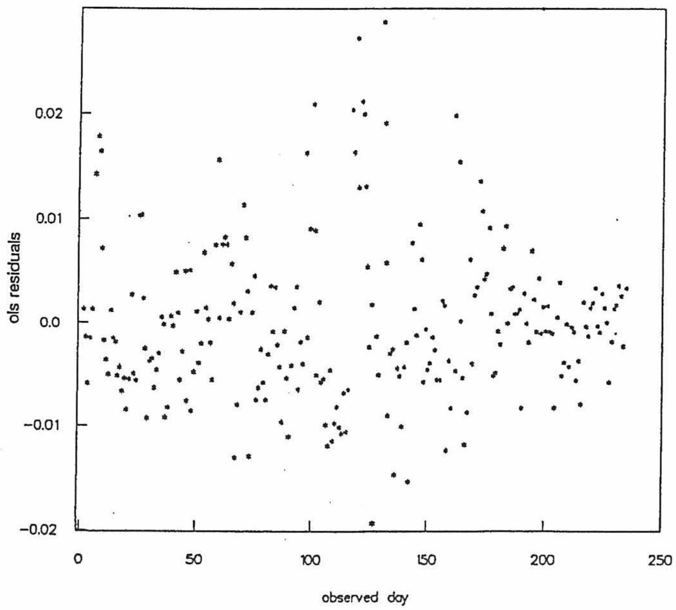


FIGURE D.5g OLS Residuals Versus Time: Site 269

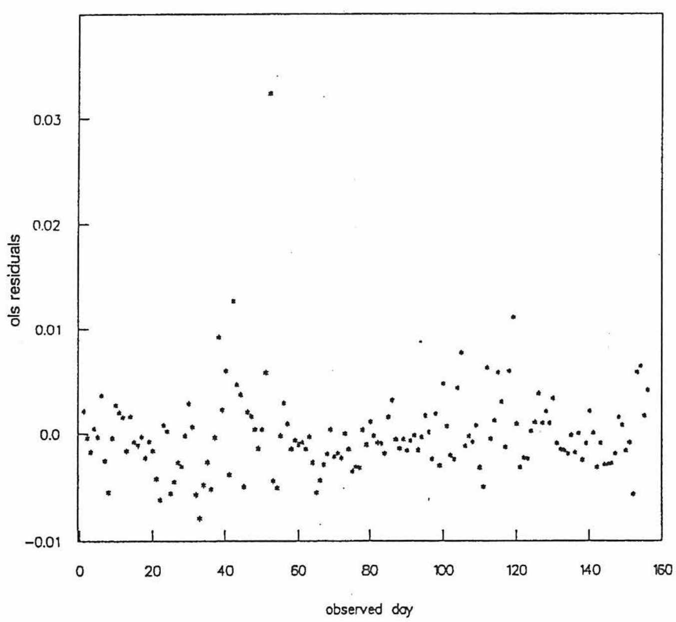


FIGURE D.5h OLS Residuals Versus Time: Site 381

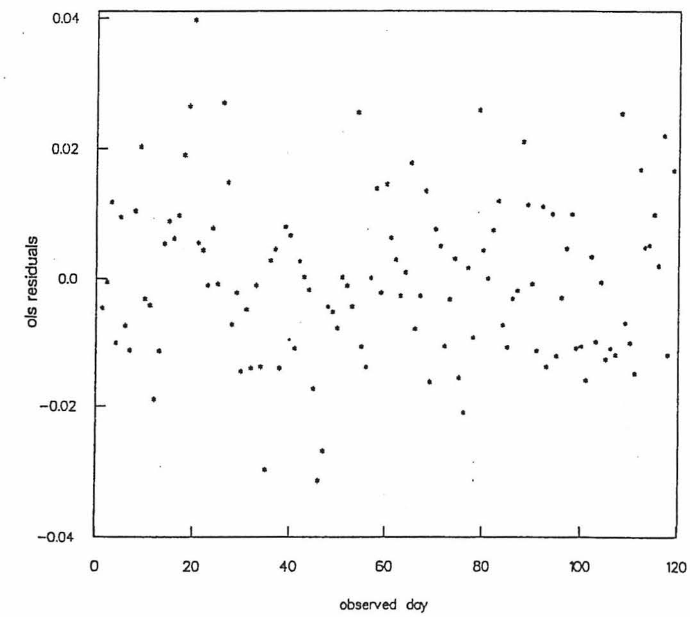


FIGURE D.5i OLS Residuals Versus Time: Site 436

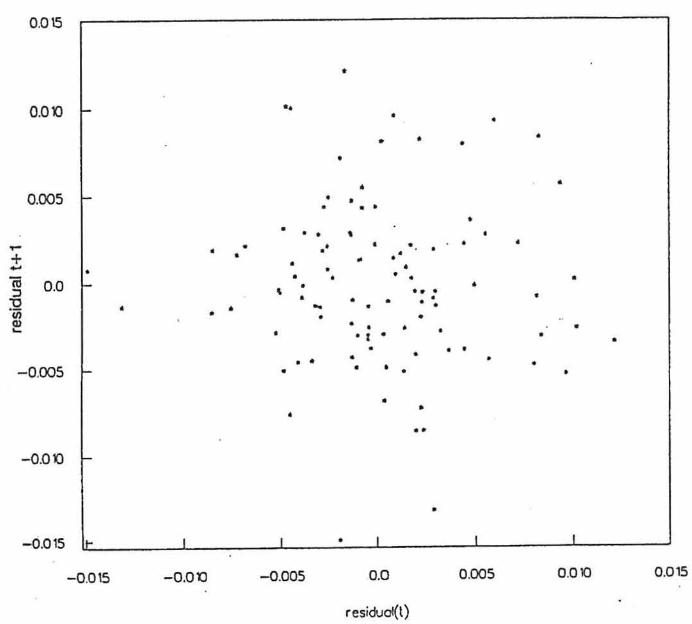
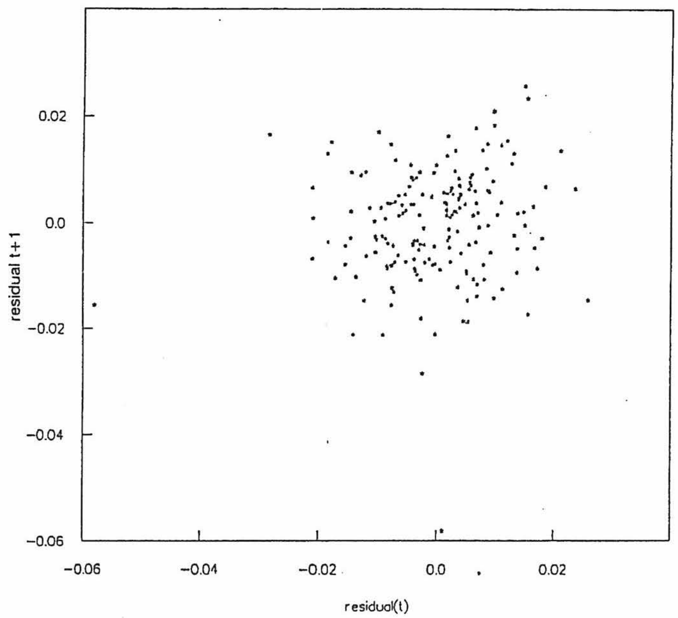
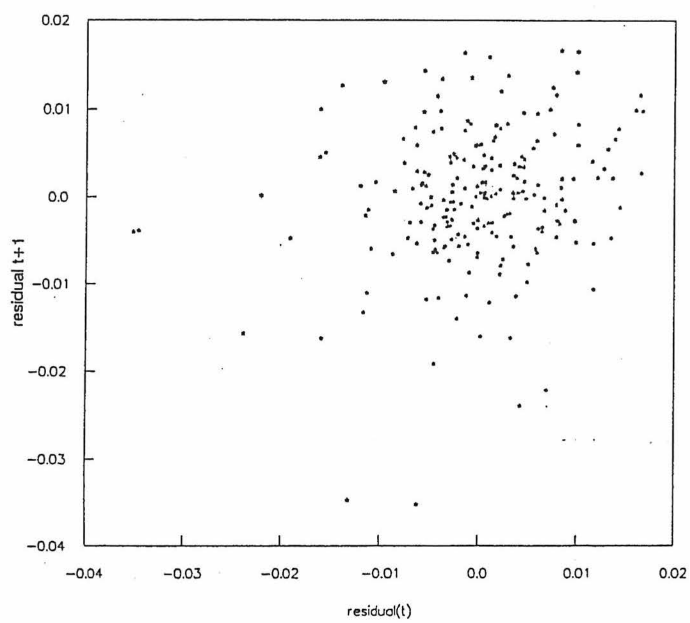


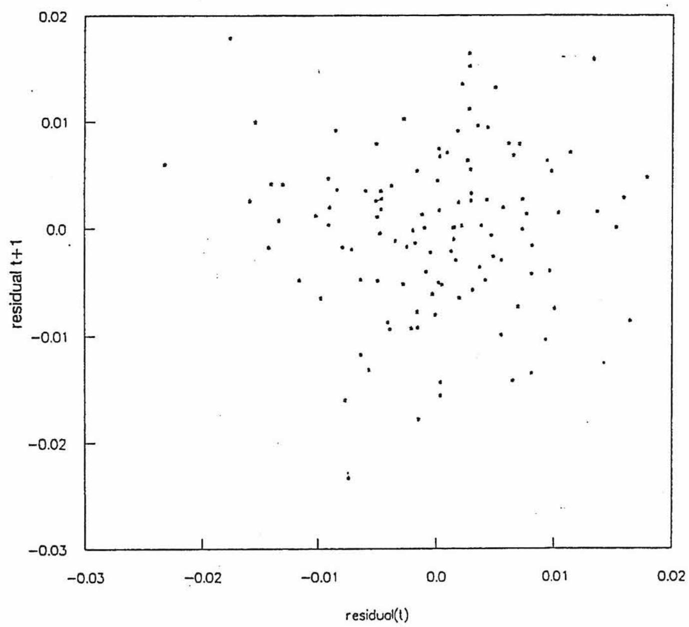
FIGURE D.6a OLS Residual(T) Versus OLS Residual(T+1): Site 44



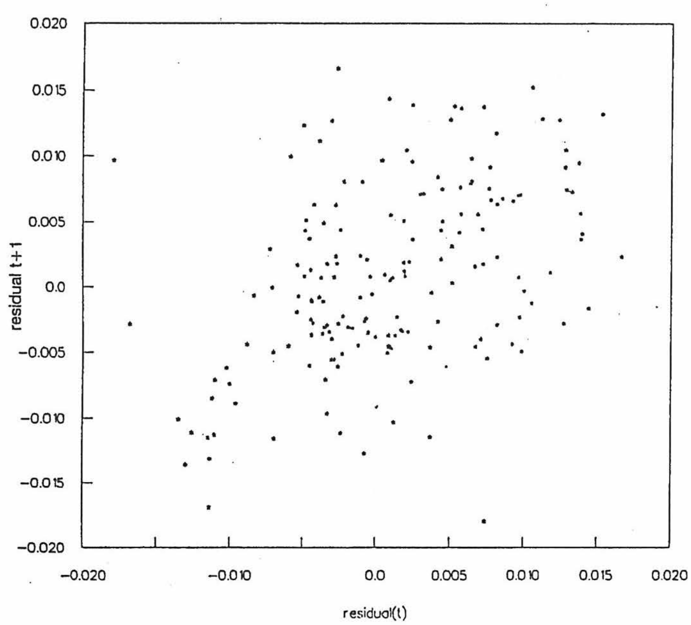
<u>FIGURE D.6b</u> OLS Residual(T) Versus OLS Residual(T+1): Site 50



<u>FIGURE D.6c</u> OLS Residual(T) Versus OLS Residual(T+1): Site 56



<u>FIGURE D.6d</u> OLS Residual(T) Versus OLS Residual(T+1): Site 62



<u>FIGURE D.6e</u> OLS Residual(T) Versus OLS Residual(T+1): Site 191

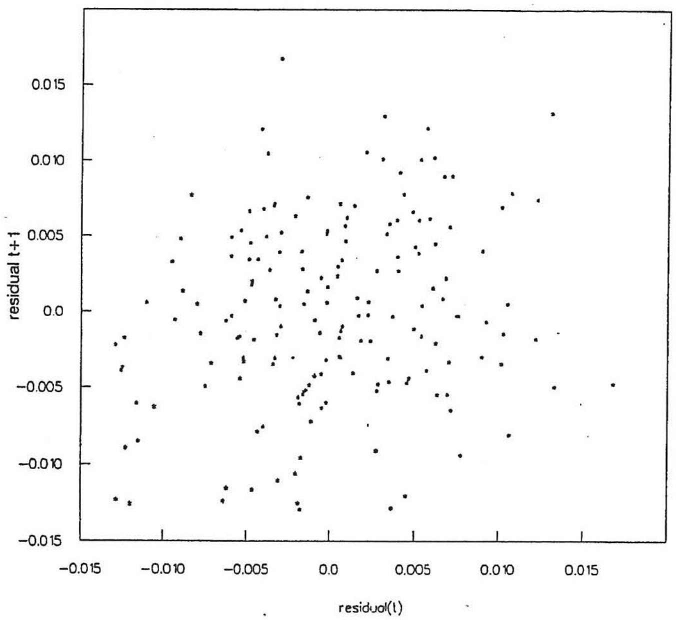


FIGURE D.6f OLS Residua(T)l Versus OLS Residual(T+1): Site 230

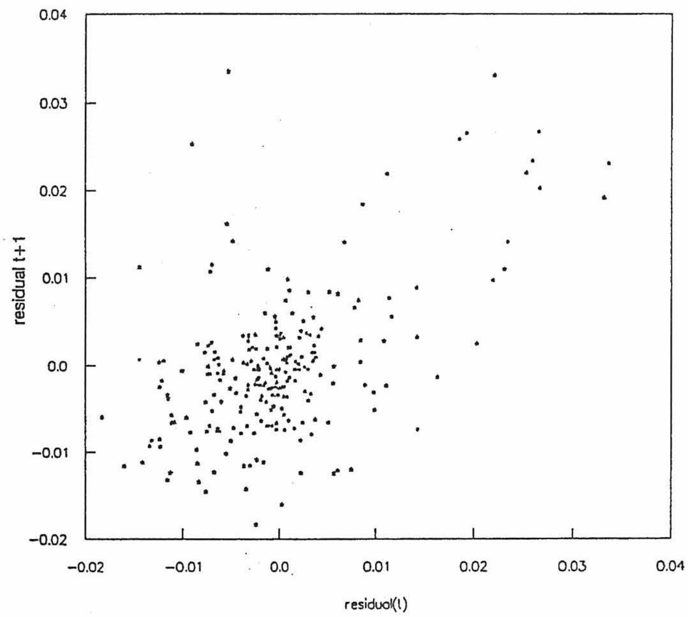


FIGURE D.6g OLS Residual(T) Versus OLS Residual(T+1): Site 269

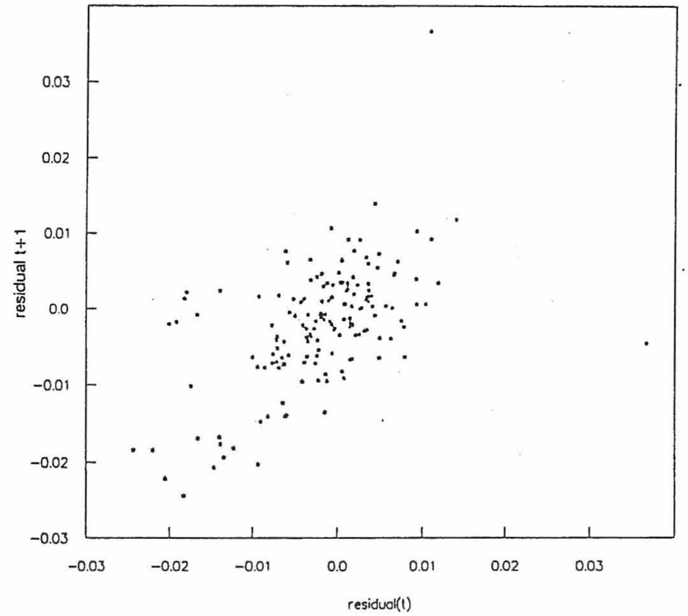


FIGURE D.6h OLS Residual(T) Versus OLS Residual(T+1): Site 381

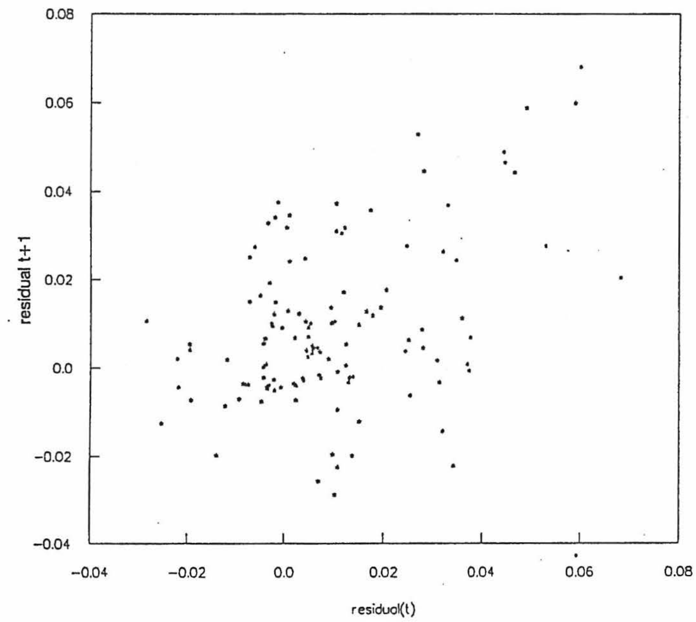


FIGURE D.6i OLS Residua(T)l Versus OLS Residual(T+1): Site 436

APPENDIX E

TOPOLOGICAL CLASSIFICATIONS OF SMOOTH-CURVE FITS

APPENDIX E

TOPOLOGICAL CLASSIFICATIONS OF SMOOTH-CURVE FITS

In the thermal characterizations for the residential base sample, the smooth-curve fits to the scatter plot of daily electrical space heating energy consumption versus temperature difference were classified according to their shape. Five shapes were distinguished during the classification process. In this section, those shapes are defined and illustrated with samples from each category. In addition, the full distribution of shapes is graphically displayed by heating system categories and then by foundation types. Finally, for those sites having both foundation type and heating system identified, Table E.1 summarizes that breakdown of topological shapes by both heating system and foundation type.

In the categorical examples that follow, each figure was selected at random. Hence the presentation does not include the best examples of the shape; rather the presentation gives an illustration of the shape category.

TOPOLOGICAL SHAPE 1

Figure E.1 displays the most purely linear category. For sites in this category, the smooth-fit curvature most closely resembles a line without a lower nonlinear region.

TOPOLOGICAL SHAPE 2

Figure E.2 illustrates the LOWESS curve that is essentially linear with a nonlinear low ΔT region. For many purposes, it may be useful to combine shapes 1 and 2 into a single linear class as was done in the body of the paper.

TOPOLOGICAL SHAPE 3

Figure E.3 displays the concave-upward shape for the space heating curve-versus-temperature difference.

TABLE E.1. Topological Shapes Split by Heating System and Foundation Type

Topology 1	Forced Air	Baseboard	Radiant	Heat Pump
heated basement (hb)	1	2	NA	NA
unheated basement (ub)	NA	1	NA	NA
slab(s)	2	1	1	NA
crawl(c)	4	13	2	1
ub+c	NA	1	NA	NA
ub+c+s	NA	NA	NA	NA
hb+s	NA	NA	NA	NA
hb+c	NA	1	1	NA
hb+c+s	2	NA	NA	NA
c+s	NA	NA	1	NA
Topology 2				
heated basement (hb)	NA	2	NA	NA
unheated basement (ub)	1	NA	NA	NA
slab(s)	NA	NA	NA	NA
crawl(c)	7	4	NA	NA
ub+c	NA	1	NA	NA
ub+c+s	NA	NA	NA	NA
hb+s	1	NA	NA	NA
hb+c	NA	NA	NA	NA
hb+c+s	1	NA	NA	NA
c+s	1	1	NA	NA
Topology 3				
heated basement (hb)	2	NA	NA	NA
unheated basement (ub)	NA	NA	1	NA
slab(s)	NA	NA	NA	NA
crawl(c)	3	3	NA	3
ub+c	NA	3	NA	1
ub+c+s	NA	NA	NA	1
hb+s	NA	1	NA	1
hb+c	1	NA	NA	1
hb+c+s	NA	NA	NA	NA
c+s	1	1	1	2
Topology 4				
heated basement (hb)	3	1	NA	NA
unheated basement (ub)	2	1	NA	NA
slab(s)	NA	NA	1	NA
crawl(c)	4	3	1	NA
ub+c	NA	1	NA	NA
ub+c+s	1	NA	NA	NA
hb+s	1	NA	NA	NA
hb+c	NA	NA	NA	NA
hb+c+s	NA	NA	NA	NA

TABLE E.1. (contd)

Topology 5	Forced Air	Baseboard	Radiant	Heat Pump
heated basement (hb)	NA	1	NA	NA
unheated basement (ub)	NA	1	NA	NA
slab(s)	NA	NA	NA	NA
crawl(c)	NA	NA	1	1
ub+c	NA	NA	NA	NA
ub+c+s	NA	NA	NA	NA
hb+s	1	1	NA	NA
hb+c	NA	NA	NA	1
hb+c+s	NA	1	NA	NA
c+s	1	NA	NA	NA

TOPOLOGICAL SHAPE 4

Figure E.4 is an example of the concave-downward shape. Note the problem associated with balance ΔT interpretation that a site with concave-downward topology may have. For many of the sites classified as type 4, the concave-downward portion of the curve is only evident for high ΔTs and does not present the severe problem with balance points as is the case in this example.

TOPOLOGICAL SHAPE 5

Figure E.5 displays the concave-upward then concave-downward topology. For many purposes, it may be useful to combine shapes 4 and 5 into a single category, concave-downward class as was done in the body of the report.

In Figures E.6 through E.9, the distribution of topological shapes is displayed by major heating system type for the residential base sample for all the all climate zones. The vertical axis for each of these figures illustrates the number of homes falling into each topological class. The heating system types included in these figures are electric forced air furnaces, baseboard, heat pumps, and radiant heat. In Figure E.6, the heat pumps appear much more likely to fall into category 3, independent of foundation type, than do the other heating systems. In Figures E.7 through E.9, half or more of the topological shapes for the remaining heating systems (forced air, baseboard, and radiant) fall into shape categories 1 or 2--the linear categories.

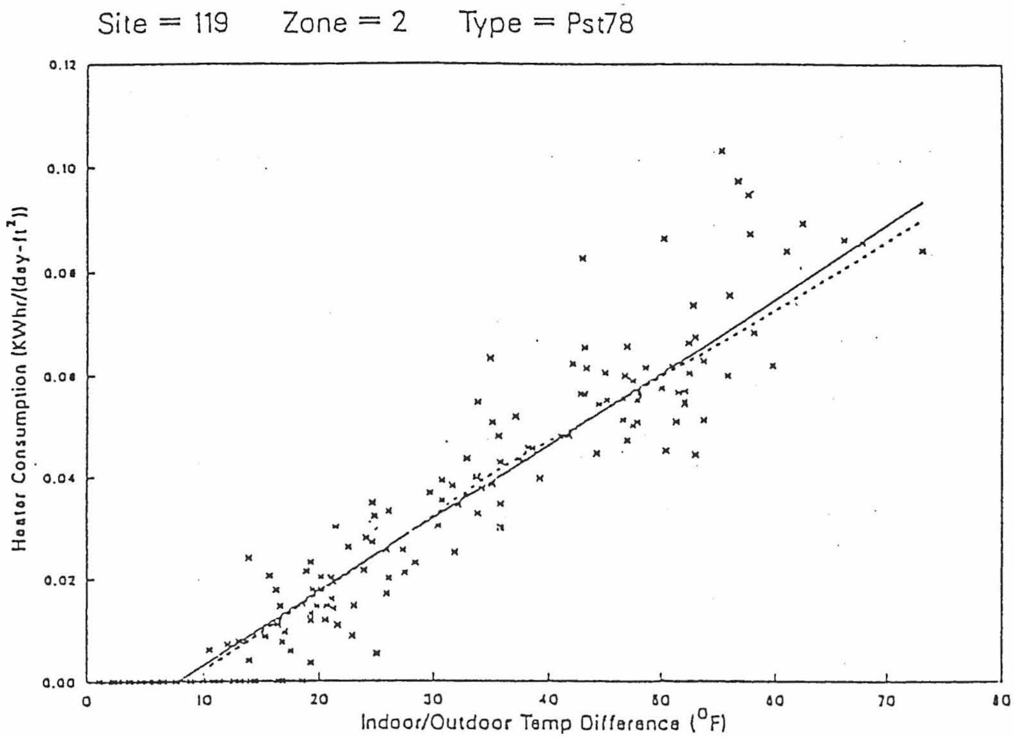


FIGURE E.1. Topological Shape 1--Linear

Table E.1 confirms the heat pump tie to the concave-upward shape. In this table, the topological shapes are broken out by heating system type and by foundation type. The entry in each cell gives the total number of sites falling into each bin. Column 5, labeled heat pumps, from the third section in Table E.1, displays the different foundation types that occur in heat-pump-system homes in the category-3 classification. It has been hypothesized that strong zoning practices may also be linked to the concave-upward topology.

In Figures E.10 through E.19, the distribution of topological shapes is displayed by foundation type for the residential base sample for the all-climate zones. The foundation types identified are those for heated basements, unheated basements, slabs, crawlspaces, unheated basements plus crawlspaces, crawlspaces plus slabs, heated basements plus slabs, heated basements plus crawlspaces, heated basements plus crawlspaces plus slabs, and crawlspaces plus slabs. The vertical axis for each of these figures displays

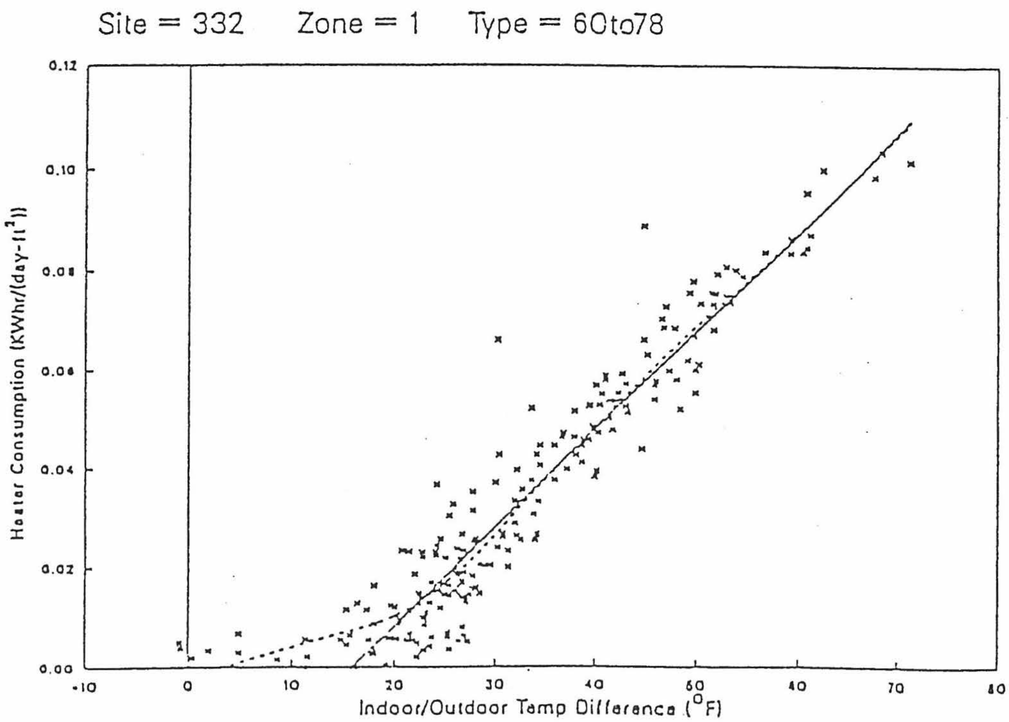


FIGURE E.2. Topological Shape 2--Linear with Nonlinear Low Delta Temperature Region

the number of homes falling into each classification scheme for the particular foundation type. In Figures E.12 and E.13, it would appear that both the slab and crawlspace homes have a tendency toward the more linear categories, 1 and 2. Most of the heating systems for these homes, however, are either baseboard or forced air, as Table E.1 indicates. There is some feeling that the basement homes may have a tendency toward the more concave-downward shapes of categories 4 and 5. This tendency is somewhat confirmed by the distributions for the pure basement types in Figures E.10 and E.11. Such a signal is much less clearly indicated, however, in the mixed-foundation homes with a basement as displayed in Figures E.14 through E.18.

Study of the topological shapes of the daily space-heating data versus indoor-outdoor temperature difference may incorporate structural features of the home, heating system type, and possibly certain occupancy control strategies. This is a desirable area for further investigation.

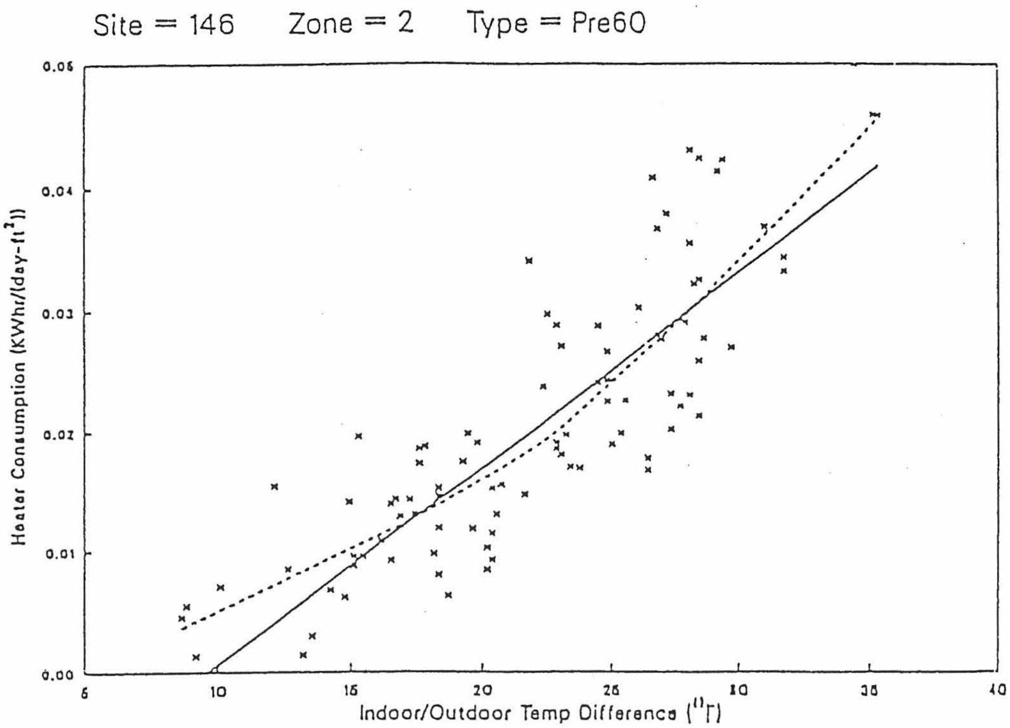


FIGURE E.3. Topological Shape 3--Concave Upward

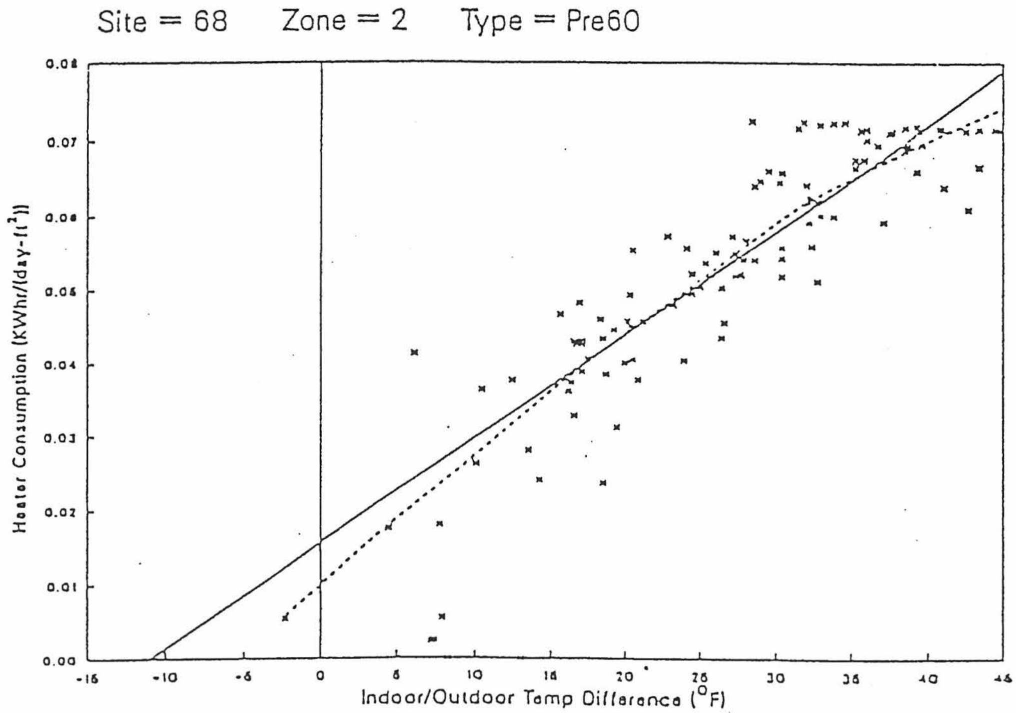


FIGURE E.4. Topological Shape 4--Concave Downward

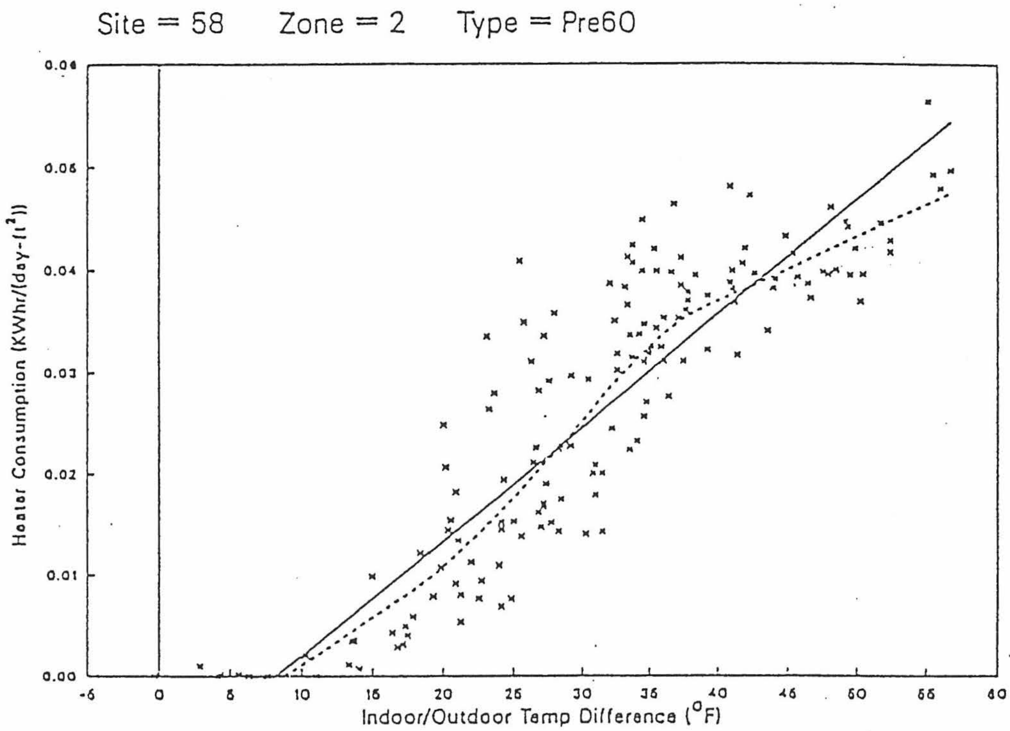


FIGURE E.5. Topological Shape 6--Concave Upward, Concave Downward

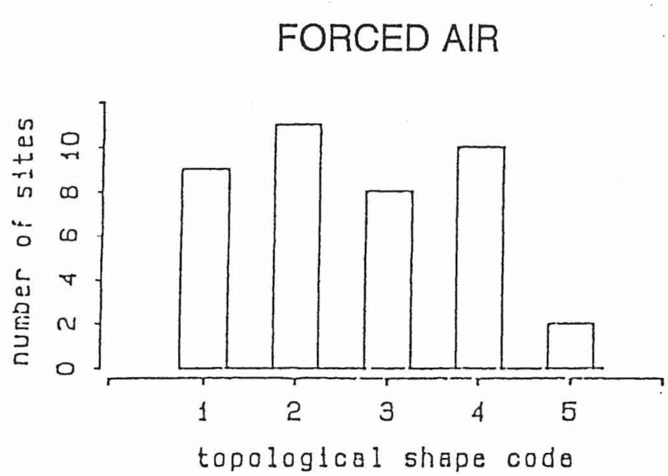


FIGURE E.6. Breakdown of Topological Shapes for Forced Air Heating System Homes

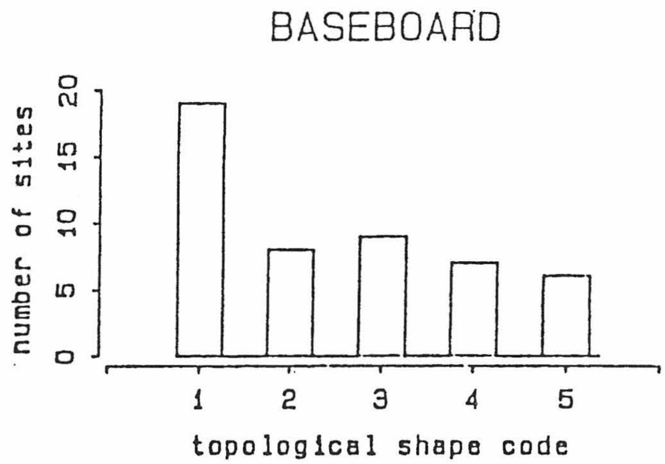


FIGURE E.7. Breakdown of Topological Shapes for Baseboard Heating System Homes

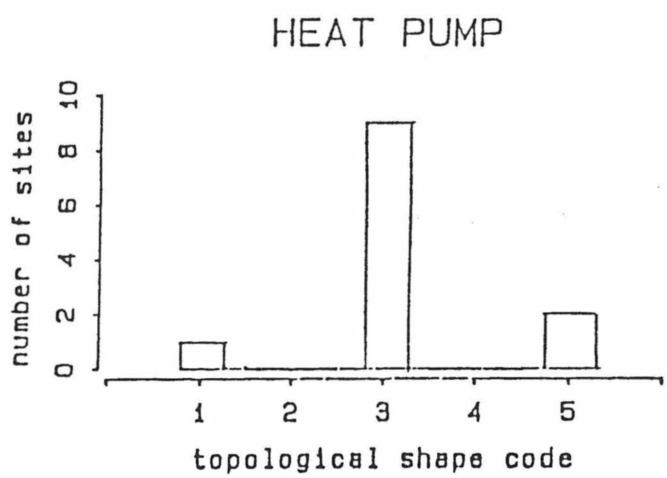


FIGURE E.8. Breakdown of Topological Shapes for Heat Pump Heating System Homes

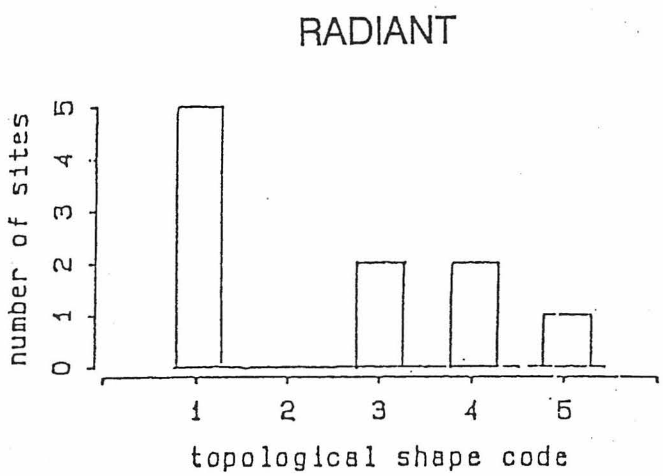


FIGURE E.9. Breakdown of Topological Shapes for Radiant Heating System Homes

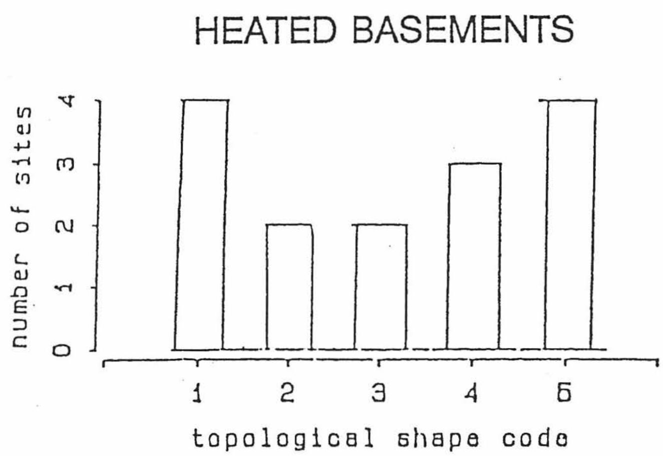


FIGURE E.10. Breakdown of Topological Shapes for Heated Basement Foundation Homes

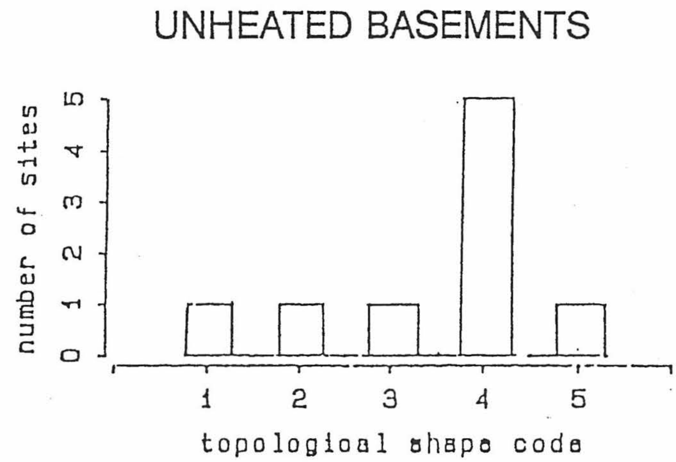


FIGURE E.11. Breakdown of Topological Shapes for Unheated Basement Foundation Homes

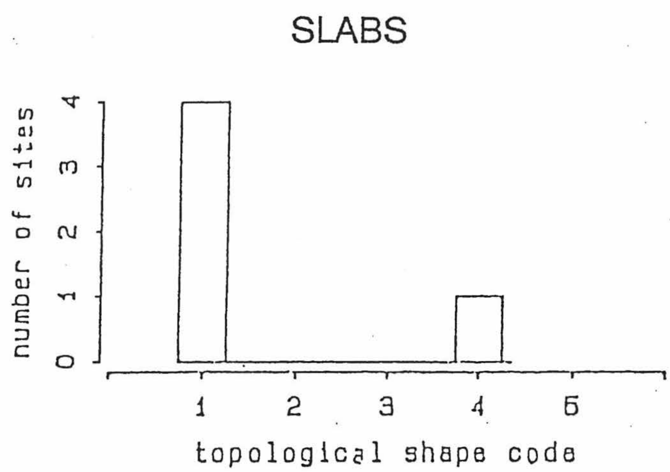


FIGURE E.12. Breakdown of Topological Shapes for Slab Foundation Homes

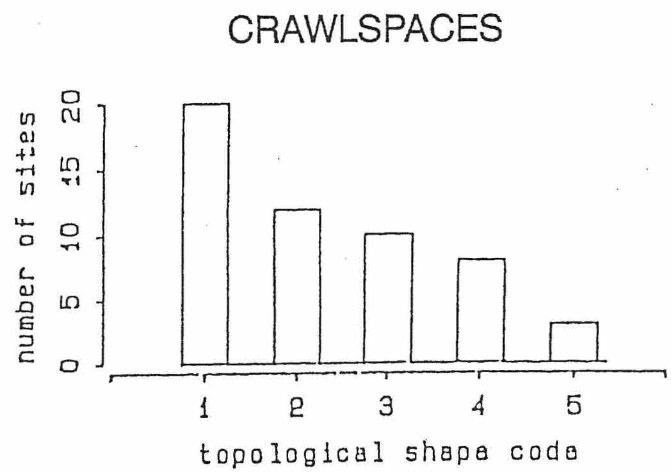


FIGURE E.13. Breakdown of Topological Shapes for Crawlspace Foundation Homes

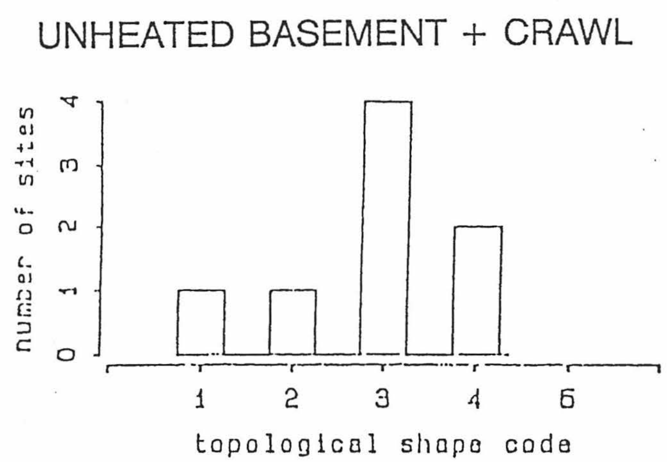


FIGURE E.14. Breakdown of Topological Shapes for Unheated Basement and Crawlspace Foundation Homes

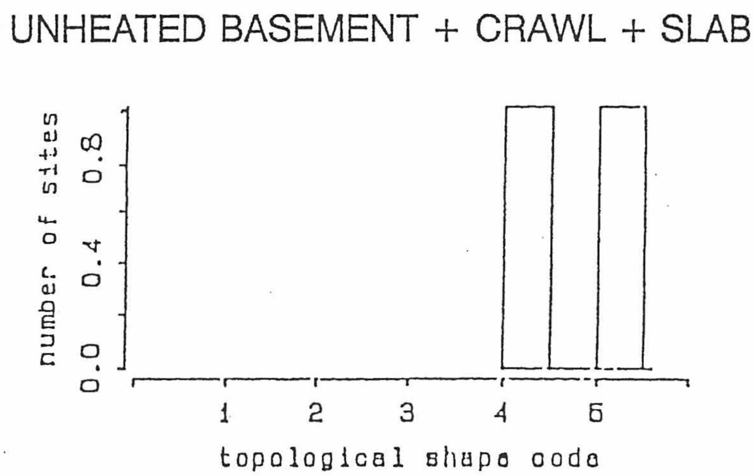


FIGURE E.15. Breakdown of Topological Shapes for Unheated Basement plus Crawlspace plus Slab Foundation Homes

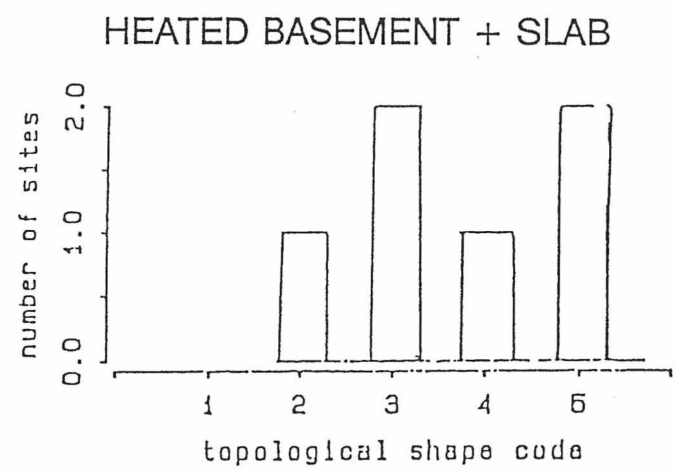


FIGURE E.16. Breakdown of Topological Shapes for Heated Basement plus Slab Foundation Homes

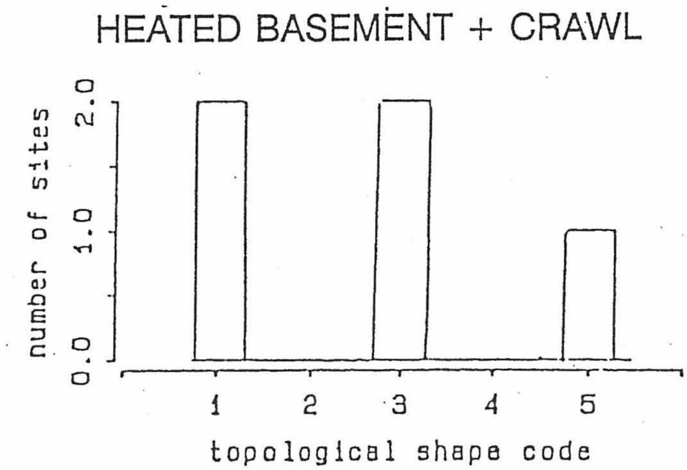


FIGURE E.17. Breakdown of Topological Shapes for Heated Basement plus Crawlspace Foundation Type

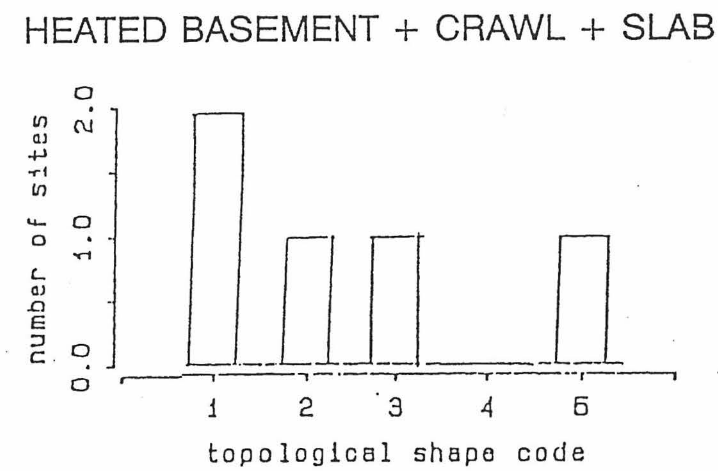


FIGURE E.18. Breakdown of Topological Shapes for Heated Basement plus Crawlspace plus Slab Foundation Homes

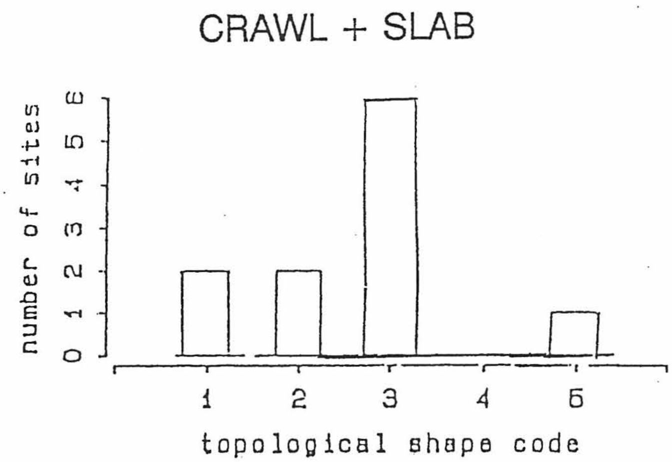


FIGURE E.19. Breakdown of Topological Shapes for Crawlspace plus Slab Foundation Homes

APPENDIX F

SECOND-YEAR ANALYSIS TABLES

APPENDIX F

SECOND-YEAR ANALYSIS TABLES

TABLE F.1. 1986-1987 ELCAP Residential Sample Characterization - Total Conditioned Floor Area (units are in ft^2)

GENERAL STATISTICS

	Base SITES	Post-78	Control	MCS
N=	121	13	20	37
Means	1729	1910.5	1496.9	1748.2
Medians	1631	2112	1488	1650
Std Dev	706	584.5	270.3	424.9
Means T=.2	1647	1956.7	1465.3	1663.5
Std Dev T=.2	697.3	865.9	258.8	359.4

STATISTICS FOR SET OF STRUCTURES IN MILD MCS CLIMATE ZONE

	CZ1 BASE	CZ1 POST-78	CZ1 Control	CZ1 MCS
N=	85	9	14	22
Means	1660.3	1985.6	1447.9	1635.3
Medians	1492	2271	1488	1488
Std Dev	641.3	609.6	172.8	431
Means T=.2	1566.8	2027.3	1459.6	1536
Std Dev T=.2	697.7	1074.3	173.9	268.8

STATISTICS FOR SET OF STRUCTURES IN COLDER MCS CLIMATE ZONES

	CZ2|3 BASE	CZ2|3 POST-78	CZ2|3 Control	CZ2|3 MCS
N=	36	4	6	15
Means	1891.1	1741.5	1611.3	1913.7
Medians	1869	1935	1611	1846
Std Dev	826.6	566.1	421.3	369
Means T=.2	1818.6	1870.5	1585.2	1859.4
Std Dev T=.2	616	934.5	706.4	372

TABLE F.2. 1986-1987 ELCAP Residential Sample Characterization - Mean Heating Season Inside Air Temperature Used in Annualized Estimated Consumption (units are in °F)

GENERAL STATISTICS

	Base SITES	Post-78	Control	MCS
N=	121	13	20	37
Means	69.8	68.7	68.9	69.1
Medians	70.1	69	69.3	69.2
Std Dev	3.4	4.2	3.7	2.5
Means T=.2	70	68.6	68.9	69.1
Std Dev T=.2	3.2	5.2	4.4	3.1

STATISTICS FOR SET OF STRUCTURES IN MILD MCS CLIMATE ZONE

	CZ1 BASE	CZ1 POST-78	CZ1 Control	CZ1 MCS
N=	85	9	14	22
Means	69.7	68.2	69.7	68.6
Medians	70.1	69	70	68.4
Std Dev	3	4.3	3.7	2.2
Means T=.2	69.9	68	69.7	68.6
Std Dev T=.2	3	5	4	2.3

STATISTICS FOR SET OF STRUCTURES IN COLDER MCS CLIMATE ZONES

	CZ2|3 BASE	CZ2|3 POST-78	CZ2|3 Control	CZ2|3 MCS
N=	36	4	6	15
Means	70	69.8	67.1	70
Medians	70.5	70.4	66.4	70.7
Std Dev	4.2	4.1	3.5	2.8
Means T=.2	70.3	70.2	66.7	69.8
Std Dev T=.2	3.9	8.3	5.1	4.1

TABLE F.3. 1986-1987 ELCAP Residential Sample Characterization - Annualized Estimated Consumption Using Mean Heating Season Inside-Outside Air Temperature and Selected Typical Meteorological Year Weather (units are in kWh/ft^2-yr)

GENERAL STATISTICS

	Base SITES	Post-78	Control	MCS
N=	121	13	20	37
Means	7.62	5.72	5.25	3.32
Medians	6.95	4.82	5.26	3.
Std Dev	3.62	3.01	1.95	1.11
Means T=.2	7.2	5.46	5.13	3.21
Std Dev T=.2	3.78	3.87	2.4	1.43

STATISTICS FOR SET OF STRUCTURES IN MILD MCS CLIMATE ZONE

	CZ1 BASE	CZ1 POST-78	CZ1 Control	CZ1 MCS
N=	85	9	14	22
Means	7.78	6.32	5.3	3.13
Medians	7.01	6.19	5.2	2.85
Std Dev	3.67	2.92	1.86	0.99
Means T=.2	7.38	6.04	5.03	2.96
Std Dev T=.2	4.05	3.47	2.12	0.82

STATISTICS FOR SET OF STRUCTURES IN COLDER MCS CLIMATE ZONES

	CZ2|3 BASE	CZ2|3 POST-78	CZ2|3 Control	CZ2|3 MCS
N=	36	4	6	15
Means	7.26	4.37	5.13	3.62
Medians	6.9	3.37	5.43	3.77
Std Dev	3.53	3.19	2.33	1.24
Means T=.2	6.84	3.7	5.31	3.64
Std Dev T=.2	3.32	5.64	3.58	1.92

TABLE F.4. 1986-1987 ELCAP Residential Sample Characterization - Total Annualized Estimated Consumption Using Mean Heating Season Inside-Outside Air Temperature and Selected Typical Meteorological Year Weather (units are in total kWh/yr)

GENERAL STATISTICS

	Base SITES	Post-78	Control	MCS
N=	121	13	20	37
Means	12065.8	10076.2	7627.8	5677.3
Medians	11736.3	10127.7	7582	5530
Std Dev	5594.1	4931.9	2624.3	1901.2
Means T=.2	11549.5	9628.1	7523.6	5482.3
Std Dev T=.2	5518.4	5400.5	3131	2310.2

STATISTICS FOR SET OF STRUCTURES IN MILD MCS CLIMATE ZONE

	CZ1 BASE	CZ1 POST-78	CZ1 Control	CZ1 MCS
N=	85	9	14	22
Means	11900.7	11772.5	7538.2	4973.3
Medians	11198.2	11655.4	7158.6	4944
Std Dev	5482.9	4897.5	2463.4	1495.6
Means T=.2	11322.7	11578.6	7198.5	4867.9
Std Dev T=.2	5892.8	3693.2	2462.4	1799.5

STATISTICS FOR SET OF STRUCTURES IN COLDER MCS CLIMATE ZONES

	CZ2|3 BASE	CZ2|3 POST-78	CZ2|3 Control	CZ2|3 MCS
N=	36	4	6	15
Means	12455.6	6259.6	7836.9	6709.8
Medians	12172.8	6278.5	9115.5	6882.2
Std Dev	5909.6	2297.4	3212.3	2004.5
Means T=.2	12083.2	6272.2	8221.8	6800.1
Std Dev T=.2	4466	5477.8	6103.2	2830.5

TABLE F.5. 1986-1987 ELCAP Residential Sample Characterization - Annualized Estimated Consumption Using Only Outside Air Temperature and Selected Typical Meteorological Year Weather (units are in kWh/ft^2-yr)

GENERAL STATISTICS

	Base SITES	Post-78	Control	MCS
N=	121	13	20	37
Means	7.39	5.4	4.97	3.2
Medians	6.91	4.49	4.89	2.96
Std Dev	3.5	3.06	1.91	1.13
Means T=.2	6.99	4.94	4.85	3.06
Std Dev T=.2	3.64	3.61	2.09	1.5

STATISTICS FOR SET OF STRUCTURES IN MILD MCS CLIMATE ZONE

	CZ1 BASE	CZ1 POST-78	CZ1 Control	CZ1 MCS
N=	85	9	14	22
Means	7.5	5.96	4.98	2.94
Medians	6.91	4.49	4.89	2.68
Std Dev	3.56	3.15	1.75	0.99
Means T=.2	7.09	5.38	4.83	2.74
Std Dev T=.2	3.96	3.95	1.83	0.86

STATISTICS FOR SET OF STRUCTURES IN COLDER MCS CLIMATE ZONES

	CZ2|3 BASE	CZ2|3 POST-78	CZ2|3 Control	CZ2|3 MCS
N=	36	4	6	15
Means	7.12	4.16	4.95	3.58
Medians	6.87	3.39	4.93	3.74
Std Dev	3.37	2.82	2.44	1.25
Means T=.2	6.83	3.65	5.02	3.61
Std Dev T=.2	3.27	5.27	4.08	1.89

TABLE F.6. 1986-1987 ELCAP Residential Sample Characterization - Slopes from Middle Linear Delta Temperature Fit (units are in kWh/day ft^2-°F)

GENERAL STATISTICS

	Base SITES	Post-78	Control	MCS
N=	121	13	20	37
Means	0.782	0.771	0.818	0.715
Medians	0.8	0.769	0.833	0.732
Std Dev	0.112	0.086	0.101	0.098
Means T=.2	0.801	0.765	0.832	0.726
Std Dev T=.2	0.101	0.092	0.116	0.117

STATISTICS FOR SET OF STRUCTURES IN MILD MCS CLIMATE ZONE

	CZ1 BASE	CZ1 POST-78	CZ1 Control	CZ1 MCS
N=	85	9	14	22
Means	0.788	0.759	0.822	0.719
Medians	0.801	0.753	0.856	0.744
Std Dev	0.111	0.101	0.103	0.099
Means T=.2	0.806	0.745	0.84	0.732
Std Dev T=.2	0.1	0.125	0.105	0.115

STATISTICS FOR SET OF STRUCTURES IN COLDER MCS CLIMATE ZONES

	CZ2|3 BASE	CZ2|3 POST-78	CZ2|3 Control	CZ2|3 MCS
N=	36	4	6	15
Means	0.768	0.797	0.81	0.71
Medians	0.786	0.786	0.812	0.72
Std Dev	0.114	0.037	0.105	0.101
Means T=.2	0.791	0.789	0.811	0.719
Std Dev T=.2	0.115	0.067	0.17	0.126

TABLE F.7. 1986-1987 ELCAP Residential Sample Characterization - Balance Point from Middle Outside Air Temperature Fit (units are in °F)

GENERAL STATISTICS

	Base-SITES	Post-78	Control	MCS
N=	121	13	20	37
Means	0.57	0.516	0.623	0.491
Medians	0.6	0.529	0.602	0.509
Std Dev	0.179	0.182	0.154	0.13
Means T=.2	0.595	0.52	0.629	0.496
Std Dev T=.2	0.206	0.2	0.158	0.136

STATISTICS FOR SET OF STRUCTURES IN MILD MCS CLIMATE ZONE

	CZ1 BASE	CZ1 POST-78	CZ1 Control	CZ1 MCS
N=	85	9	14	22
Means	0.577	0.494	0.628	0.485
Medians	0.62	0.529	0.623	0.497
Std Dev	0.183	0.198	0.157	0.124
Means T=.2	0.604	0.491	0.638	0.488
Std Dev T=.2	0.219	0.229	0.166	0.133

STATISTICS FOR SET OF STRUCTURES IN COLDER MCS CLIMATE ZONES

	CZ2|3 BASE	CZ2|3 POST-78	CZ2|3 Control	CZ2|3 MCS
N=	36	4	6	15
Means	0.555	0.566	0.611	0.5
Medians	0.569	0.563	0.589	0.548
Std Dev	0.169	0.154	0.161	0.143
Means T=.2	0.574	0.564	0.597	0.512
Std Dev T=.2	0.17	0.265	0.225	0.153

TABLE F.8. 1986-1987 ELCAP Residential Sample Characterization - Balance Delta Temperature from Middle Linear Delta Temperature Fit (units are in °F)

GENERAL STATISTICS

	Base-SITES	Post-78	Control	MCS
N=	121	13	20	37
Means	0.00183	0.00167	0.00164	0.00109
Medians	0.00166	0.00144	0.00157	0.0011
Std Dev	0.00081	0.0009	0.00062	0.00037
Means T=.2	0.00173	0.00153	0.00157	0.00107
Std Dev T=.2	0.00084	0.00091	0.00067	0.00032

STATISTICS FOR SET OF STRUCTURES IN MILD MCS CLIMATE ZONE

	CZ1 BASE	CZ1 POST-78	CZ1 Control	CZ1 MCS
N=	85	9	14	22
Means	0.00202	0.00201	0.0019	0.00124
Medians	0.00198	0.00174	0.00179	0.0012
Std Dev	0.00079	0.00087	0.00053	0.00035
Means T=.2	0.00195	0.0019	0.00184	0.00121
Std Dev T=.2	0.00071	0.001	0.00062	0.00032

STATISTICS FOR SET OF STRUCTURES IN COLDER MCS CLIMATE ZONES

	CZ2|3 BASE	CZ2|3 POST-78	CZ2|3 Control	CZ2|3 MCS
N=	36	4	6	15
Means	0.00137	0.00092	0.00101	0.00087
Medians	0.00119	0.00088	0.00109	0.0009
Std Dev	0.00066	0.00036	0.00028	0.00028
Means T=.2	0.00124	0.00089	0.00108	0.00089
Std Dev T=.2	0.00043	0.00065	0.00028	0.00037

APPENDIX G

SECOND-YEAR ANALYSIS FIGURES

APPENDIX G

SECOND YEAR ANALYSIS FIGURES

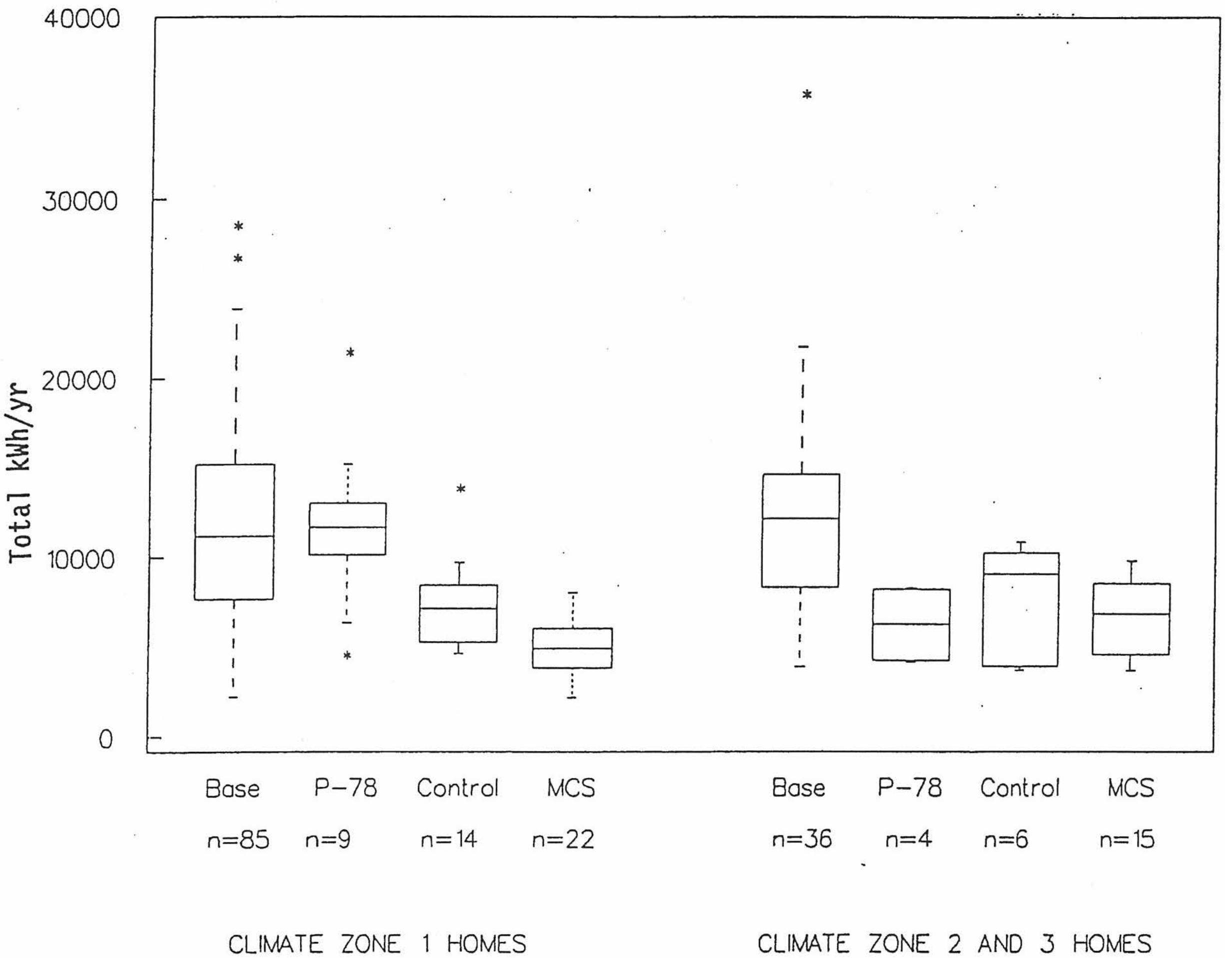


FIGURE G.1. 1986-1987 ELCAP Residential Sample Characterization - Total Annualized Estimated Consumption Using Mean Heating Season Inside-Outside Air Temperature and Selected Typical Meteorological Year Weather

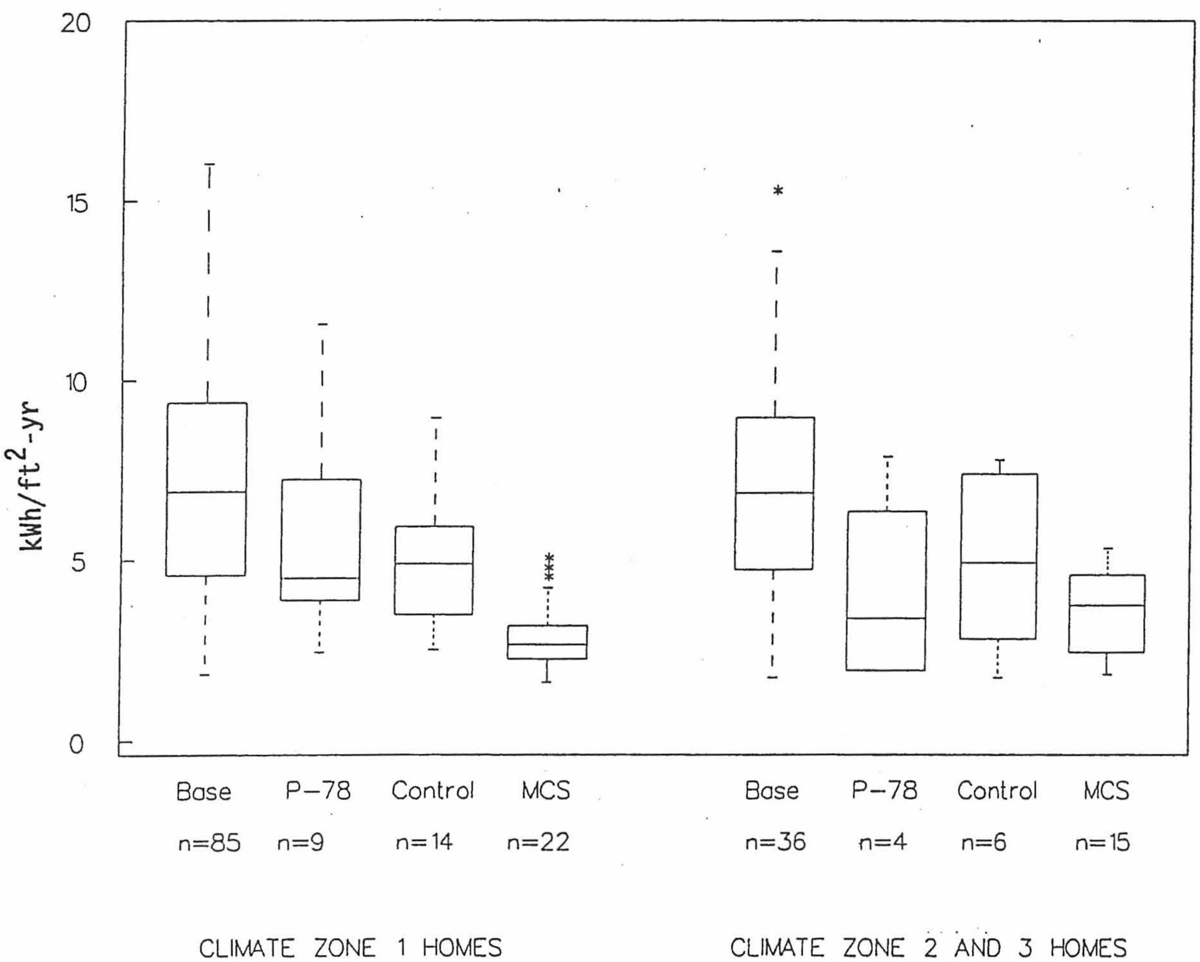


FIGURE G.2. 1986-1987 ELCAP Residential Sample Characterization - Annualized Estimated Consumption Using Only Outside Air Temperature and Selected Typical Meteorological Year Weather

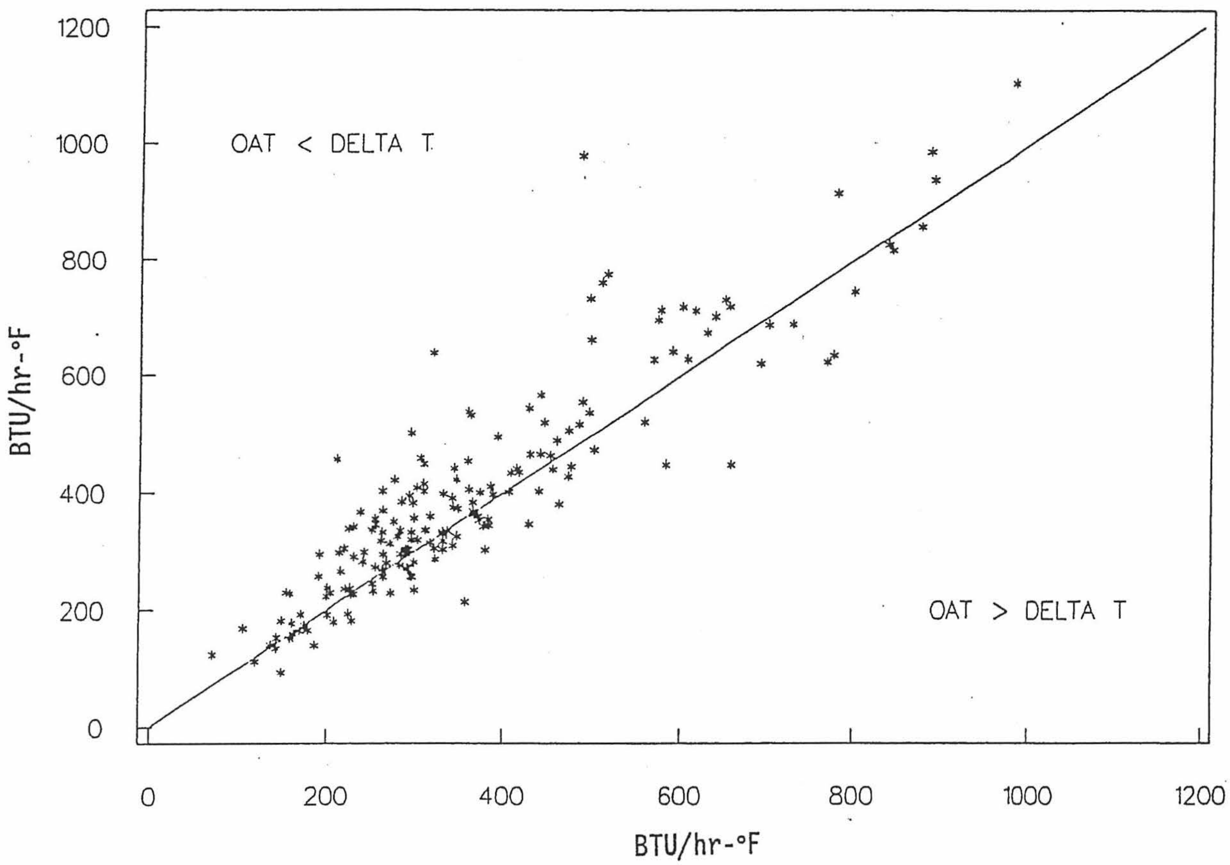
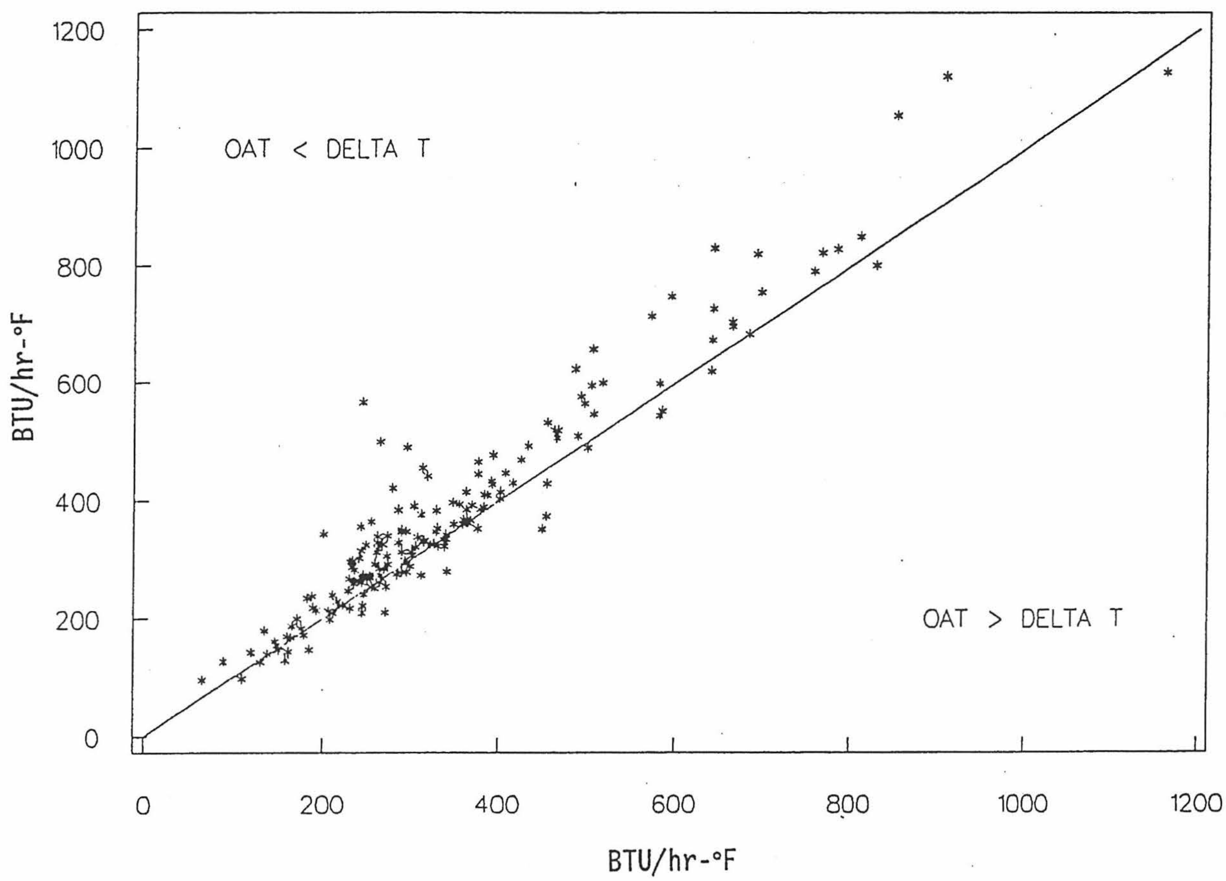


FIGURE G.3. 1986-1987 ELCAP Residential Sample Characterization - As-Operated Effective Conductance Calculated from Delta Temperature Difference Versus As-Operated Effective Conductance Calculated from Outside Air Temperaure Only. As-operated effective conductances are from the slopes of the midrange fit.



<u>FIGURE G.4</u>. 1986-1987 ELCAP Residential Sample Characterization - As-Operated Effective Conductance Calculated from Delta Temperature Difference Versus As-Operated Effective Conductance Calculated from Outside Air Temperature Only. As-operated effective conductances are from the slopes of the robust linear fit.

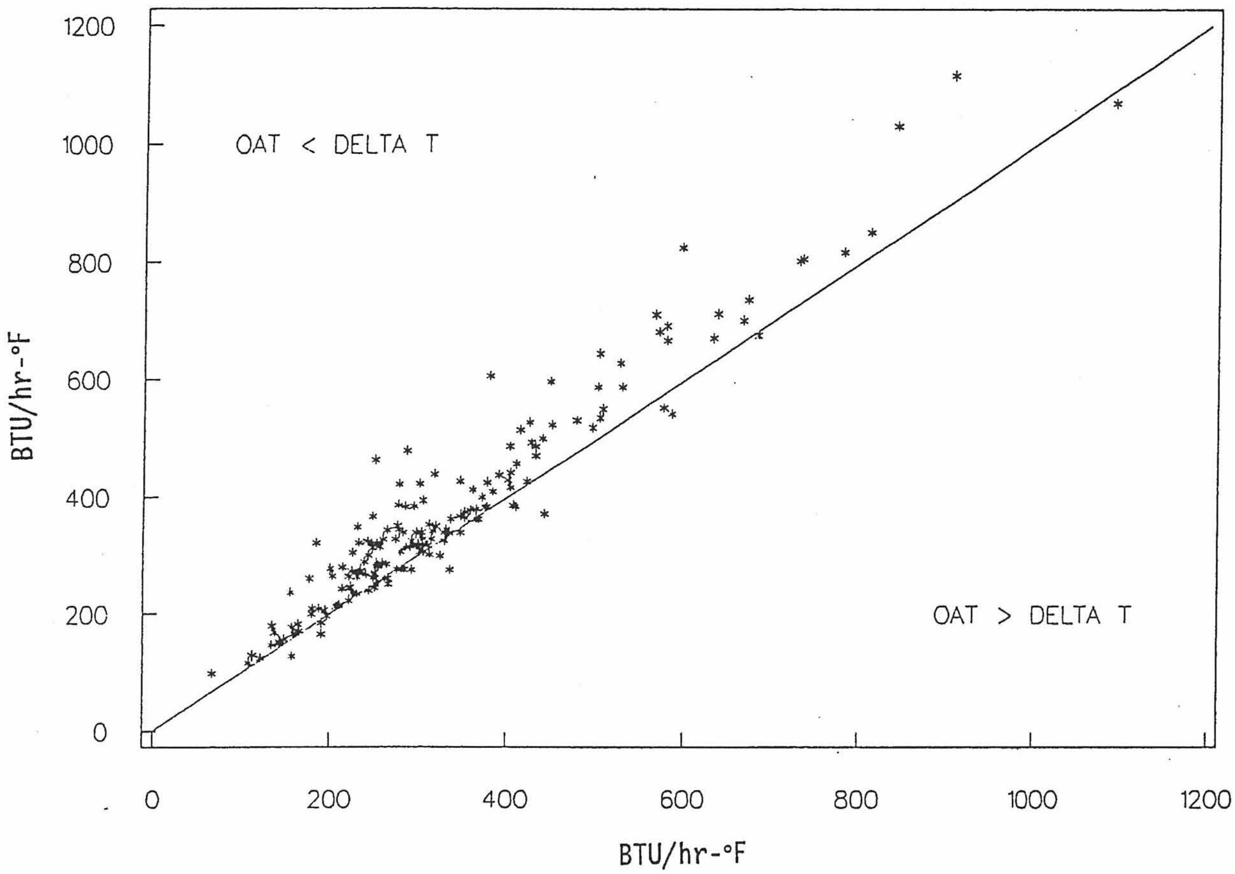


FIGURE G.5. 1986-1987 ELCAP Residential Sample Characterization - As-Operated Effective Conductance Calculated from Delta Temperature Difference Versus As-Operated Effective Conductance Calculated from Outside Air Temperature Only. As-operated effective conductances are from the slopes of the standard linear fit.

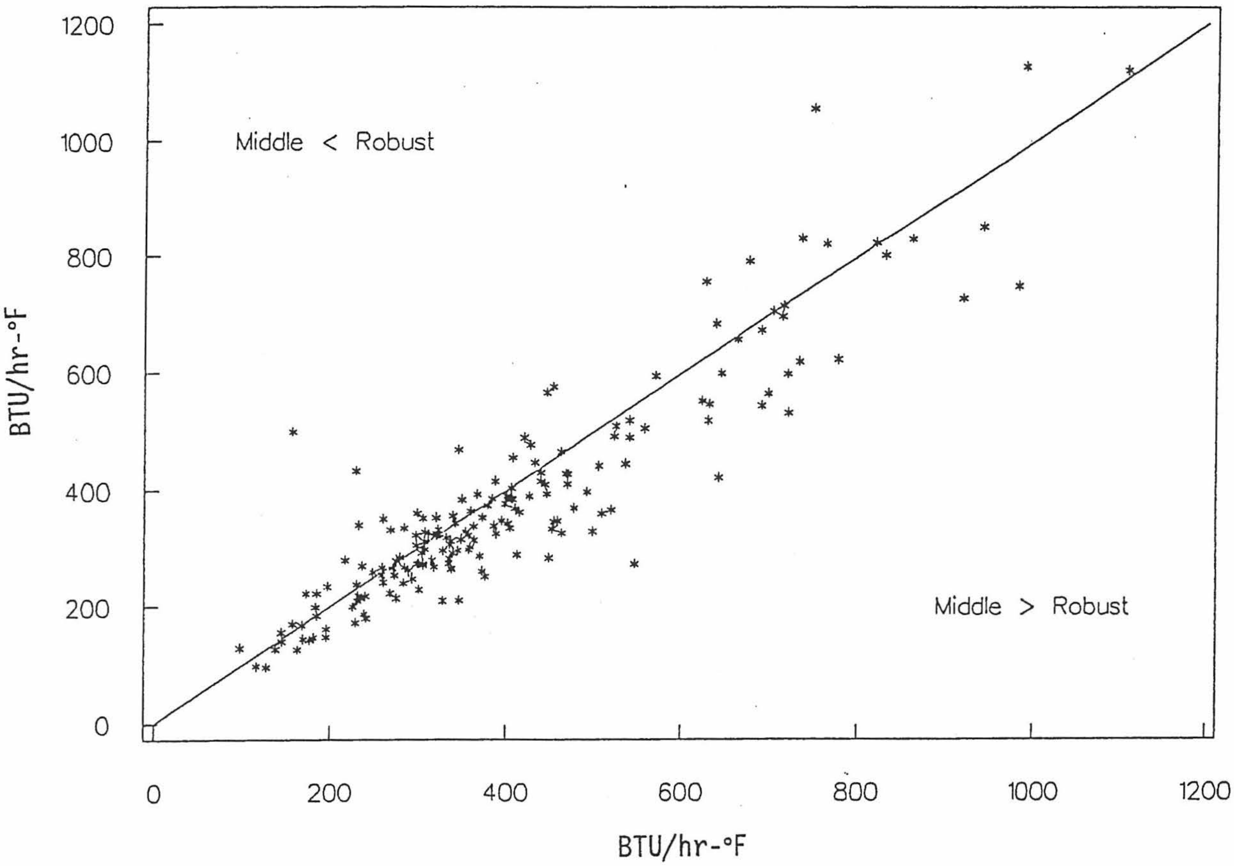


FIGURE G.6. 1986-1987 ELCAP Residential Sample Characterization Comparison of As-Operated Effective Conductances Across Methods - Robust Linear Fit (heater versus delta temperature) Versus Midrange Fit (heater versus delta temperature)

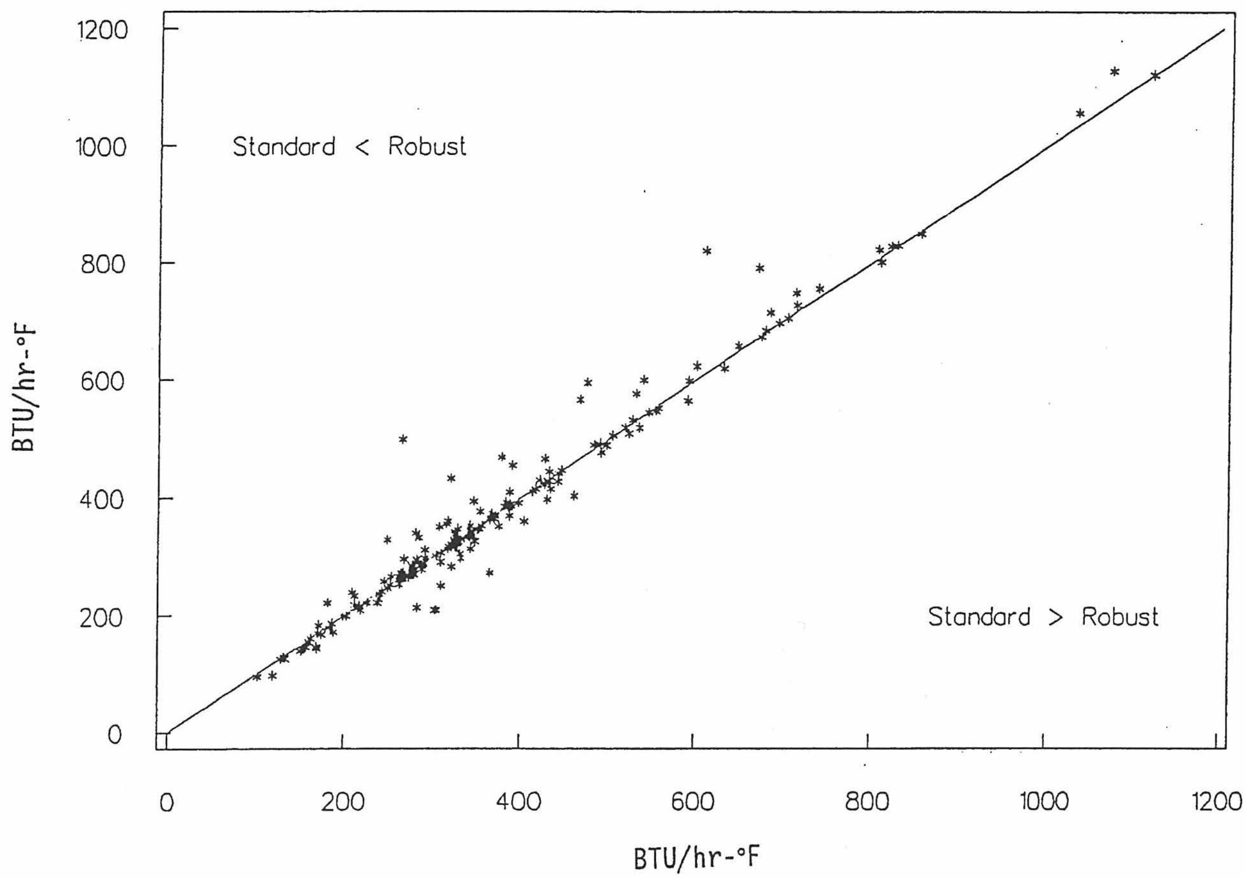


FIGURE G.7. 1986-1987 ELCAP Residential Sample Characterization Comparison of As-Operated Effective Conductances Across Methods - Robust Linear Fit (heater versus delta temperature) Versus Standard Linear Fit (heater versus delta temperature)

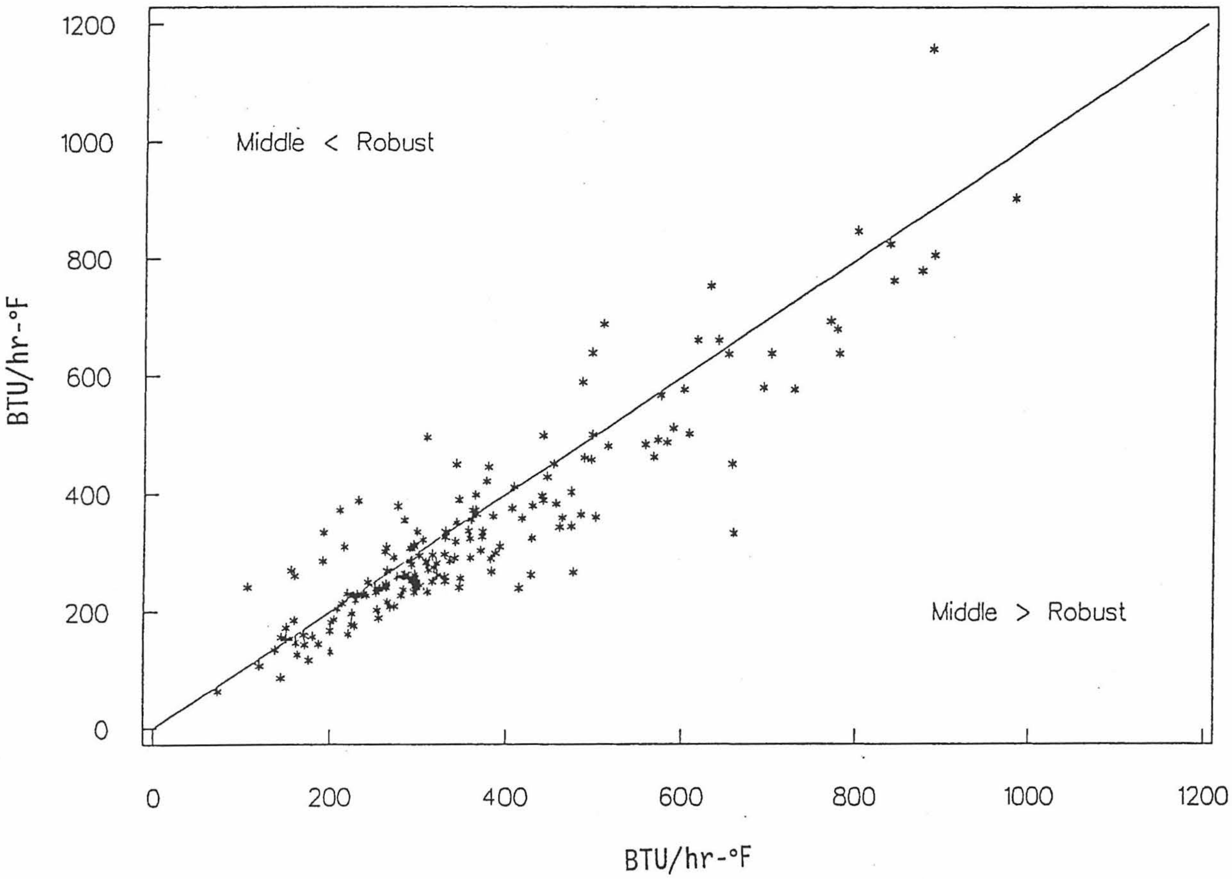


FIGURE G.8. 1986-1987 ELCAP Residential Sample Characterization Comparison of As-Operated Effective Conductances Across Methods - Robust Linear Fit (heater versus outside air temperature) Versus Midrange Fit (heater versus outside air temperature)

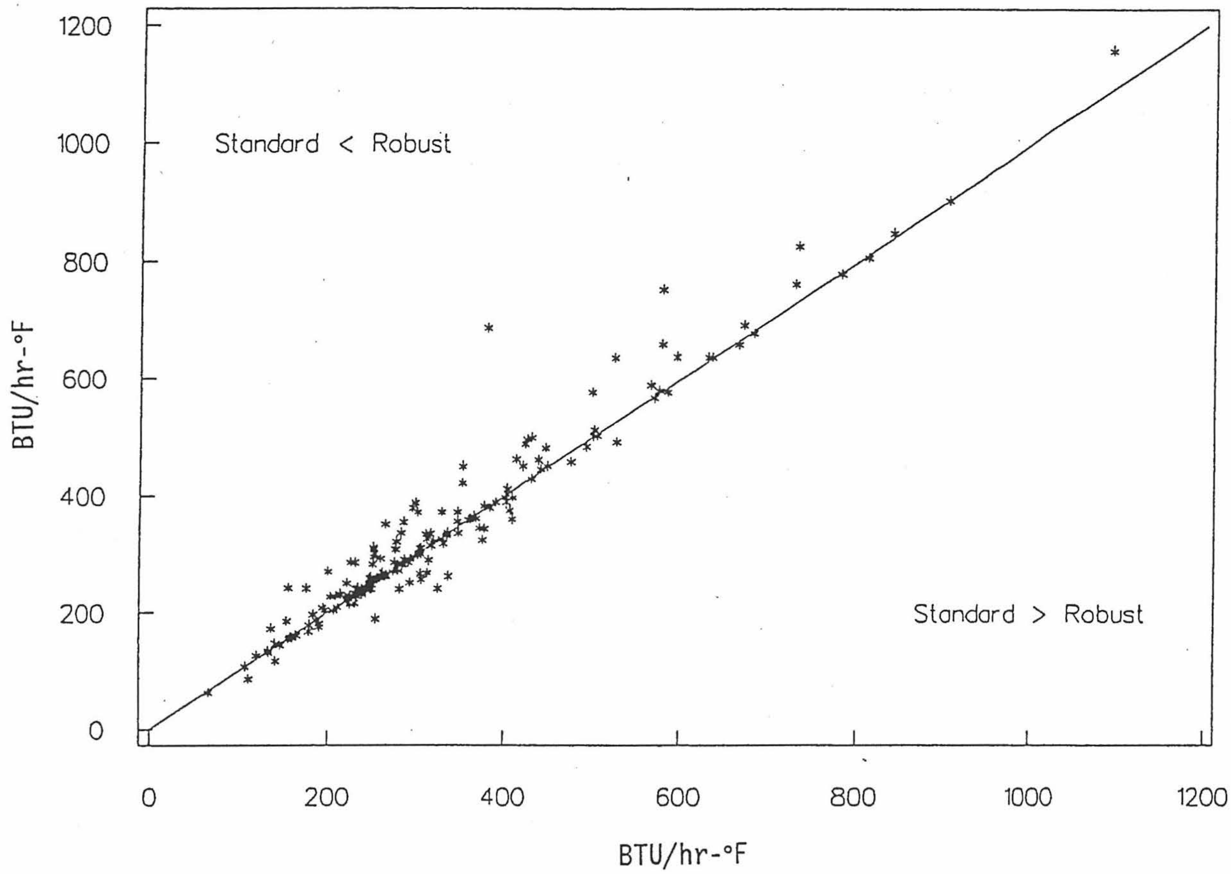


FIGURE G.9. 1986-1987 ELCAP Residential Sample Characterization Comparison of As-Operated Effective Conductances Across Methods - Robust Linear Fit (heater versus outside air temperature) Versus Standard Linear Fit (heater versus outside air temperature)

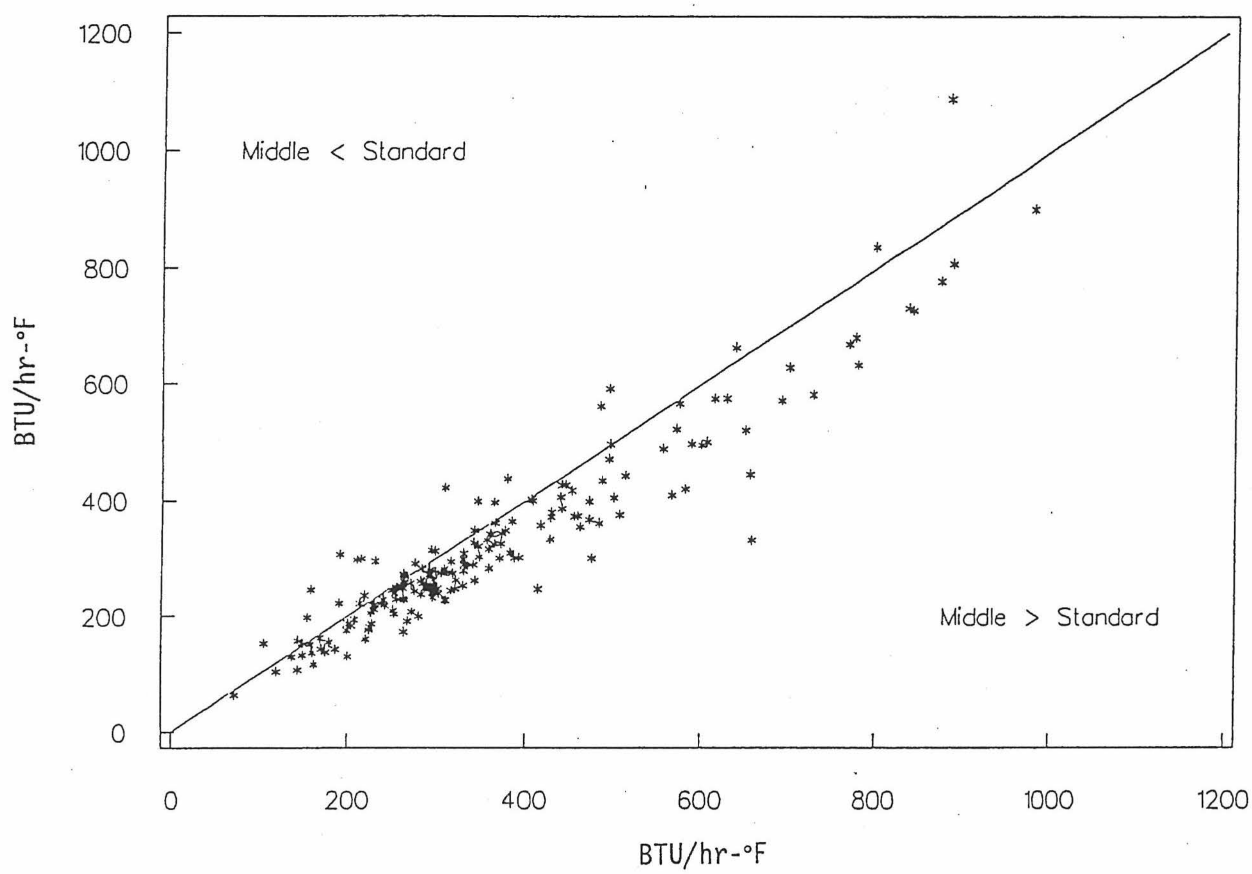


FIGURE G.10. 1986-1987 ELCAP Residential Sample Characterization Comparison of As-Operated Effective Conductances Across Methods - Standard Linear Fit (heater versus outside air temperature) Versus Midrange Fit (heater versus outside air temperature)

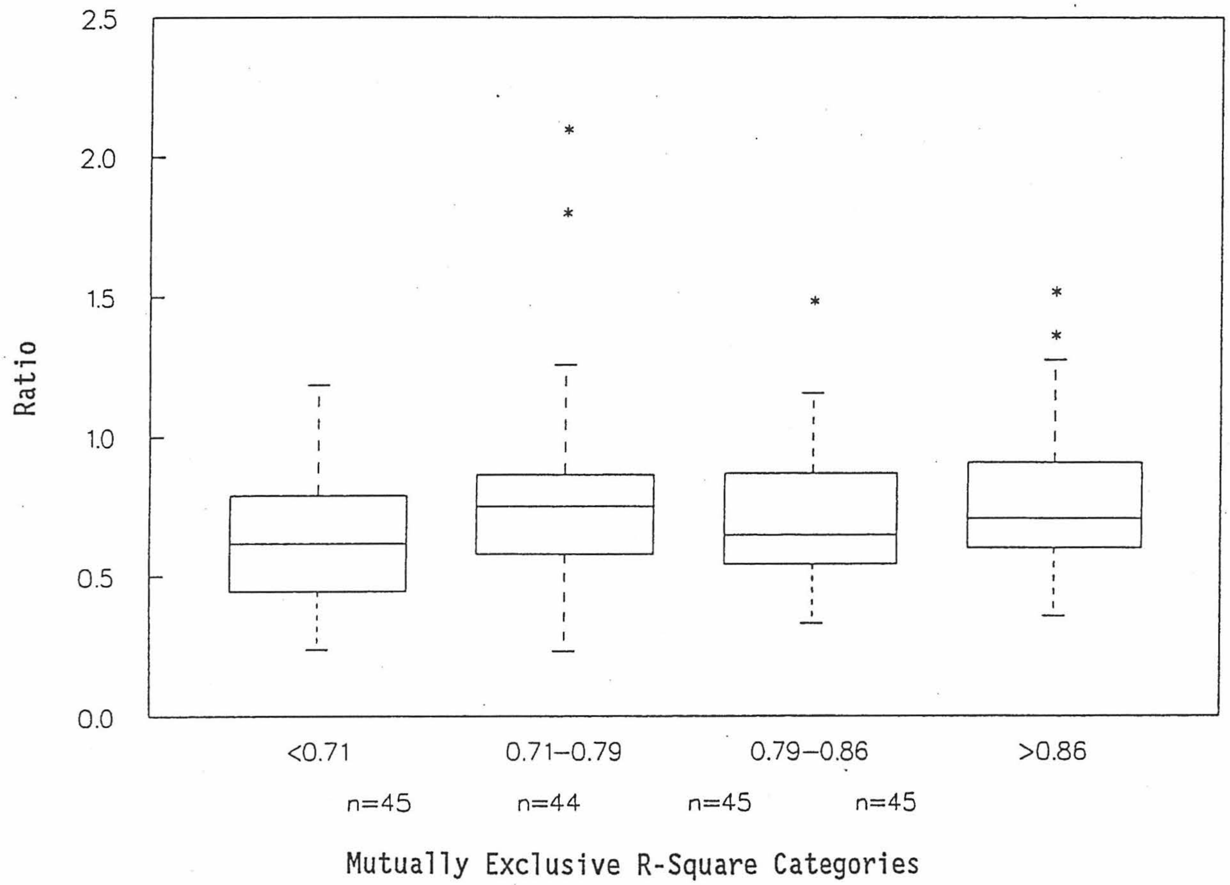


FIGURE G.11. 1986-1987 ELCAP Residential Sample Characterization Ratio of As-Operated Effective Conductances to Nameplate Effective Conductances - Infiltration Split by R-Squares from Standard Linear Fit of Daily Heater to Inside-Outside Temperature Difference

APPENDIX H

FIRST- AND SECOND-YEAR COMPARISONS

APPENDIX H

FIRST- AND SECOND-YEAR COMPARISONS

FOREWORD TO THE APPENDIX PLOTS

For the plots which contrast values for base, MCS, and control homes, several data flags are used. These flags may be ignored by the reader or used when looking at outlier points. The data flags differentiate between four conditions: best, loose, scatter, and density. These are briefly described below.

- b = best - Best is the characterization for both heating season, in terms of data densities, and minimum scatter.
- l = loose - One or both years having a bit more scatter in the space heat characterization curve than the best sites.
- s = scatter - Having more scatter than the loose or best categories.
- e = density - The amount of data present differ considerably between years.

Subjective judgment was used to allocate the data quality flags.

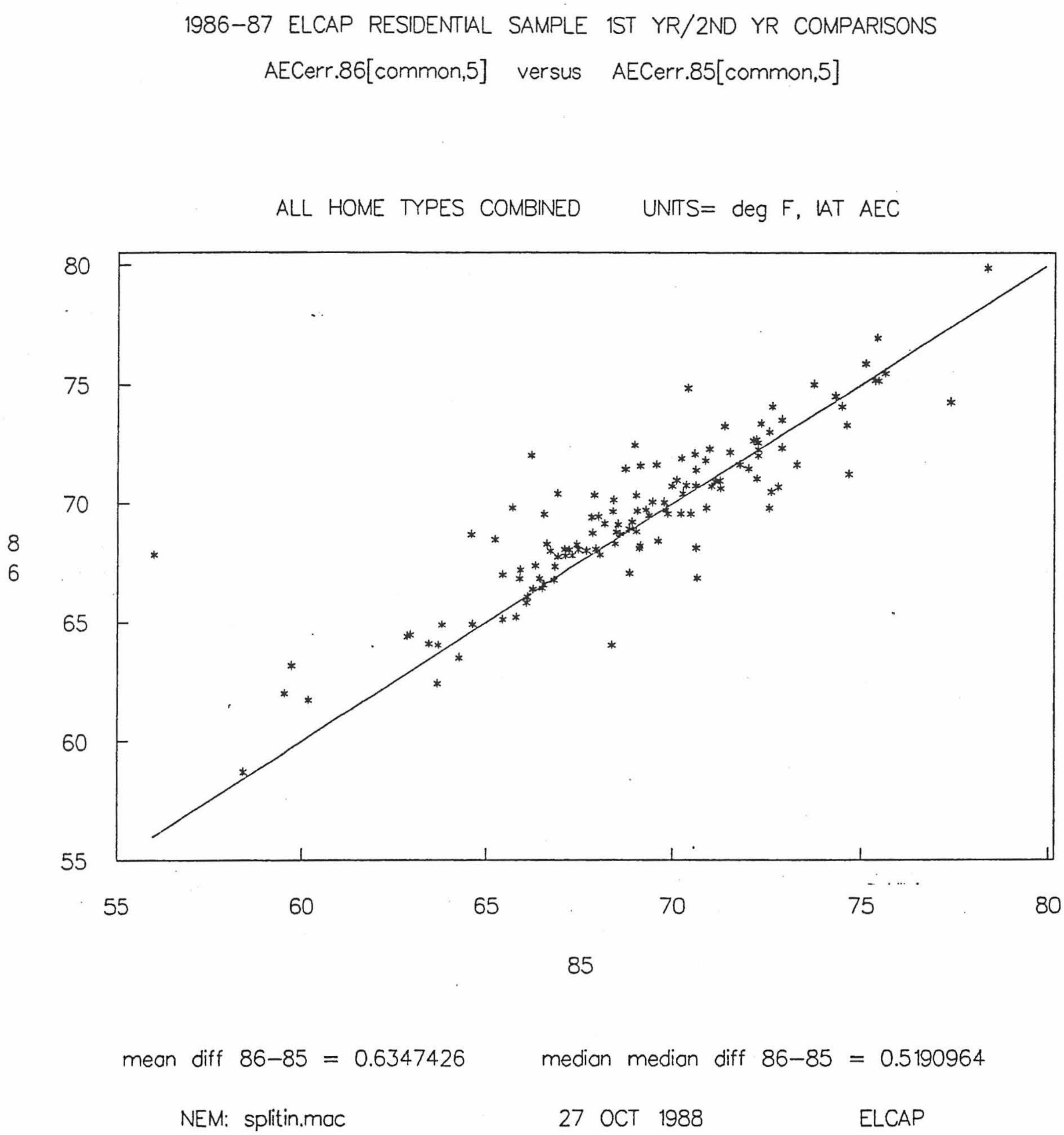


FIGURE H.1. Comparison of First- and Second-Year Mean Measured Heating Season Inside Air Temperature for the Combined Set of ELCAP Homes

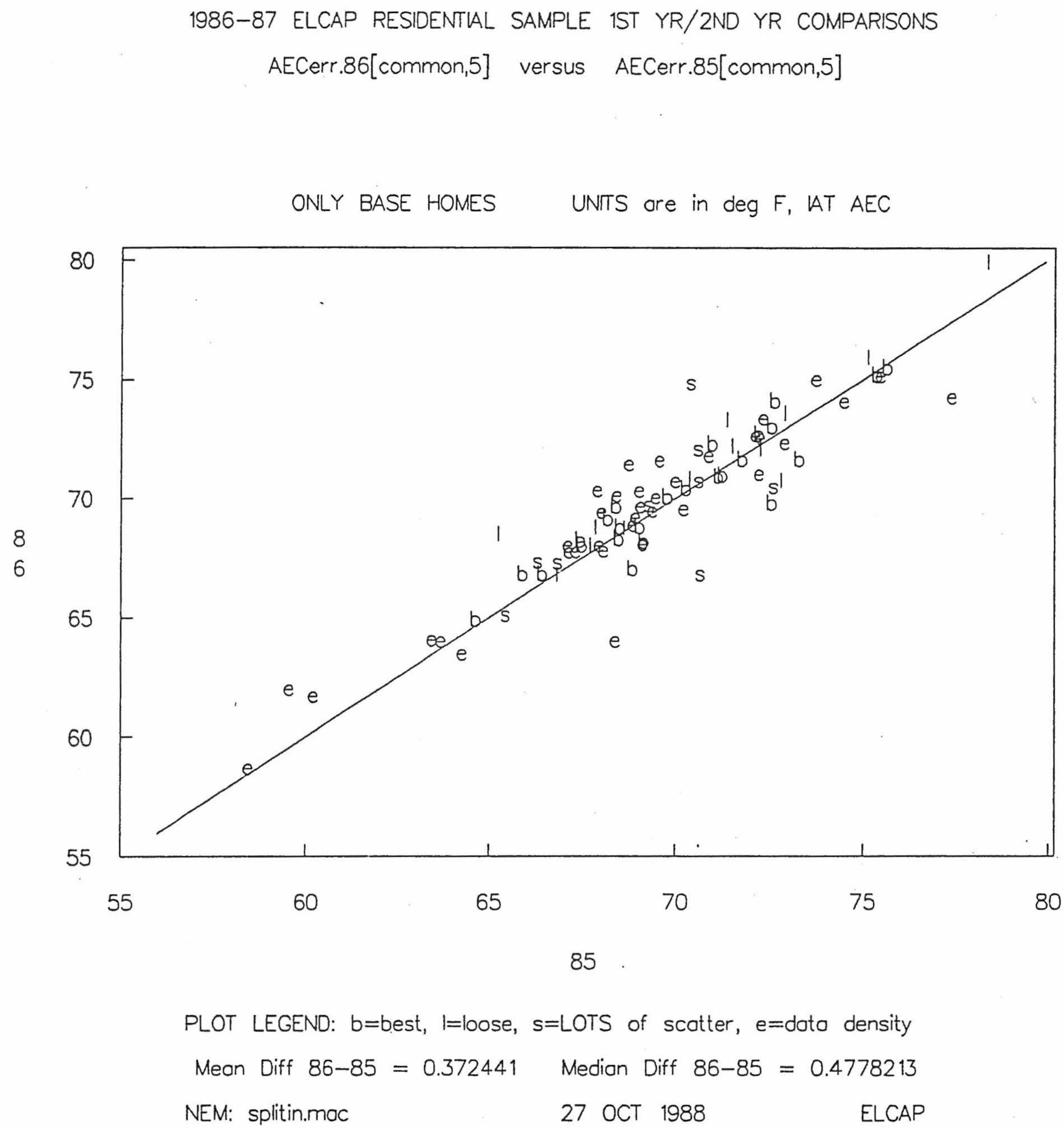


FIGURE H.2. Comparison of First- and Second-Year Mean Measured Heating Season Inside Air Temperature for the Residential Base ELCAP Homes

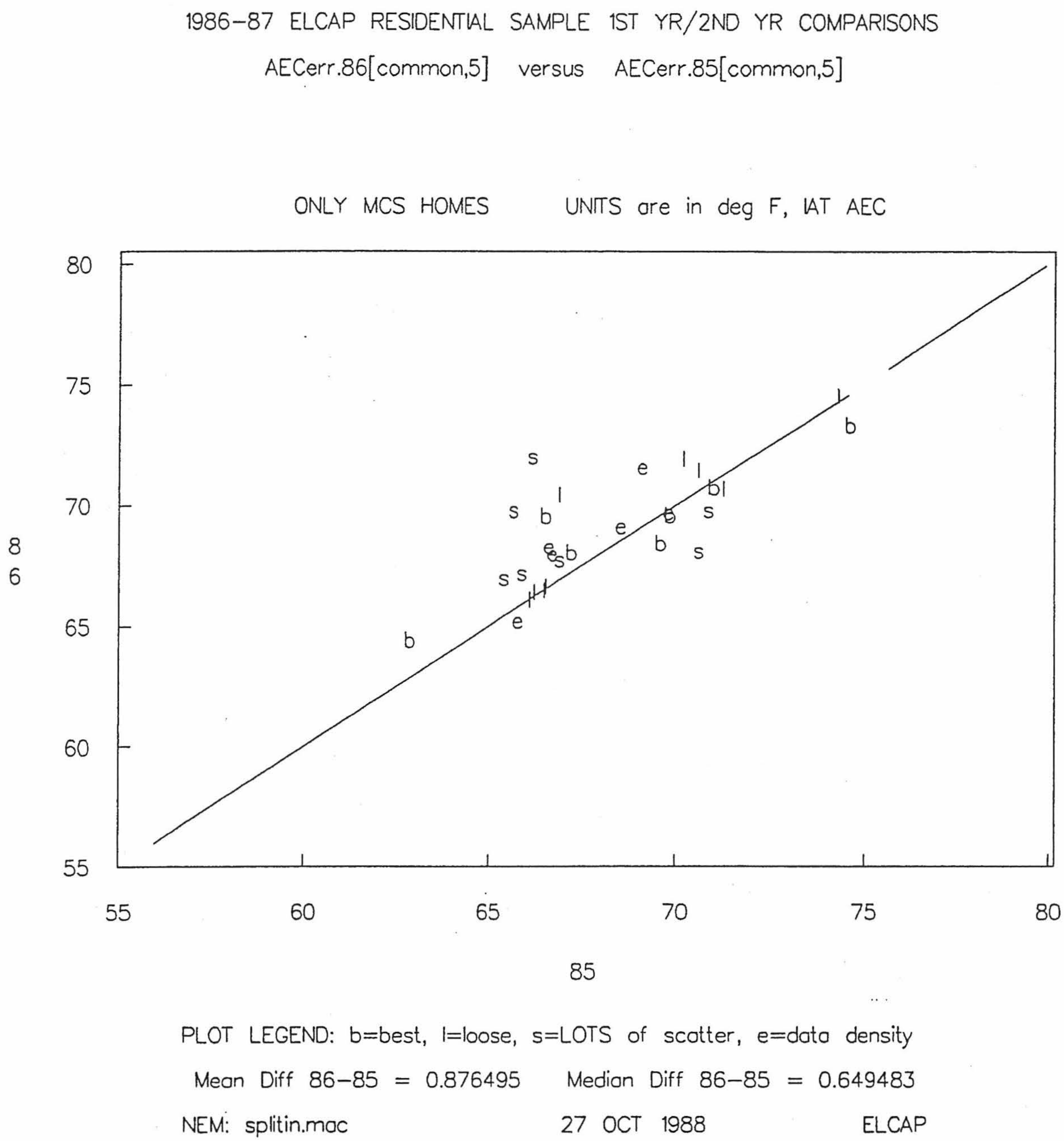


FIGURE H.3. Comparison of First- and Second-Year Mean Measured Heating Season Inside Air Temperature for the Model Conservation Standards ELCAP Homes

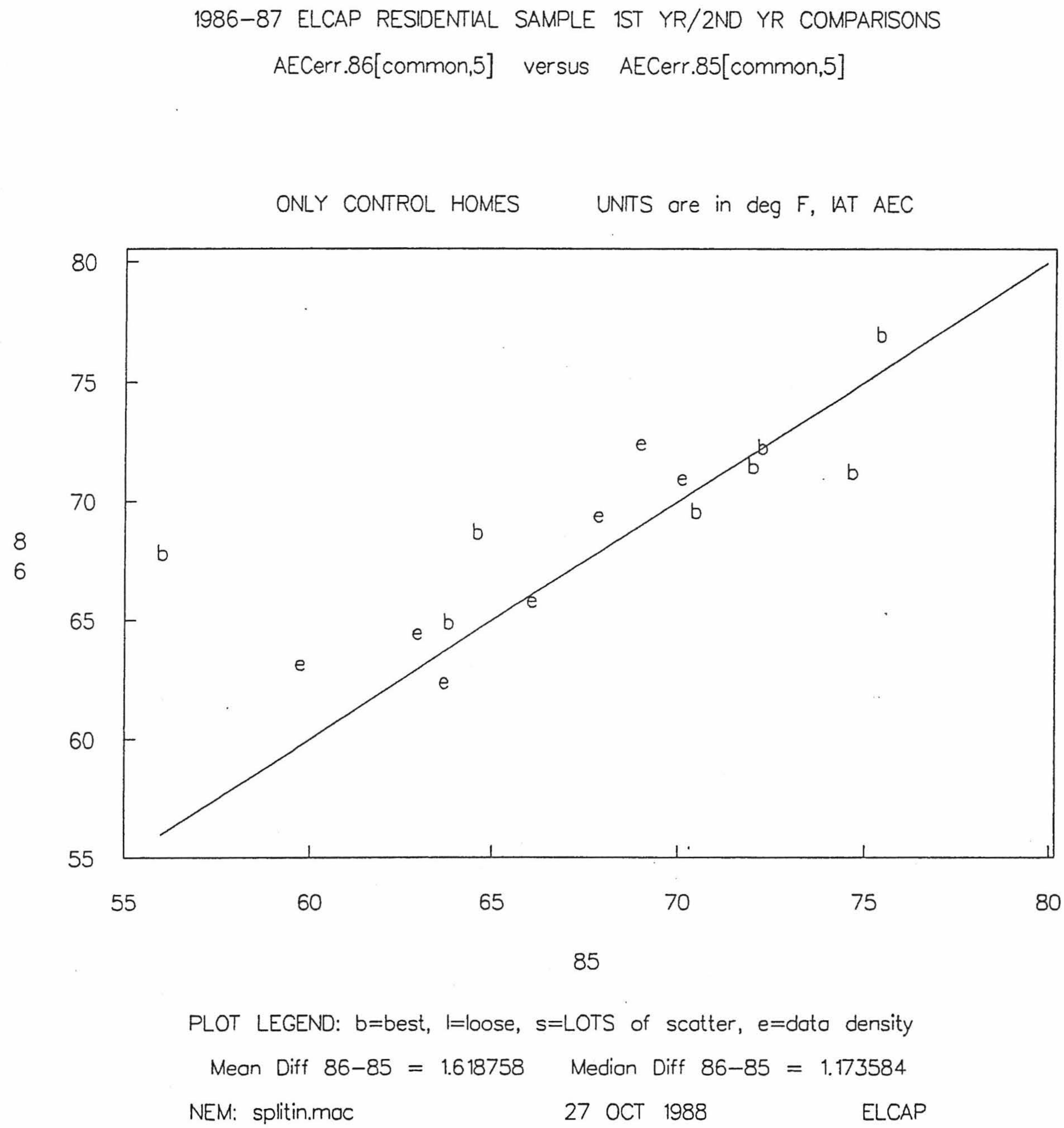


FIGURE H.4. Comparison of First- and Second-Year Mean Measured Heating Season Inside Air Temperature for the Control ELCAP Homes

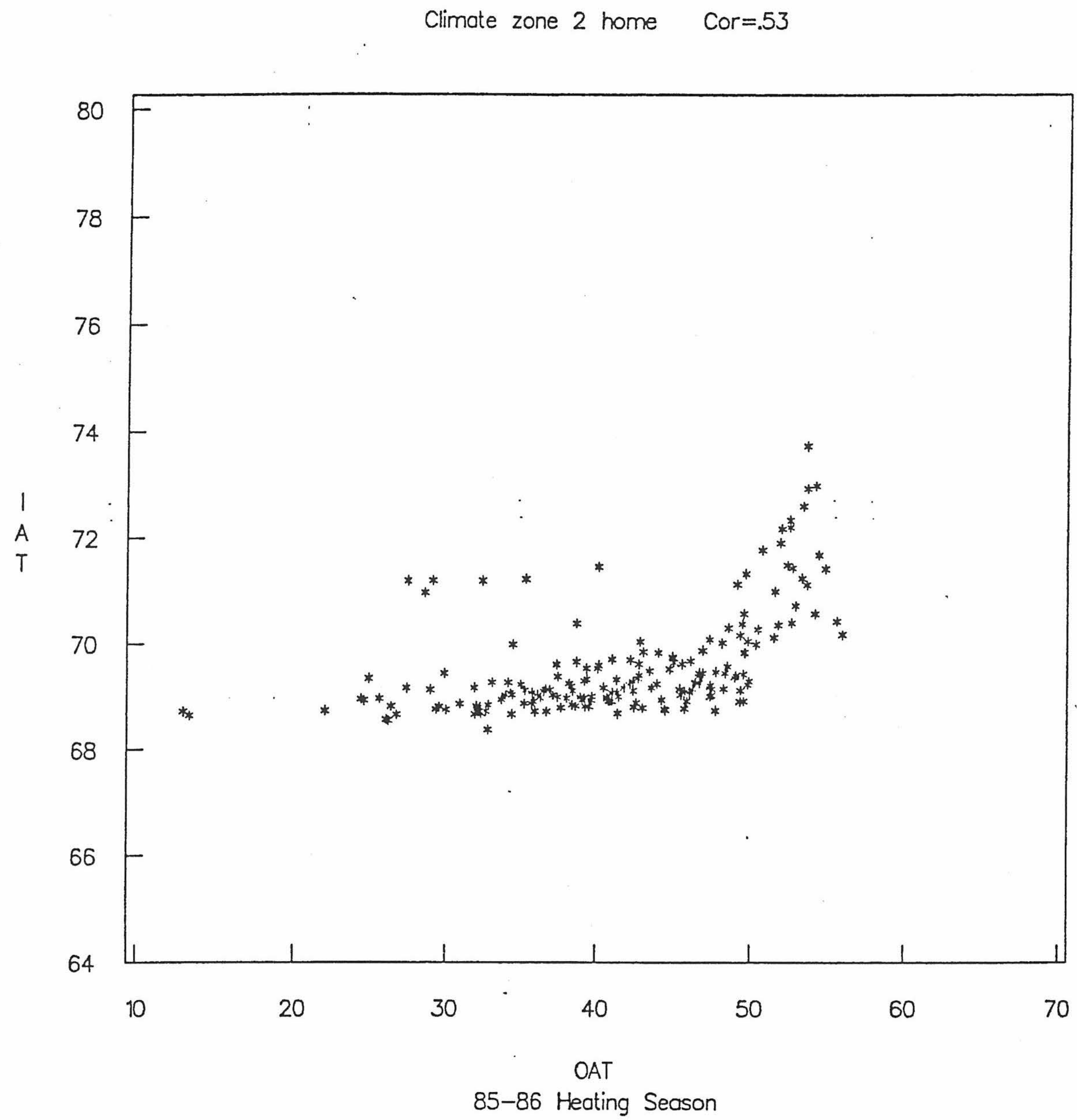


FIGURE H.5. Mean Daily Inside Air Temperature Versus Mean Daily Outside Air Temperature for a Single Home (°F)

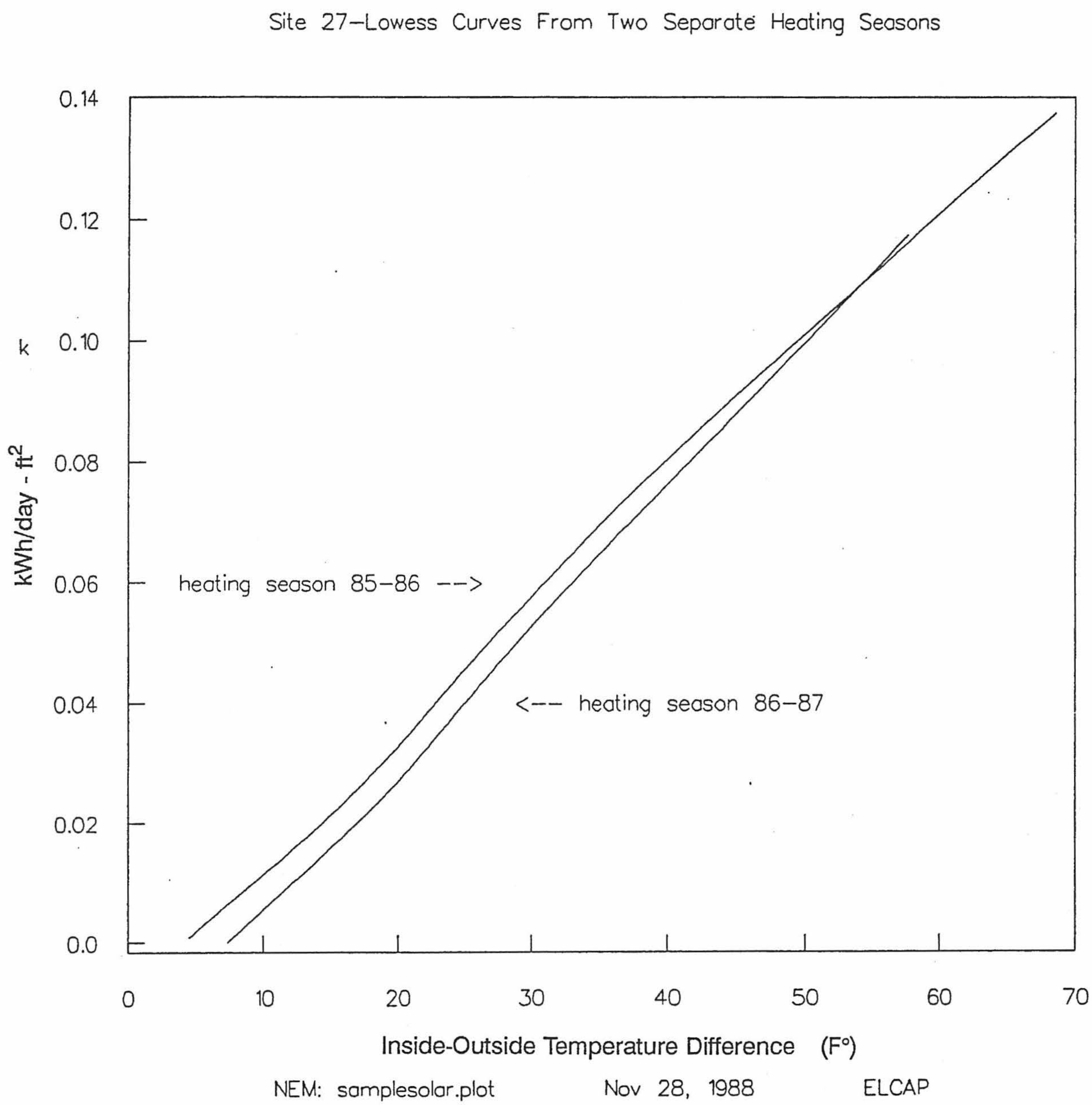


FIGURE H.6. LOWESS Fits from the First- and Second-Heating Season Superimposed on the Same Graph for a Base Home--Site 27

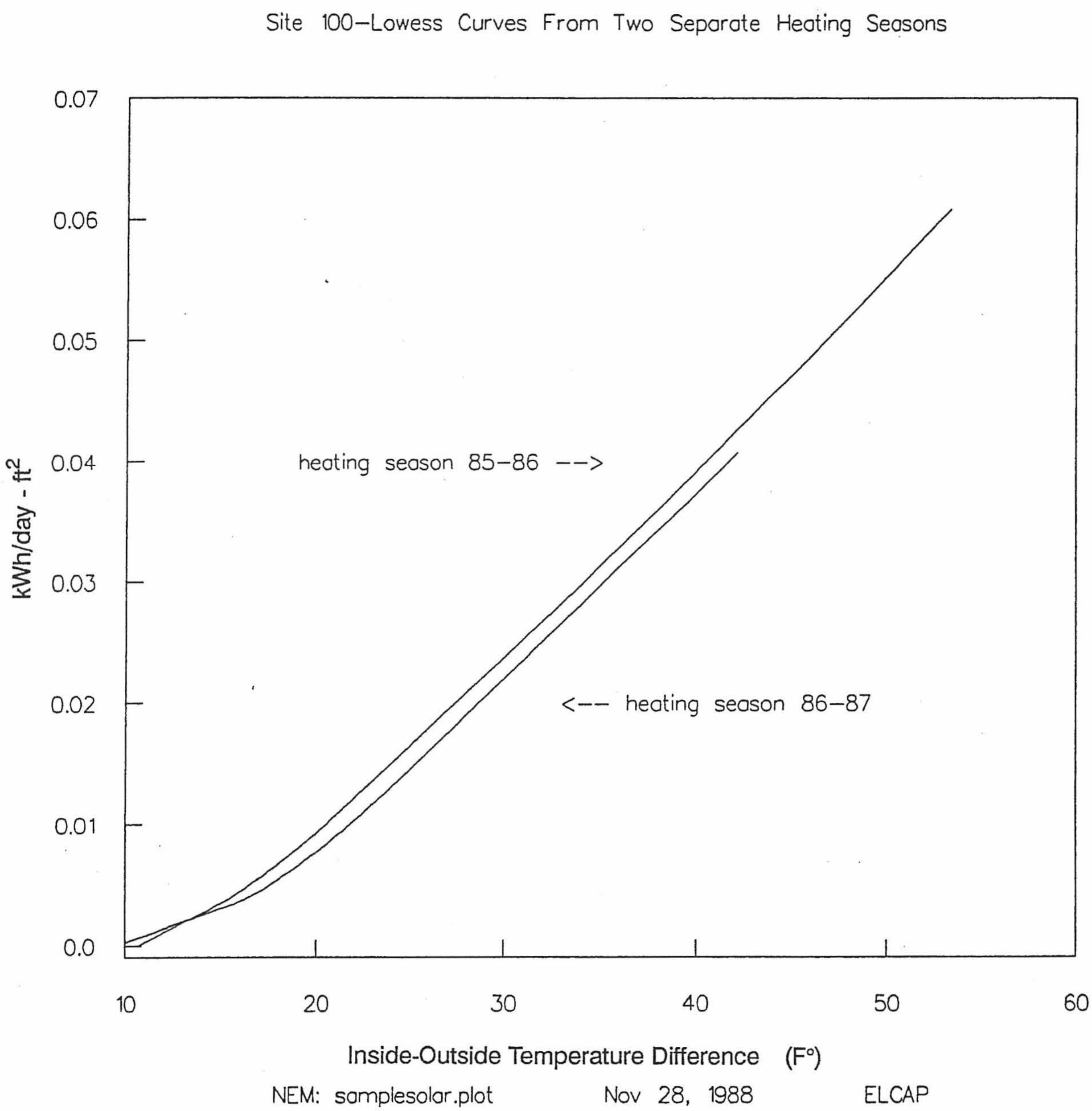


FIGURE H.7. LOWESS Fits from the First- and Second-Heating Season Superimposed on the Same Graph for a Residential Standards Demonstration Program Home--Site 100

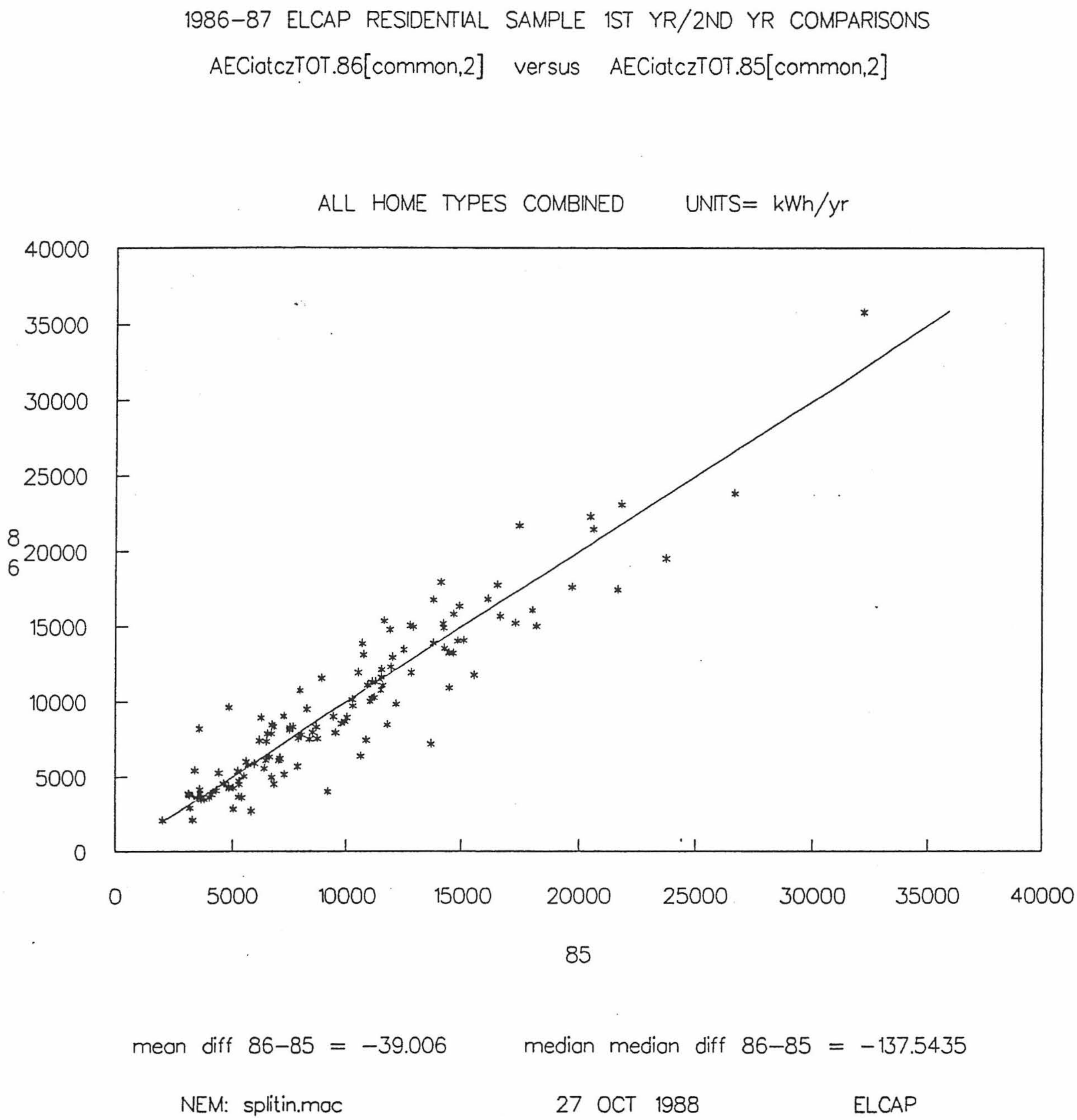


FIGURE H.8. Comparison of First- and-Second-Year AEC_{iat} for the Combined Set of ELCAP Homes

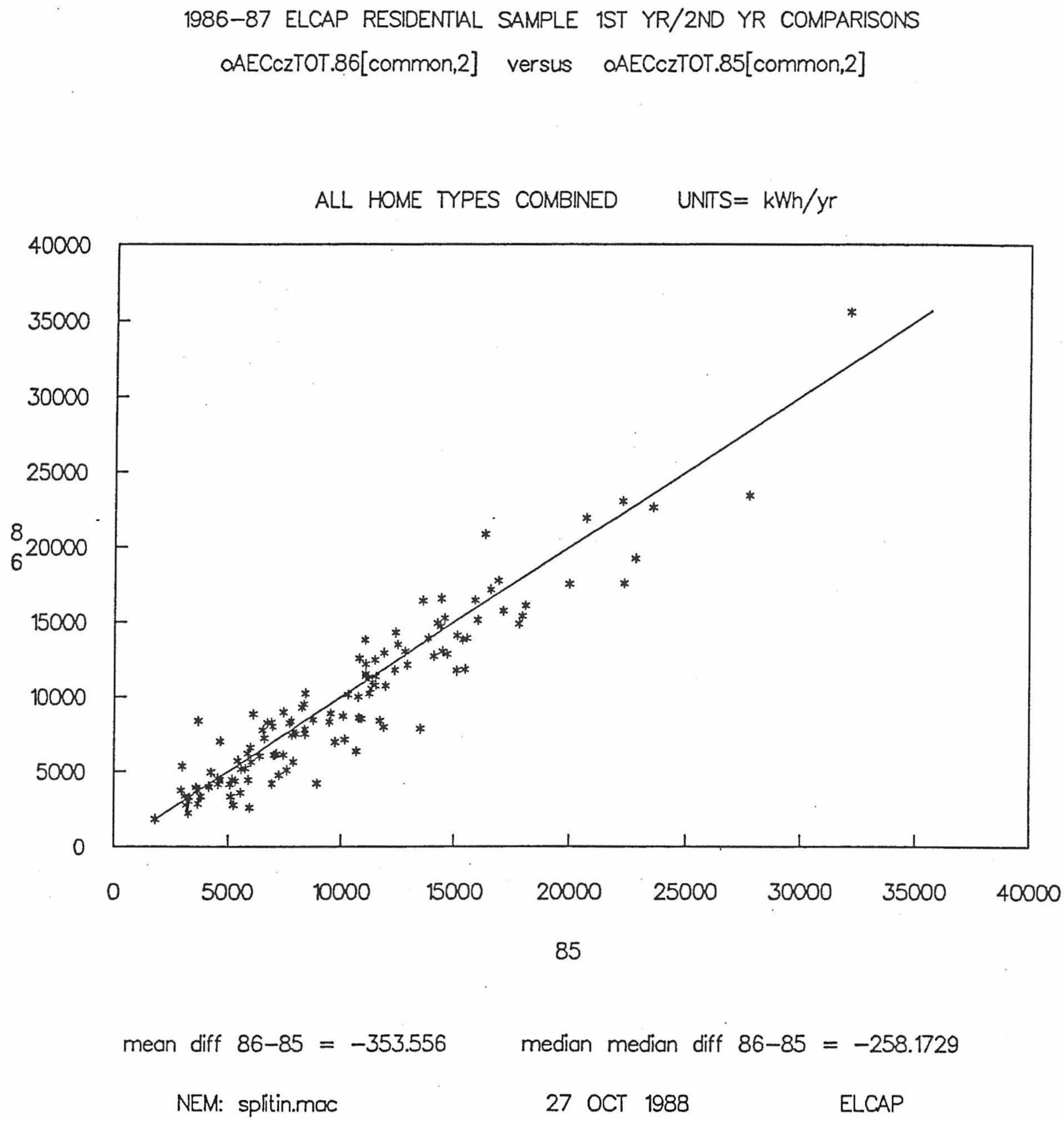


FIGURE H.9. Comparison of First- and Second-Year AEC_{oat} for the Combined Set of ELCAP Homes

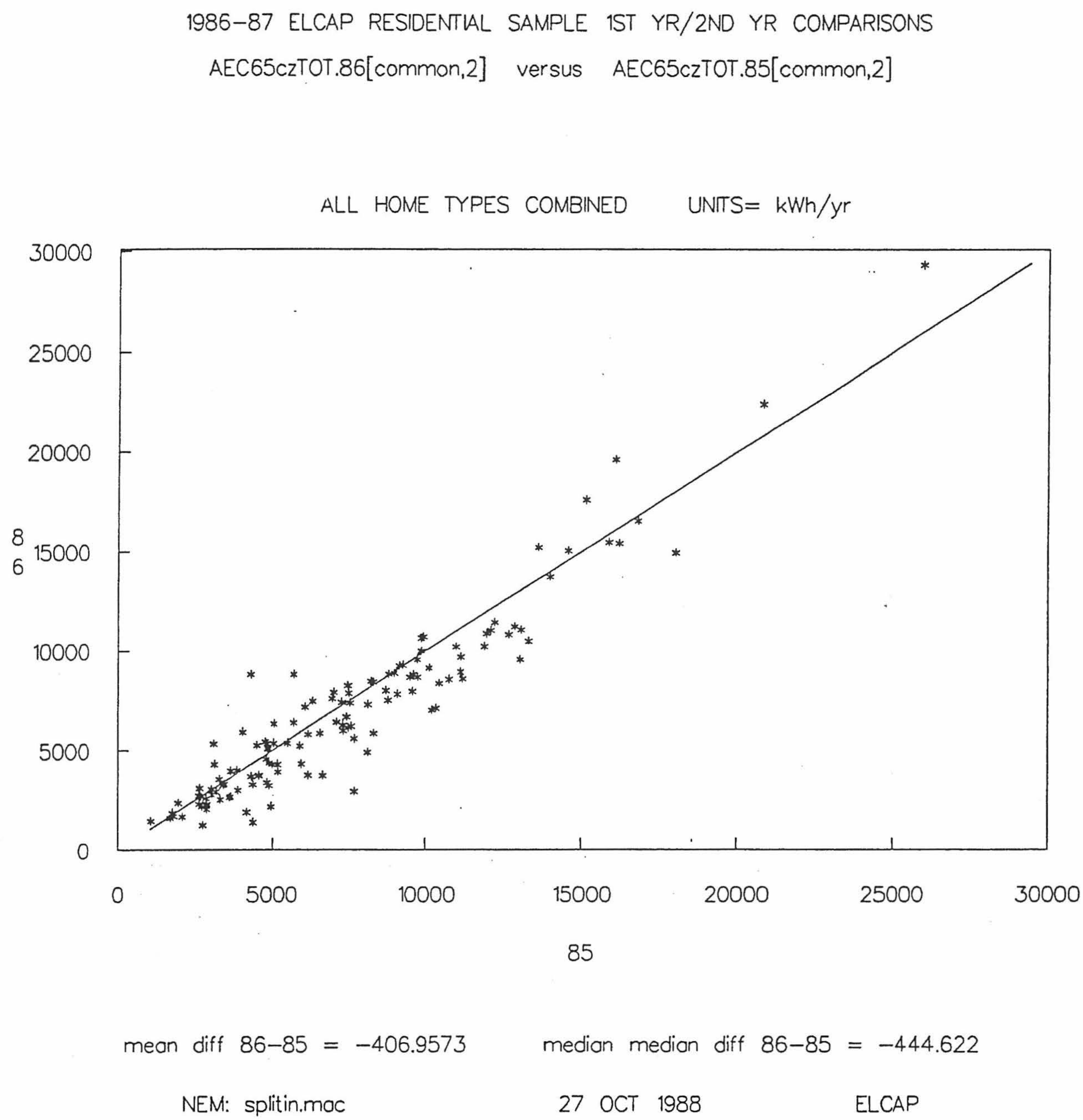
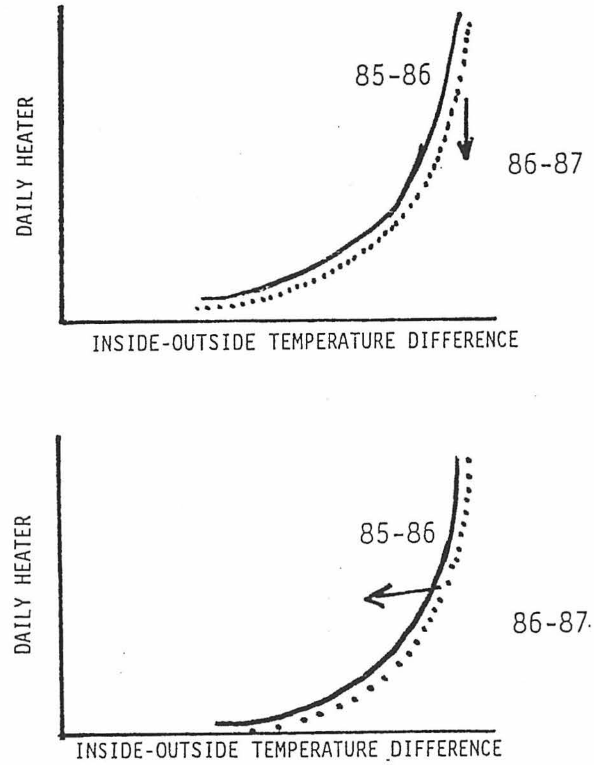


FIGURE H.10. Comparison of First- and Second-Year AEC_{65} for the Combined Set of ELCAP Homes

Expected Shifts in AECs



- Differences in Solar
  - $solar_{86} > solar_{85}$
    (4)%
  - observed in AEC_{oat}

- Differences in mean inside air temperatures
  - $\overline{IAT}_{86} > \overline{IAT}_{85}$
  - observed in AEC_{65}

- Effects balance in AEC_{iat}

FIGURE H.11. Idealized Shifts in the LOWESS Curve Fit of Heater to Inside-Outside Temperature Difference from Greater Solar Second-Year (top panel) and Higher Mean Internal Temperature in the Second-Year (bottom panel)

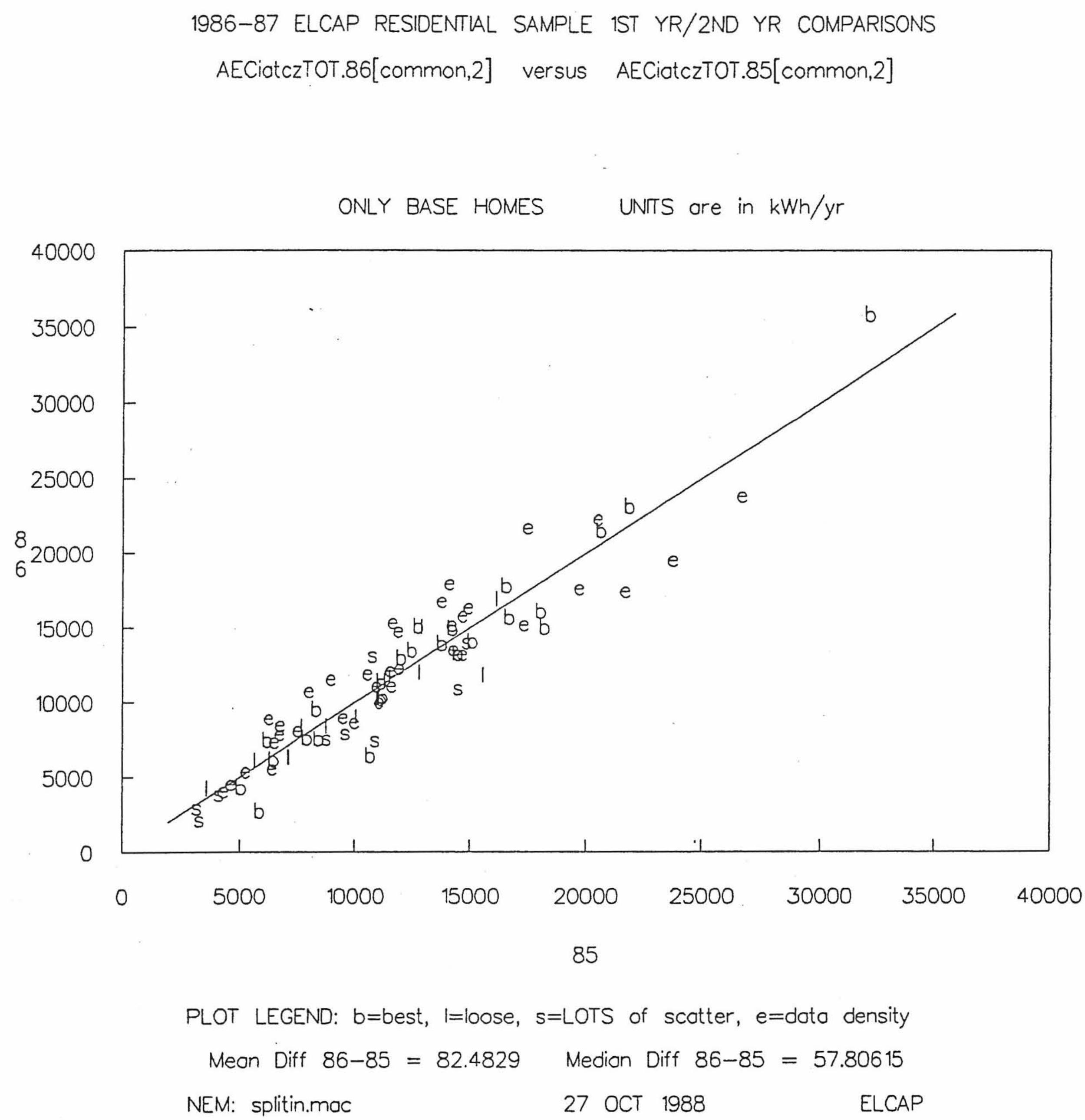
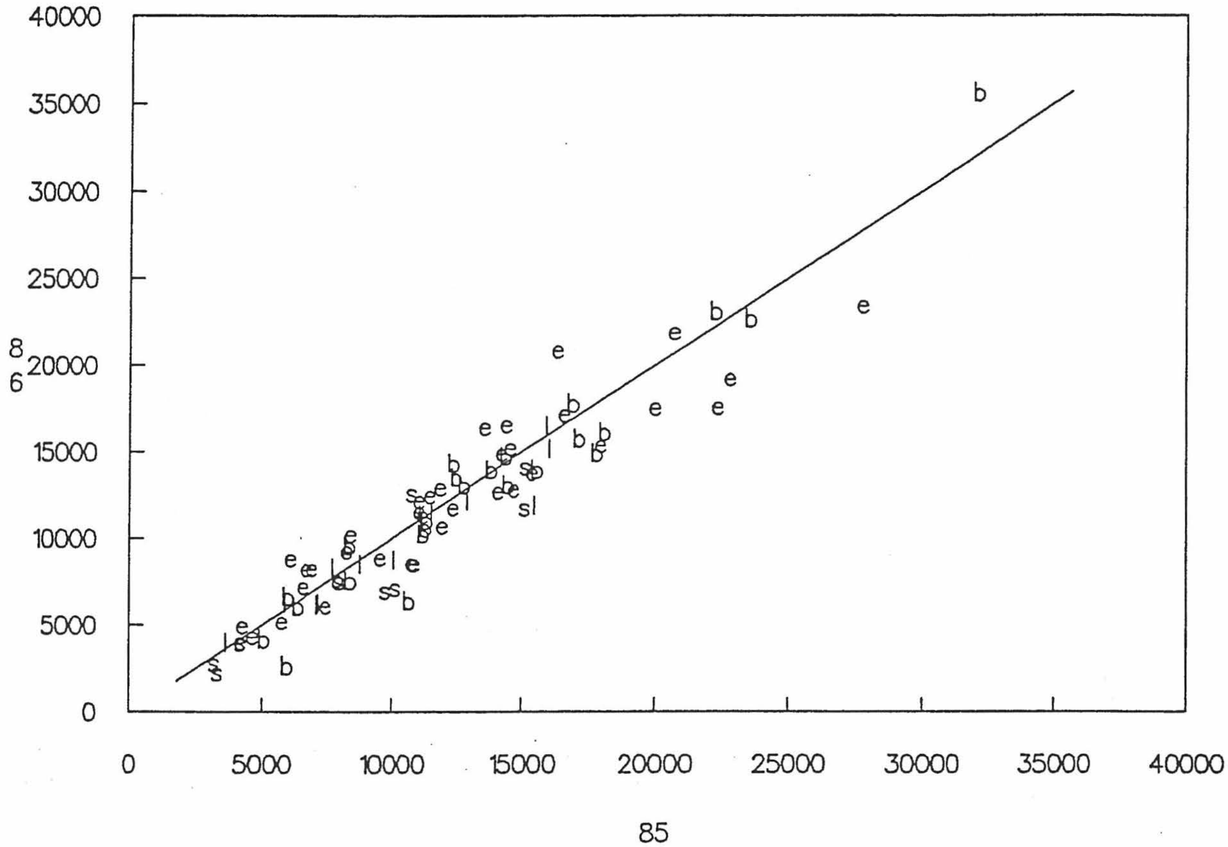


FIGURE H.12. Comparison of First- and Second-Year AEC_{iat} for the Residential Base ELCAP Homes

1986–87 ELCAP RESIDENTIAL SAMPLE 1ST YR/2ND YR COMPARISONS

oAECczTOT.86[common,2] versus oAECczTOT.85[common,2]

ONLY BASE HOMES UNITS are in kWh/yr



PLOT LEGEND: b=best, l=loose, s=LOTS of scatter, e=data density

Mean Diff 86–85 = –288.055 Median Diff 86–85 = –196.4014

NEM: spltin.mac 27 OCT 1988 ELCAP

FIGURE H.13. Comparison of First- and Second-Year AEC_{oat} for the Residential Base ELCAP Homes

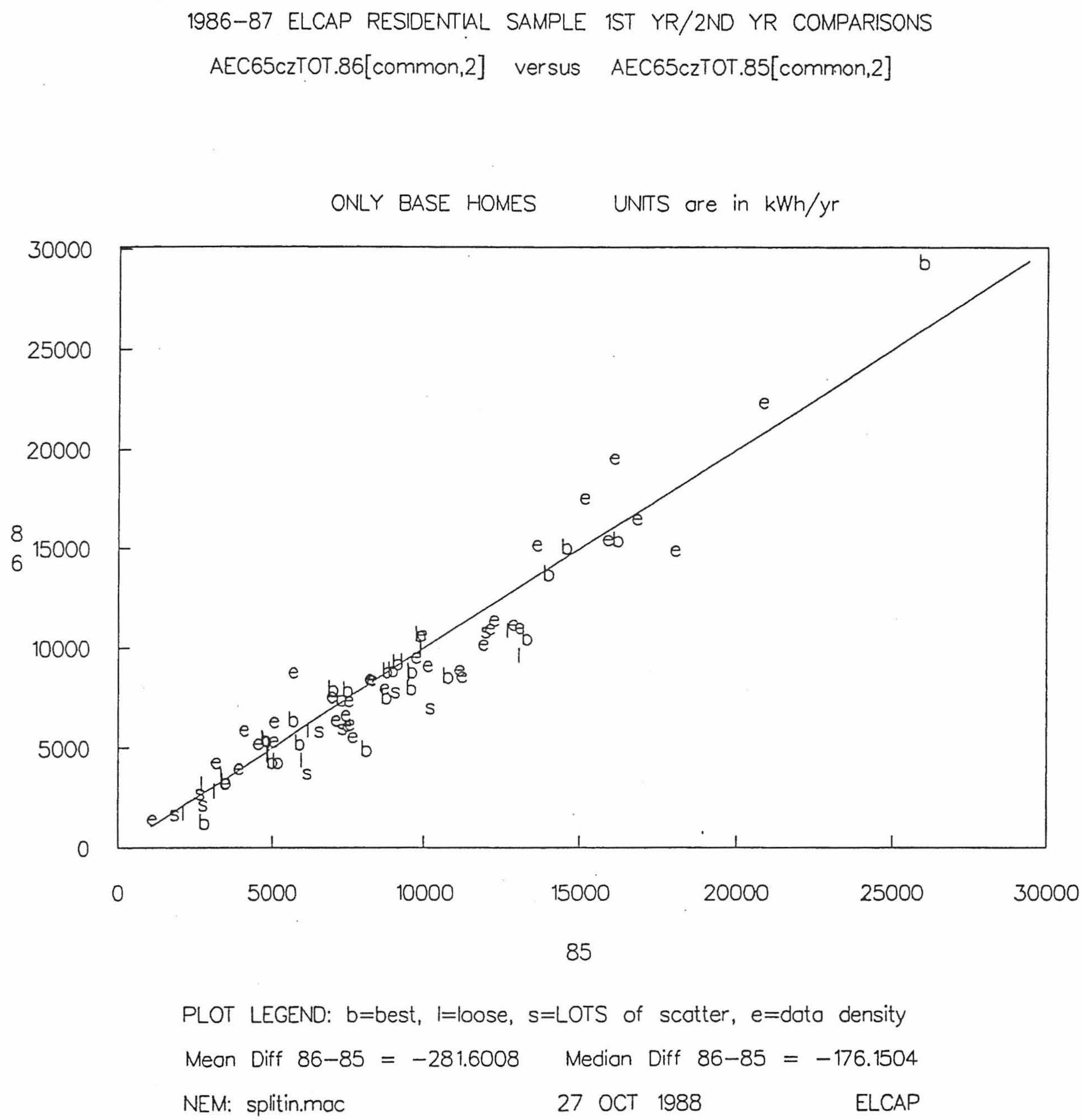


FIGURE H.14. Comparison of First- and Second-Year AEC_{65} for the Residential Base ELCAP Homes

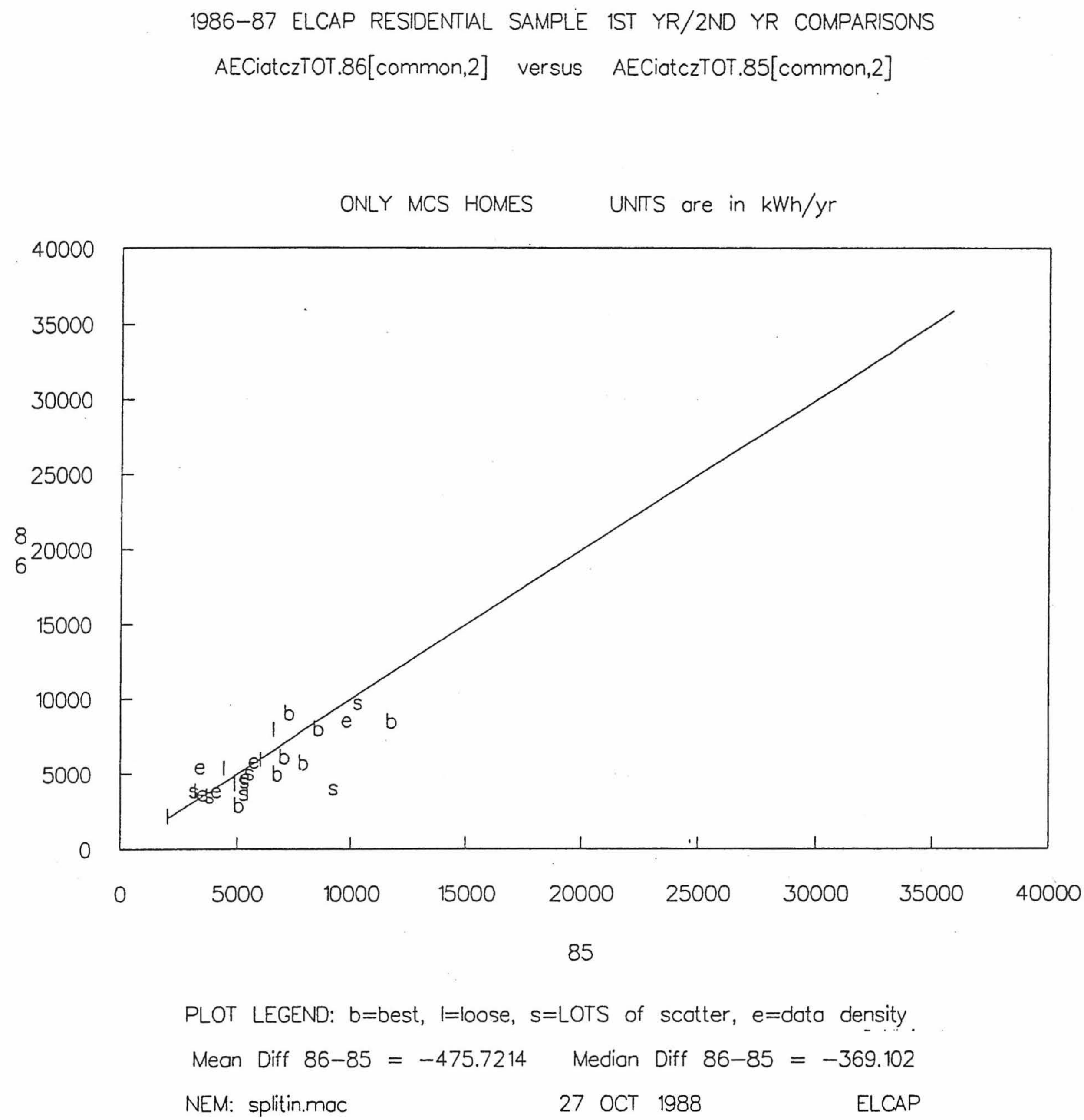


FIGURE H.15. Comparison of First- and Second-Year AEC_{iat} for the Model Conservation Standards ELCAP Homes

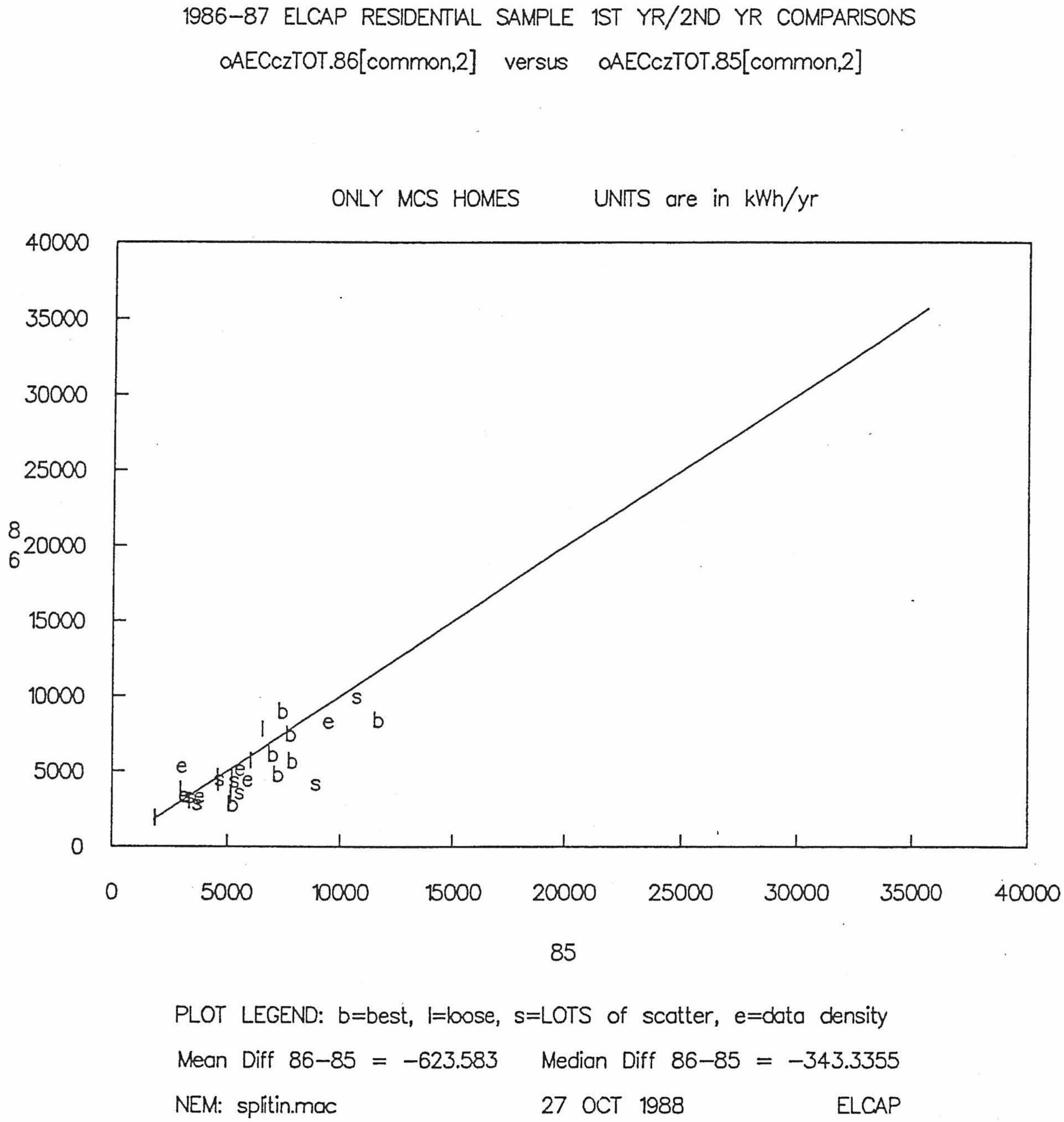


FIGURE H.16. Comparison of First- and-Second Year AEC_{oat} for the Model Conservation Standards ELCAP Homes

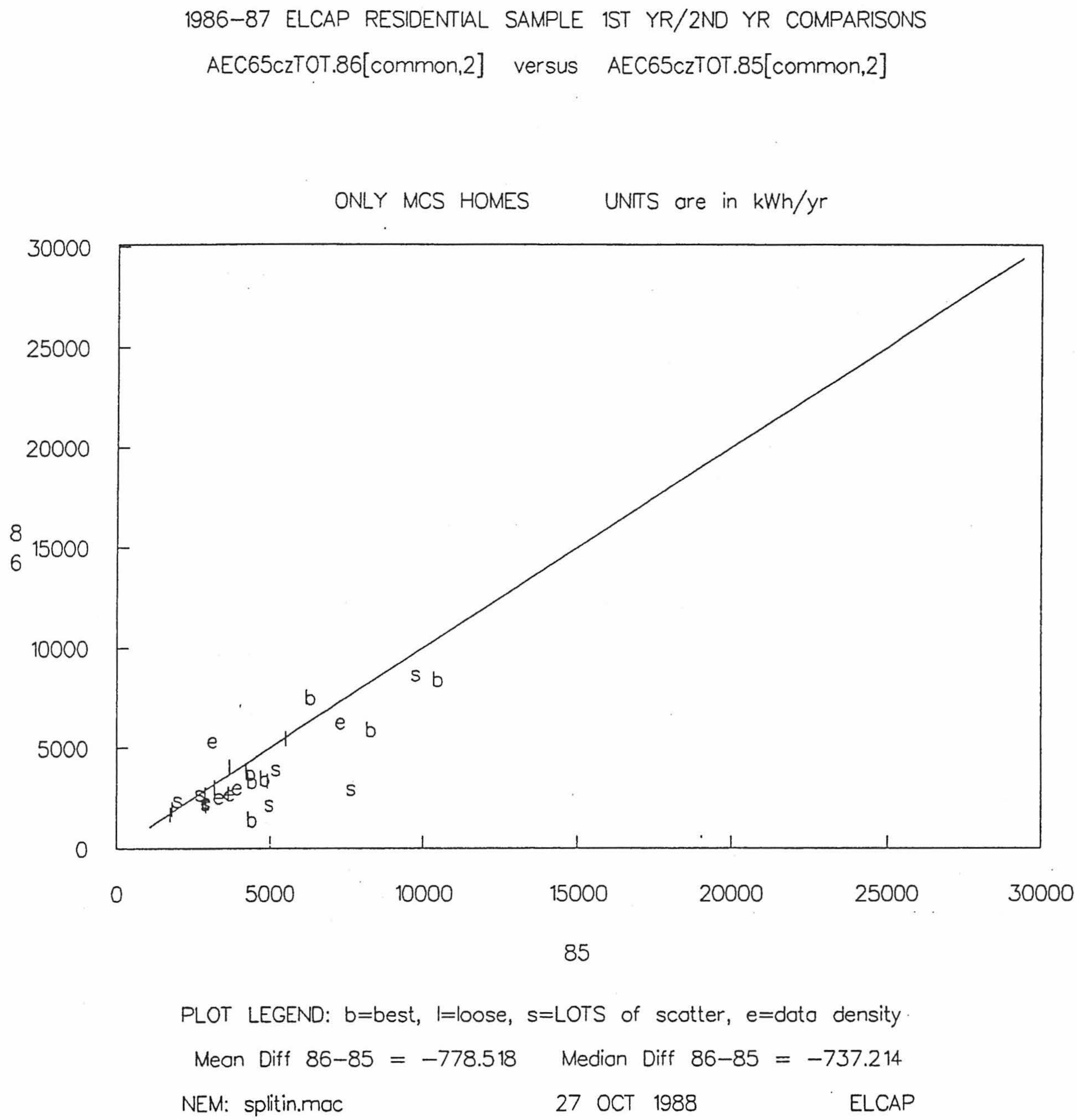


FIGURE H.17. Comparison of First- and-Second Year AEC_{65} for the Model Conservation Standards ELCAP Homes

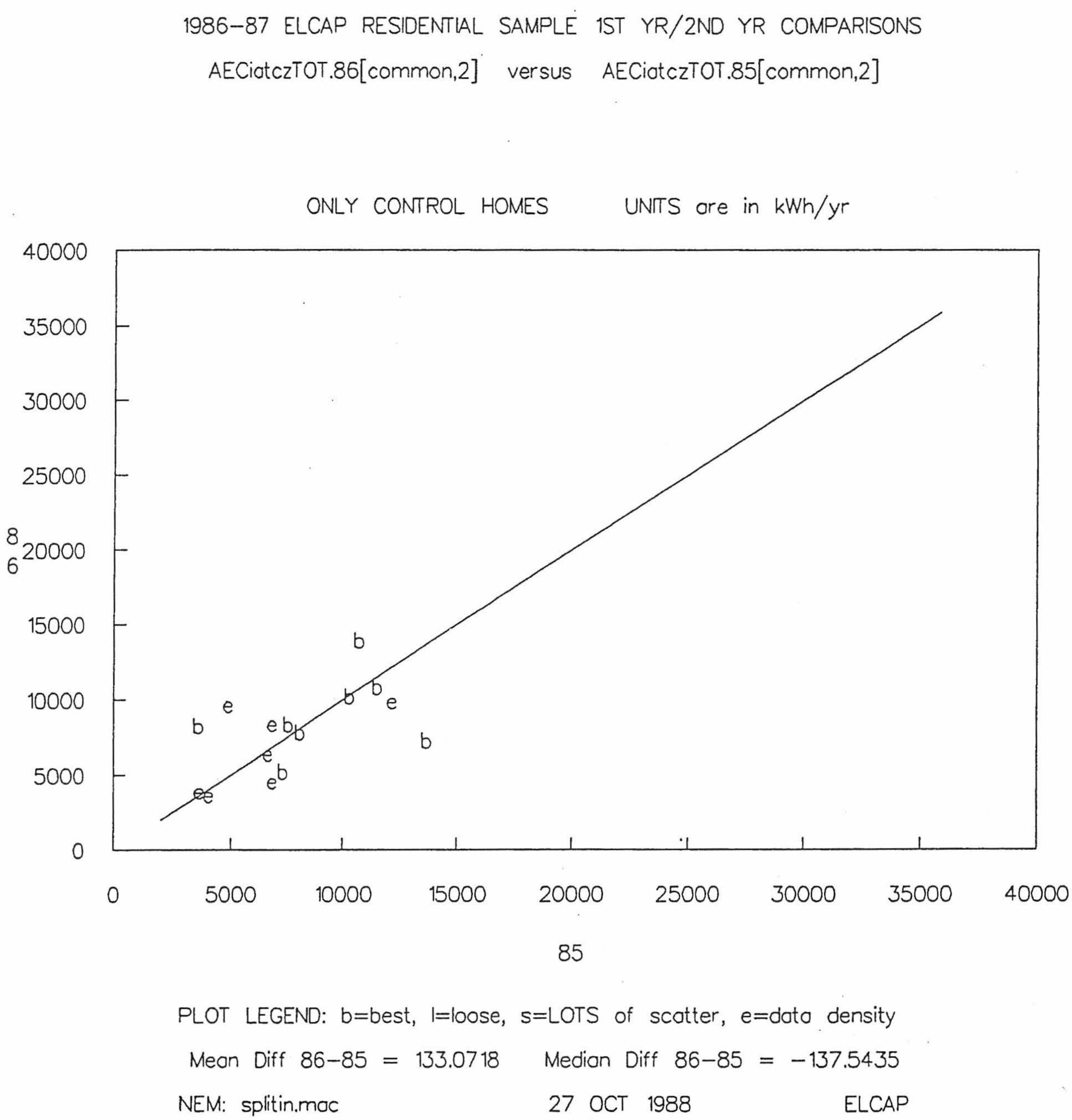


FIGURE H.18. Comparison of First- and Second-Year AEC_{iat} for the Control ELCAP Homes

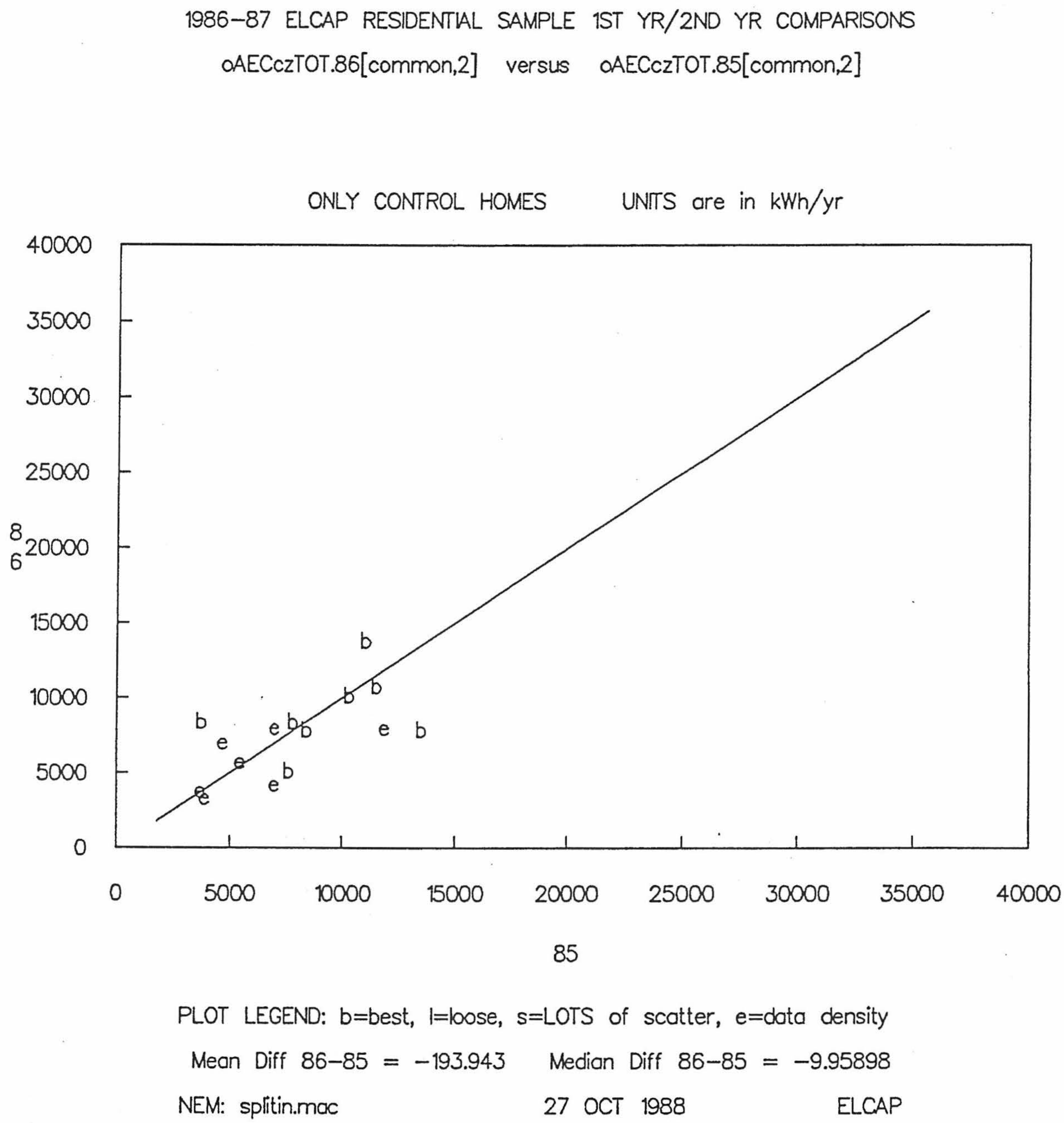


FIGURE H.19. Comparison of First- and Second-Year AEC_{oat} for the Control ELCAP Homes

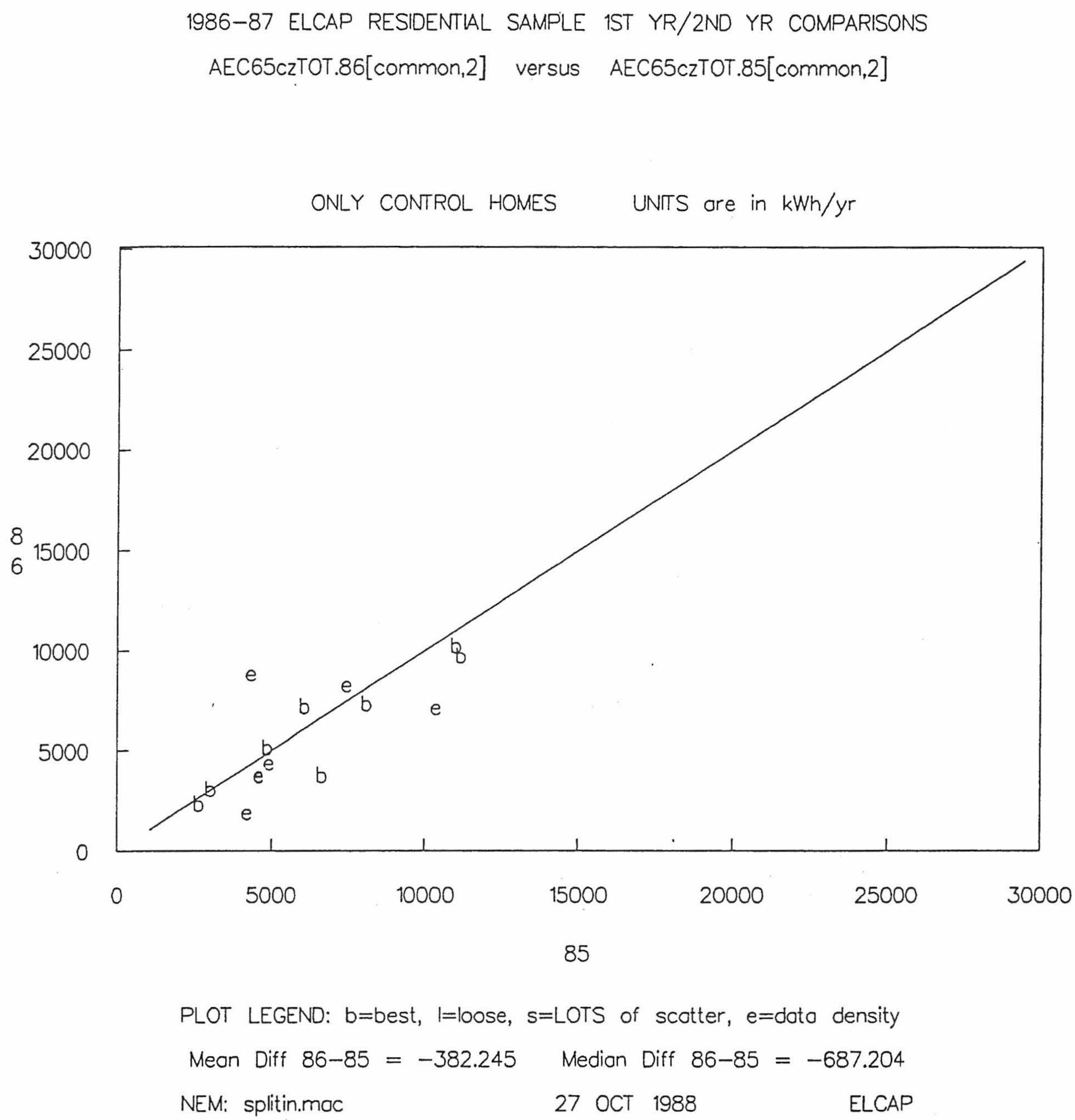


FIGURE H.20. Comparison of First- and Second-Year AEC_{65} for the Control ELCAP Homes

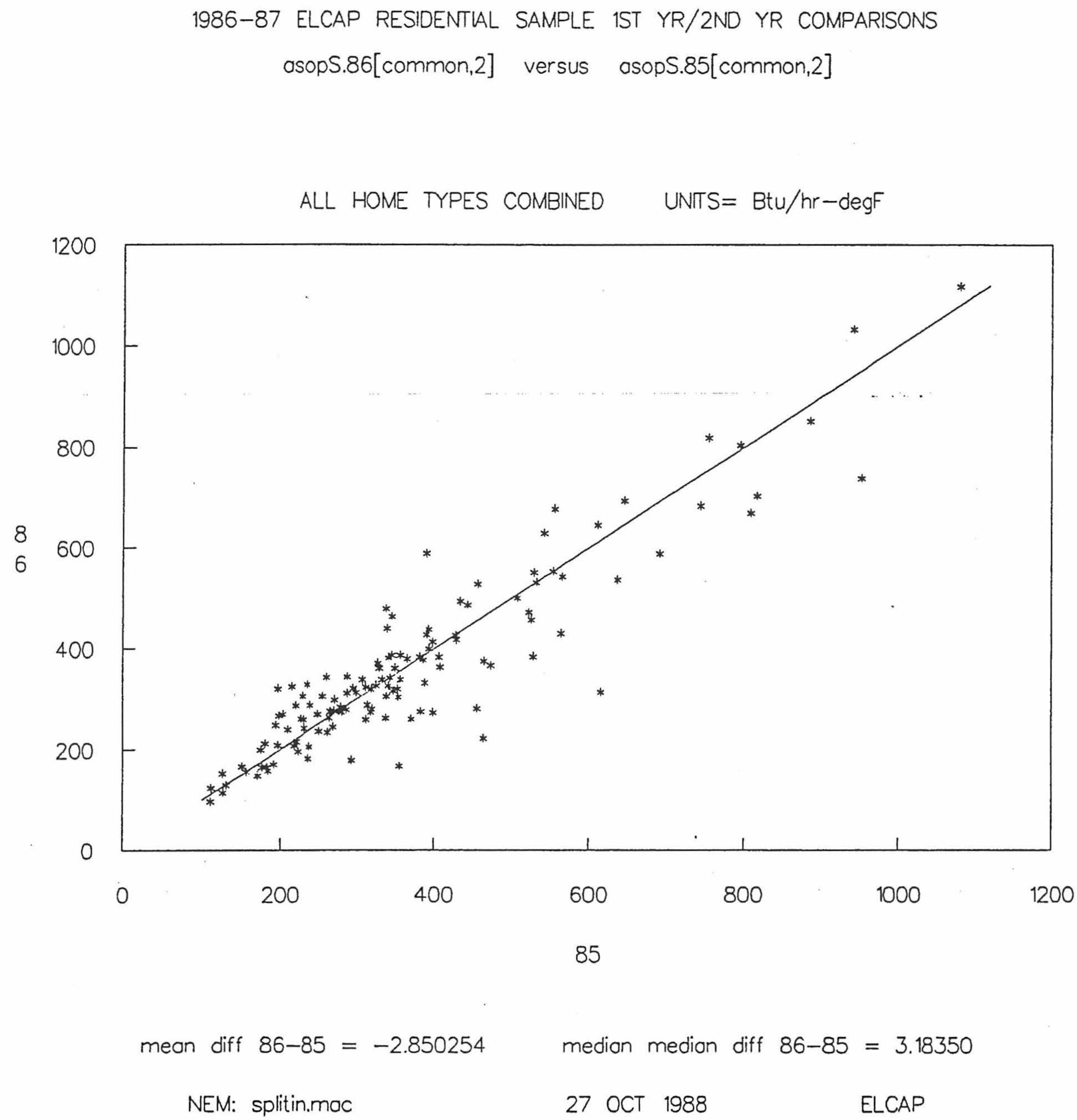
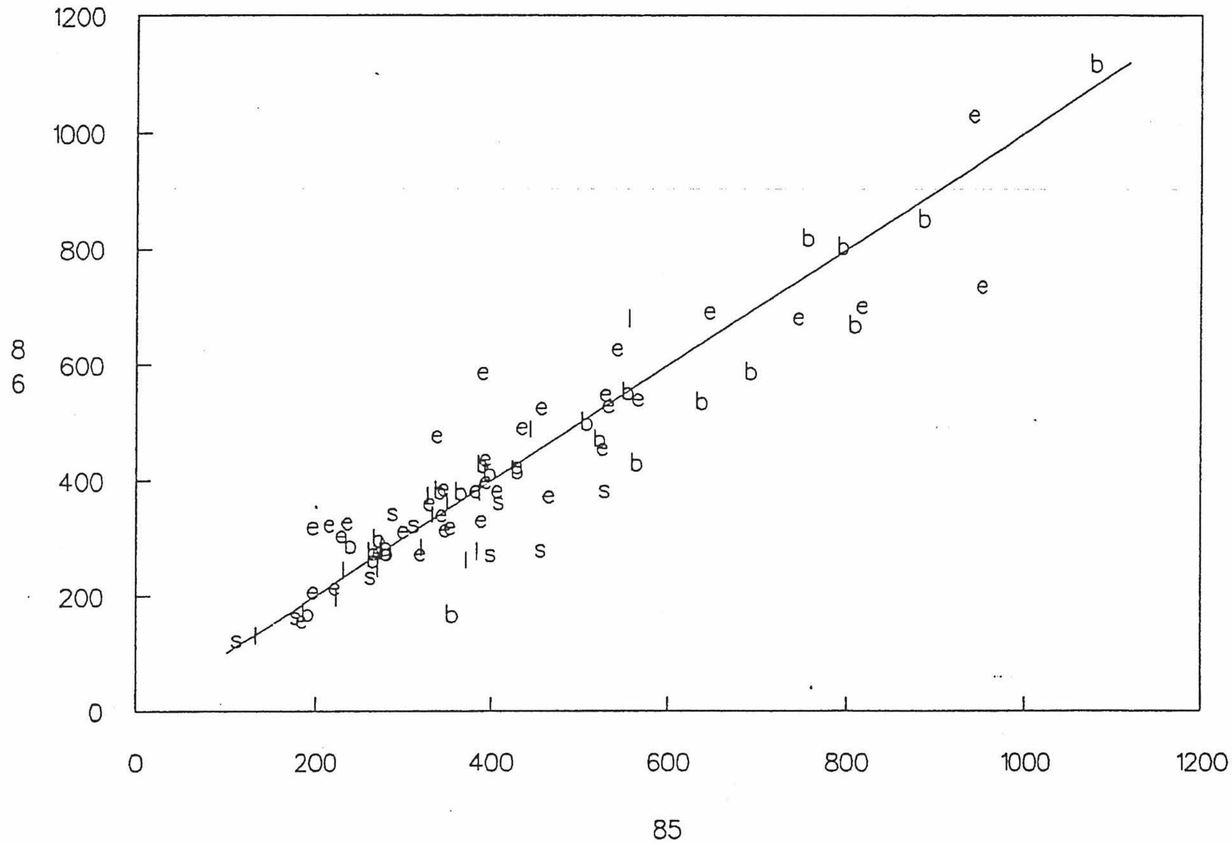


FIGURE H.21. Comparison of First- and Second-Year As-Operated Effective Conductances from the Standard Linear Fit of Daily Heater Load to Inside-Outside Air Temperature for the Combined Set of ELCAP Homes

1986-87 ELCAP RESIDENTIAL SAMPLE 1ST YR/2ND YR COMPARISONS

asopS.86[common,2] versus asopS.85[common,2]

ONLY BASE HOMES UNITS are in Btu/hr-degF



PLOT LEGEND: b=best, l=loose, s=LOTS of scatter, e=data density

Mean Diff 86-85 = -3.09967 Median Diff 86-85 = 2.924805

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FIGURE H.22. Comparison of First- and Second-Year As-Operated Effective Conductances from the Standard Linear Fit of Daily Heater Load to Inside-Outside Air Temperature for the Residential Base ELCAP Homes

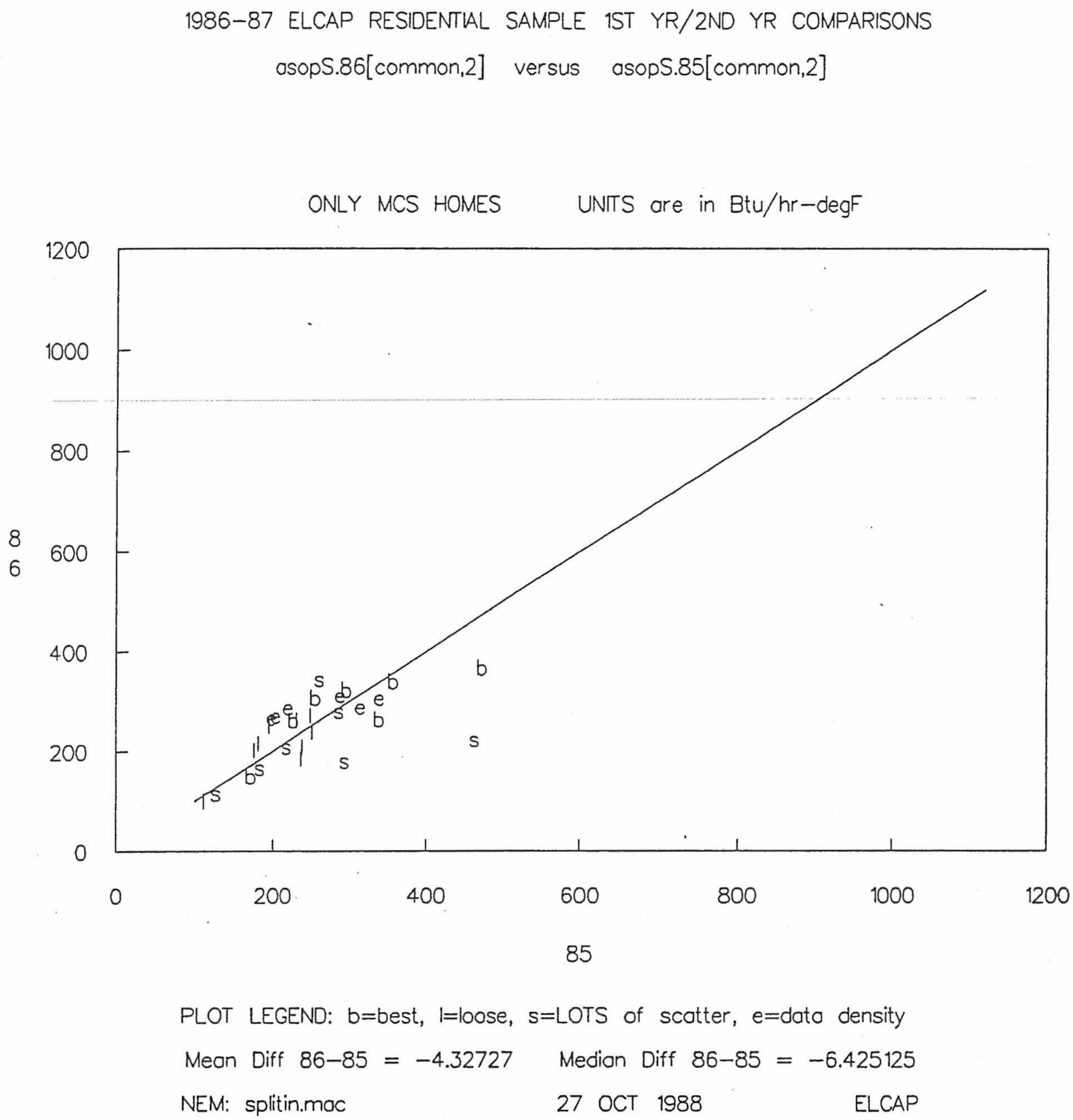


FIGURE H.23. Comparison of First- and Second-Year As-Operated Effective Conductances from the Standard Linear Fit of Daily Heater Load to Inside-Outside Air Temperature for the Model Conservation Standards ELCAP Homes

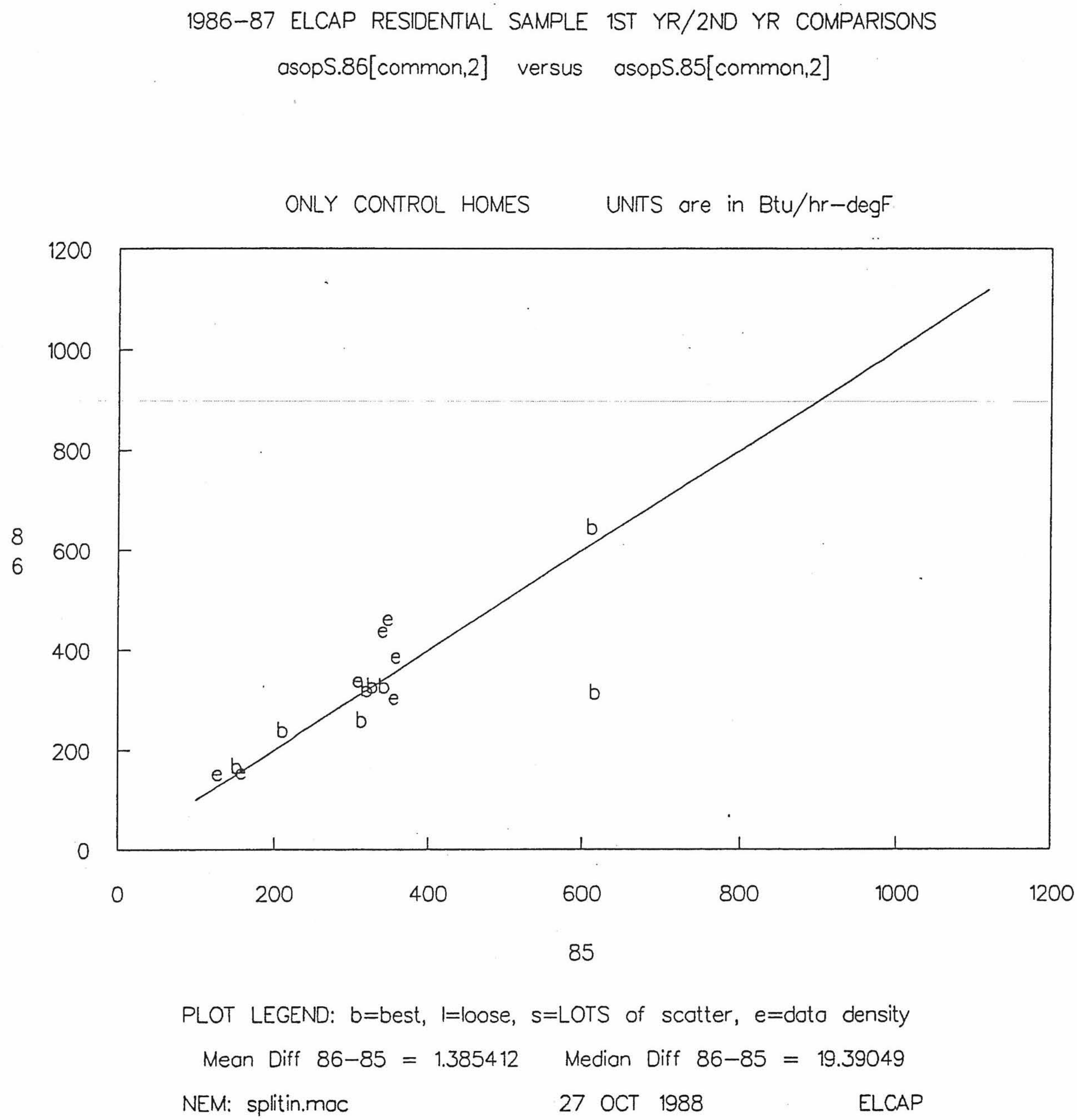


FIGURE H.24. Comparison of First- and Second-Year As-Operated Effective Conductances from the Standard Linear Fit of Daily Heater Load to Inside-Outside Air Temperature for the Control ELCAP Homes

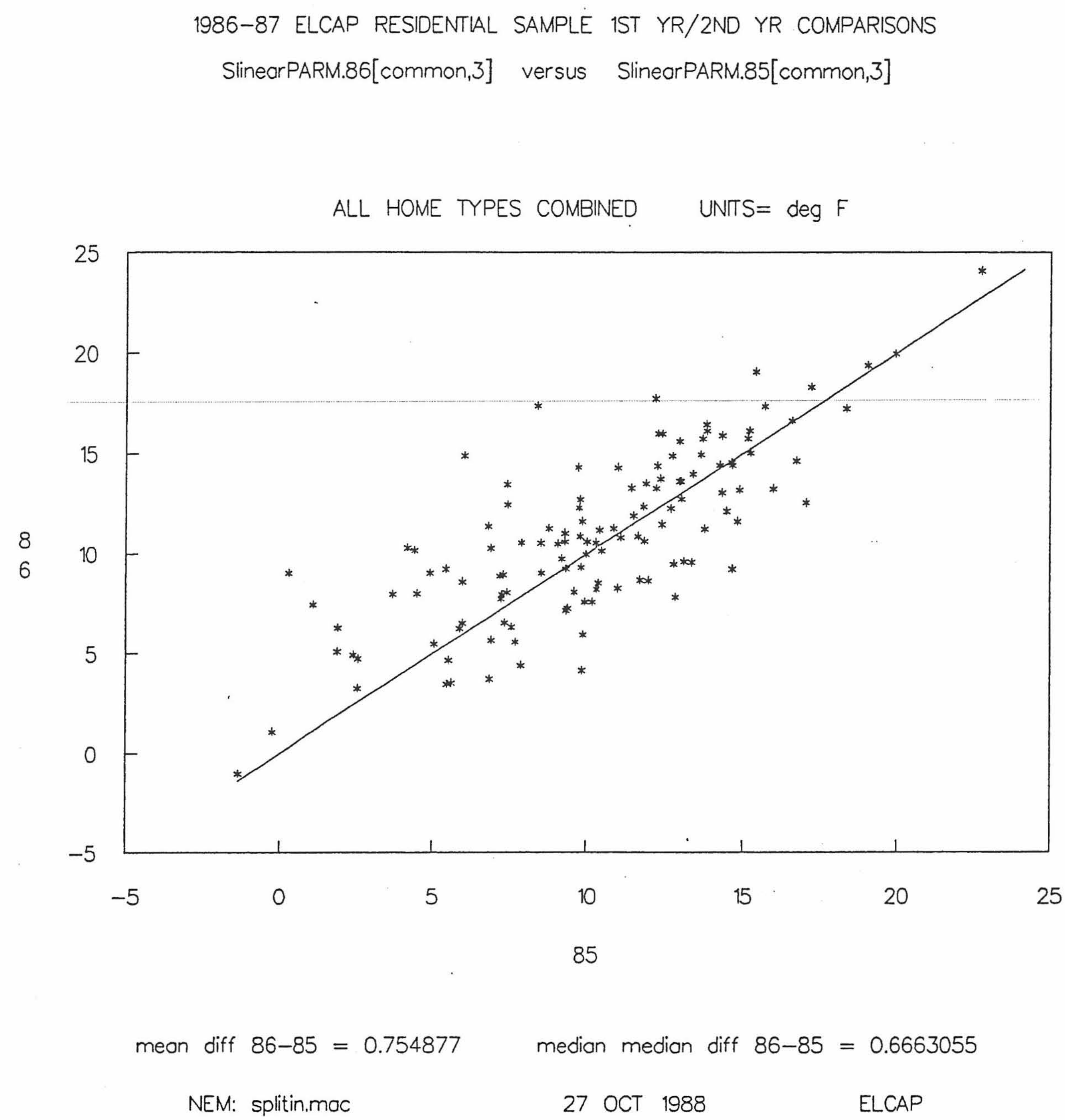


FIGURE H.25. Comparison of First- and Second-Year Balance Temperature Differences from the Standard Linear Fit of Daily Heater Load to Inside-Outside Air Temperature for the Combined Set of ELCAP Homes

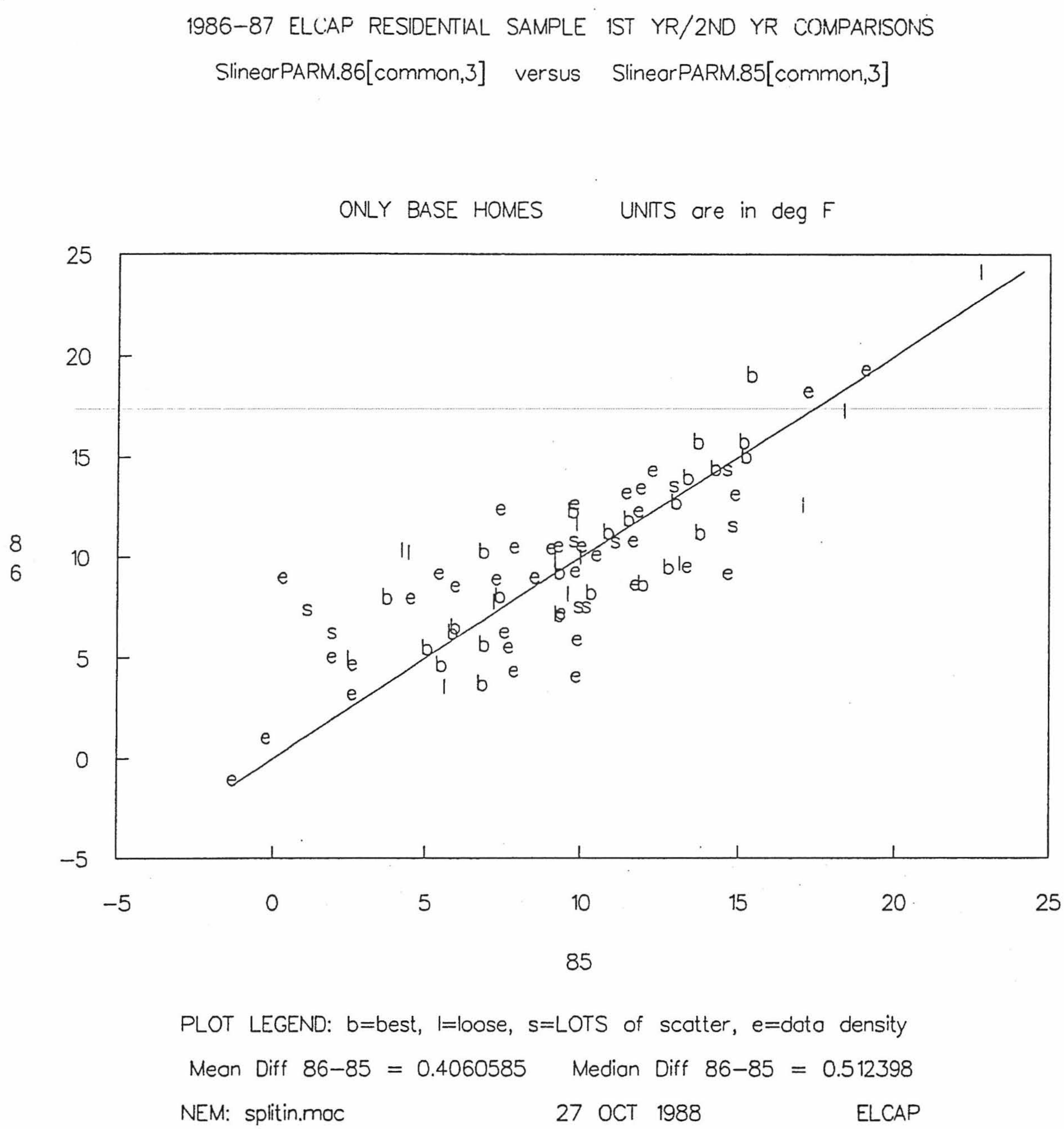
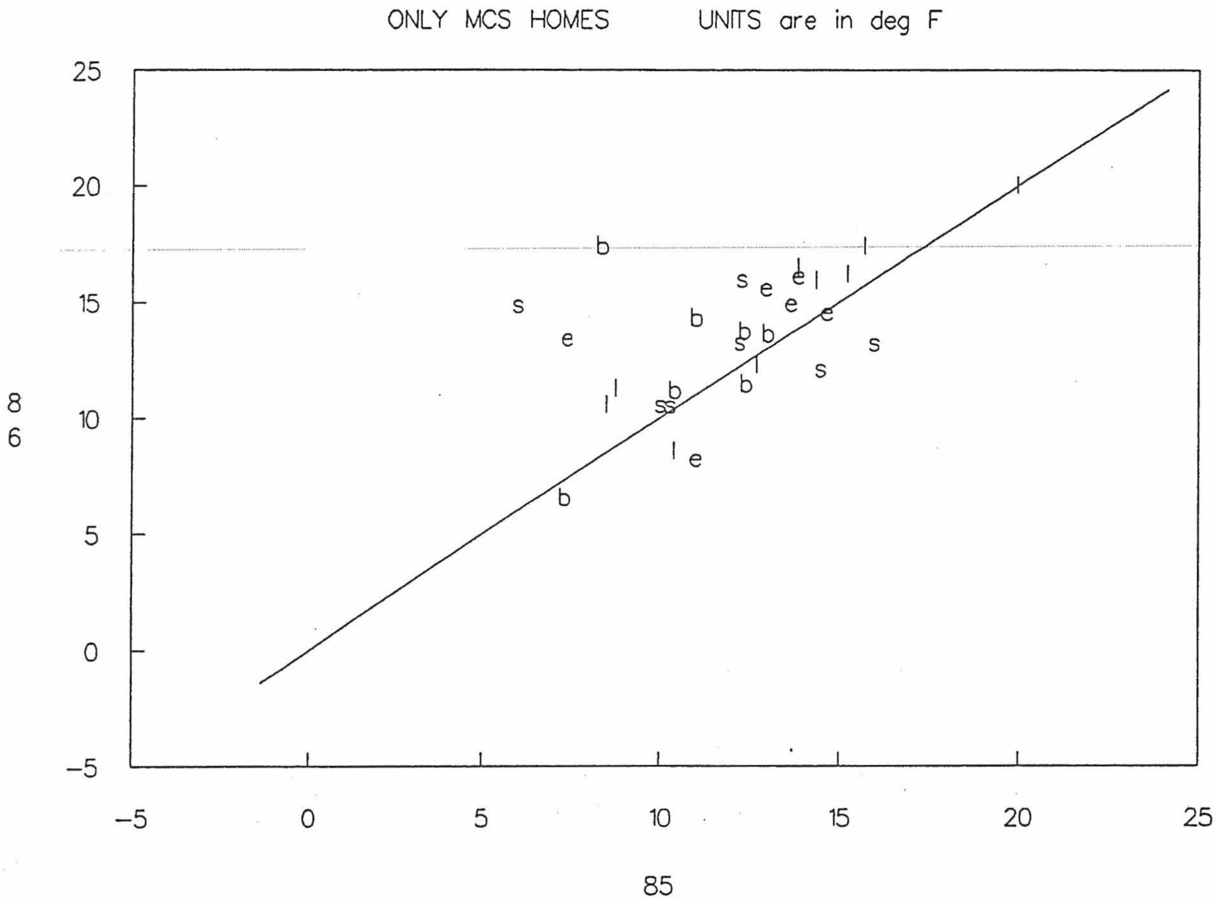


FIGURE H.26. Comparison of First- and Second-Year Balance Temperature Differences from the Standard Linear Fit of Daily Heater Load to Inside-Outside Air Temperature for the Residential Base ELCAP Homes

1986-87 ELCAP RESIDENTIAL SAMPLE 1ST YR/2ND YR COMPARISONS

SlinearPARM.86[common,3] versus SlinearPARM.85[common,3]



PLOT LEGEND: b=best, l=loose, s=LOTS of scatter, e=data density

Mean Diff 86-85 = 1.50722 Median Diff 86-85 = 1.130265

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FIGURE H.27. Comparison of First- and Second-Year Balance Temperature Differences from the Standard Linear Fit of Daily Heater Load to Inside-Outside Air Temperature for the Model Conservation Standards ELCAP Homes

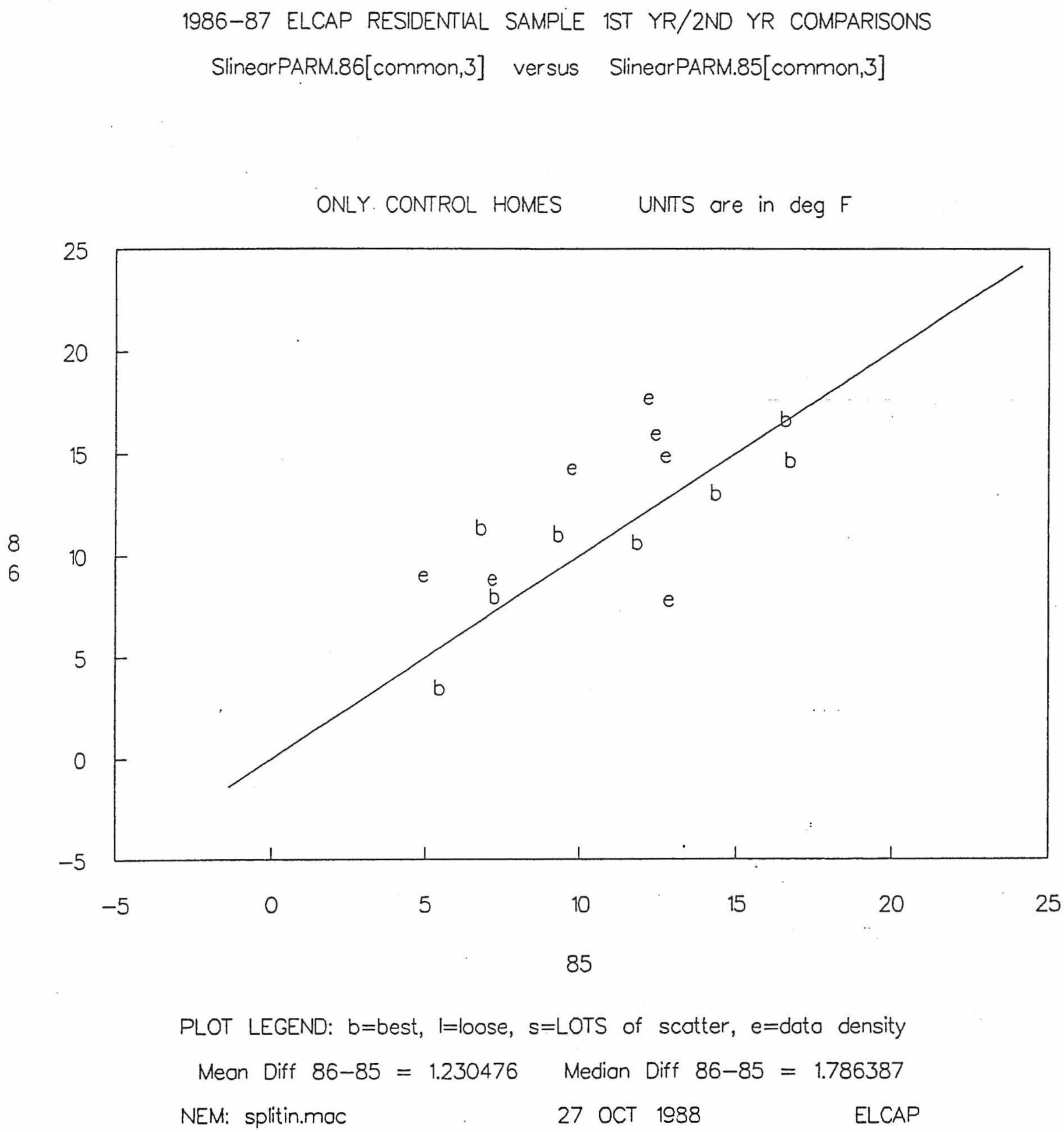

FIGURE H.28. Comparison of First- and Second-Year Balance Temperature Differences from the Standard Linear Fit of Daily Heater Load to Inside-Outside Air Temperature for the Control ELCAP Homes

APPENDIX I

CROSS-YEAR COMPARISONS FOR SPACE HEAT CHARACTERIZATION CURVES

APPENDIX I

CROSS-YEAR COMPARISONS FOR SPACE HEAT CHARACTERIZATION CURVES

Preliminary work by Miller (1987) indicated some associations between the topological shape of the LOWESS fit to the space-heating characterization curve and the heating system and foundation type. A concave downward or rolloff shape during a period of coldest weather may be important for load forecasters if the determinants for the phenomenon can be found. For the analysis reported here, the LOWESS fit to the space-heating characterization curve is classified via an automated routine. Classification is based on an analysis of the curvature for a cubic polynomial fit to the LOWESS fit of heater-to-formulation inside-outside temperature difference. The algorithm uses a heuristic to decide if changes in concavity are visually significant. The shape of the LOWESS curve for each heating season is classified into one of several categories: essentially linear, linear but with a foot or hook in the low-delta temperature region, concave upward, and rolloff during periods of highest temperature differences. In some cases, the algorithm encountered a nonclassified shape.

The transition matrix for these shapes is provided in Table I.1. If no change were detected between the years, then all off-diagonal entries would be zero. If the nonclassified category is ignored, two observations are made:

- For any particular row or column, the maximum entry occurs on the diagonal. The best single predictor for the topological shape from one season to the next is the current shape.
- Considerable migration occurs to the off diagonal elements about half of the shapes from a particular category end up in a different category from one year to the next.

TABLE I.1. Transition Matrix for LOWESS Fits of Daily Heater Load to Inside-Outside Temperature Difference For Sample Sites Using Two Heating Seasons

	1985-1986 Heating Season					
1986-1987 Heating Season	Non-classified	Linear	Linear with Foot	End Rolloff	Concave Upward	Total
Nonclassified	0	4	1	1	0	6
Linear	0	26	5	8	2	41
Linear with Foot	3	4	10	5	3	25
End Rolloff	3	9	5	19	4	40
Concave Upward	0	3	3	2	7	15
Total	6	46	24	35	16	

Table I.2 compares classifications from sites with nearly comparable amounts of data and tighter fits about LOWESS curve for both heating seasons. Some patterns emerge:

- Only about a third of the sites are scatter free having an abundance of data for both years.
- No transition occurs in the concave upward category.
- More sites with rolloff occur in the colder first-heating season.

The migration observed in topological shape indicates that there is a weather component that also impacts the curvatures. If the shape is to be a property of the structure, then it is best to use data from a number of years. Thus the effects of averaging the various weather and occupancy data are evident.

TABLE I.2. Transition Matrix for LOWESS Fits of Daily Heater Load to Inside-Outside Temperature Difference for Sample Sites Using Two Heating Seasons

1986-1987 Heating Season	1985-1986 Heating Season: Non-classified	Linear	Linear With Foot	End Rolloff	Concave Upward	Total
Nonclassified	0	1	0	0	0	1
Linear	0	11	4	5	0	20
Linear With Foot	1	1	1	1	0	4
End Rolloff	1	1	1	8	0	11
Concave Upward	0	0	0	0	4	4
Total	2	14	6	14	4	

APPENDIX J

RECOMMENDATIONS FOR FURTHER EMPIRICAL CHARACTERIZATIONS BASED ON FIRST- AND SECOND-YEAR COMPARISONS

APPENDIX J

RECOMMENDATIONS FOR FURTHER EMPIRICAL CHARACTERIZATIONS BASED ON FIRST- AND SECOND-YEAR COMPARISONS

The goal of an AEC estimate is to produce a weather-standardized estimate of annual heating requirements for a structure attempting to remove two sources of occupant-induced variation, displacement from wood burning and atypical heating consumption from extended vacancies. The technique is ideally suited to metered data and is easily applied to large groups of residences. No provision is currently made for standardizing internal or solar gains in the technique. By comparing AEC estimates for several populations within the ELCAP residential sample, several observations are made which clearly point to enhancements in future applications of this methodology.

The AEC_{iat} estimate of consumption is a more robust estimate than either AEC_{oat} or AEC_{65} for the two heating seasons studied. This is from the two counter balancing effects. These effects are a natural consequence of the weather. First, increased solar gains displace some of the heating load in the second year thus producing a lower space-heating characterization curve relative to the first year. Second, warmer, sunnier weather increased the mean measured inside air temperature during the second heating season. Consequently, higher inside-outside temperature differences are produced when the standard weather year is used to calculate AEC_{iat}. These higher delta temperatures increase the annual space-heating estimate. When AEC_{iat} is compared over the two heating seasons, the difference in combined population means is close to zero. The mean AEC_{oat} and AEC_{65} fall in the second-year category. The mean AEC_{oat} estimates drop by a statistically significant difference of 3.5%. Using outside air temperature as the predictor variable implicitly adjusts for changes in inside air temperatures between the heating seasons. Thus AEC_{oat} helps isolate the changes from differences in solar gains alone. When mean AEC_{65} estimates are compared, the changes in indoor air temperatures explicitly included in AEC_{iat} and implicitly included in AEC_{oat} are disabled and highly significant differences on the order of 5.5%.

The level of disagreement for mean AECs between heating seasons is not constant across the Base, MCS, and Control Homes. The Base home estimates are more stable than those for the RSDP homes. The tighter, more energy efficient MCS homes appear to be more strongly affected by solar availability and internal temperature float than are the Base homes. All mean AEC estimates for the MCS homes are lower in the second year. Marginally significant differences are noted in AEC_{iat} on the order of 8%. Significant differences of 11% are observed in mean AEC_{oat} estimates and highly significant differences of approximately 17% are observed for the AEC_{65} estimates. These large differences are probably from omission of solar effects and the methodology assumption of a constant mean inside air temperature over the heating season.

The changes suggested below for the AEC methodology would stabilize the estimates considerably. The AEC thus moves closer to a property for the structure with greater resistance to the particulars of any weather year:

- Combine the metered data from all heating seasons into a single analysis. These data would have wood usage and extended vacancy removed as before.
- A multiple LOWESS model that computes daily heater as a function of inside air temperature, outside air temperature, horizontal solar radiation, and appliance internal gains.

All the data for this type of multiple predictor analysis is currently available within the ELCAP project. A multiple predictor LOWESS approach should do a better job of incorporating the complex dependencies between weather, internal setpoints and gains, and heating requirements.

In order to compute the new AEC estimates, a standard year of solar data is needed in conjunction with the standard year of outside air temperature data. A standard set of internal gains could also be used, if desired. An AEC estimate, referenced to a particular setpoint strategy, such as AEC_{65}, is computed using a year's worth of realistic daily internal temperatures for that setpoint and weather year. This internal data and the standard inputs are used with the multiple LOWESS relation to compute annual space-heating requirements. Computation of the AEC_{oat} estimate is analogous except that treatment of inside air temperatures is omitted altogether. To compute the AEC_{iat} estimate, the measured inside air temperatures are first modeled at the site as a function of the other measured "at-site" predictor variables. This produces a year long, site-specific data set of inside air temperatures. Next, the standard set of inputs are used with the derived internal temperature model to calculate the as-observed internal temperature input year. This approach makes use of all the metered data at the site and assumes no particular relation among the variables.

In Table J.1, AEC_{iat} and AEC_{oat} along with their respective (standard) linear fit based parameters are substituted into the last expression of Table J.2. The mean changes for both inside-outside temperature-based analysis and outside air temperature based analyses indicate the changes in AEC_{oat} and AEC_{iat} to be within half a percent of the sum of mean changes for the slope and intercept-based HDD parameters. This exercise indicates a general agreement for the relative changes averaged over the combined group of homes for the AEC estimate and the parameters from the linear fit sample.

TABLE J.1. Change Over the Combined Set of Homes for the Two Predictor Variables - With Percentage Changes Relative to 1985-1986

	Error	=	AEC	- {	(S) slopes	(S)	HDD }
oat	.4%		-3.5%		-1.9%		-2.0%
delta t	.4%		-0.4%		-0.007%		-0.8%

TABLE J.2. A Method for Reconciling Changes in the Derived Thermal Parameters

Step 1 $$AEC = asopUA * HDD$$

Step 2 $$\Delta AEC = \Delta(asopUA * HDD)$$

Step 3 $$d(AEC) = HDD*d(asopUA) + asopUA*d(HDD)$$

Step 4 $$\frac{d(AEC)}{AEC} = \frac{d(asopUA)}{asopUA} + \frac{d(HDD)}{HDD}$$

Step 5 $$Error = \frac{d(AEC)}{AEC} - \left\{ \frac{d(asopUA)}{asopUA} + \frac{d(HDD)}{HDD} \right\}$$

CONCLUSIONS AND RECOMMENDATIONS FOR LINEAR FITS

Many of the mean differences between years in the parameters from the linear fits of space heating to temperature differences or outside air temperatures are statistically nonsignificant. Small, nonsignificant changes are observed whether the slopes are based on delta temperature or outside air temperature. The one exception is a marginally significant 10% relative drop in mean robust outside air temperature based as-operated UAs for the MCS homes. Several significant changes are noted in the intercepts from the inside-outside temperature fits between years. The mean differences in intercepts from the outside air temperature based fits are nonsignificant.

When heating degree days are calculated, the change in total heating degree days between years, which averages about 2%, is also nonsignificant regardless of the choice for base temperature. If mean relative changes in AEC are compared to the mean relative changes for the as-operated UA from the standard fit and effective heating degree days for the combined group of homes, agreement within half a percent is obtained. This is true for parameters derived from both types of predictor variables.

For this set of homes, the greatest and most statistically significant changes in the parameters from the linear fit appear to be in the intercepts rather than the slopes. This is an important conclusion for future empirical characterizations based on this methodology. Solar availability should be taken into consideration before a building balance point, calculated from a specific year of metered data, is generalized to be a property of the structure. Although the as-operated UAs showed less change, the tighter or more thermally efficient the home, the more unstable the empirically derived parameters appear to be. A recommendation for future work is to combine metered data over many years before performing the linear fit.

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