

End-Use Load and Consumer Assessment Program

Significant ELCAP Analysis Results: Summary Report

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ABSTRACT

The evolution of the End-Use Load and Consumer Assessment Program (ELCAP) since 1983 at Bonneville Power Administration (Bonneville) has been eventful and somewhat tortuous. The birth pangs of a data set so large and encompassing as this have been overwhelming at times. The early adolescent stage of data set development and use has now been reached and preliminary results of early analyses of the data are becoming well known. However, the full maturity of the data set and the corresponding wealth of analytic insights are not fully realized.

This document is in some sense a milestone in the brief history of the program. It is a summary of the results of the first five years of the program, principally containing excerpts from a number of previous reports. It is meant to highlight significant accomplishments and analytical results, with a focus on the principal results. Many of the results have a broad application in the utility load research community in general, although the real breadth of the data set remains largely unexplored.

The first section of the document introduces the data set: how the buildings were selected, how the metering equipment was installed, and how the data set has been prepared for analysis. Each of the sections that follow the introduction summarize a particular analytic result. A large majority of the analyses to date involve the residential samples, as these were installed first and had highest priority on the analytic agenda. Two exploratory analyses using commercial data are included as an introduction to the commercial analyses that are currently underway. Most of the sections reference more complete technical reports which the reader should refer to for details of the methodology and for more complete discussion of the results.

SUMMARY

The End-Use Load and Consumer Assessment Program (ELCAP) conducted by Pacific Northwest Laboratory for the Bonneville Power Administration (Bonneville) was initiated to support both conservation assessment and load forecasting missions. ELCAP involves the collection and analysis of hourly end-use electricity usage data together with detailed characteristics from over 400 residences and 140 commercial buildings. Section 1.0 discusses the operational aspects of ELCAP from the initial selection and recruitment of sites, to the installation of metering equipment, and the verification and data processes. Annual and monthly end-use loads and shares for the residential sector are discussed in Section 2.0.

A principal result of the analysis of heat loss characteristics in the ELCAP residences (Section 3.0) is that home insulation levels are primarily related to vintage rather than climate severity. The general trend toward vintage as a determinant of thermal integrity of residences can be interpreted as indicative of the consequences of a lack of climatically appropriate energy standards. The lost opportunities for achieving an energy-efficient housing population can be large in the face of a tendency to build to common practices that are not adapted to particular climates.

An early goal of ELCAP analysis was to evaluate the performance of the Northwest Power Planning Council's Model Conservation Standards (MCS). The residential MCS are a key element of regional resource planning, and a substantial portion of the savings attributed to conservation programs are concentrated in new construction. A number of homes built to the MCS were metered and their thermal performance analyzed as a part of ELCAP (Section 4.0). Theoretical heat loss calculations for MCS and Control homes based on the ELCAP on-site inspections (Section 3.0) shows that both samples of homes metered by ELCAP were designed and constructed to accurately represent the MCS requirements and current practice, respectively. The MCS homes clearly exceed the historical trends when they are viewed as representative of the next decade of construction. The most important result of this study, summarized in Section 4.0, is that the Control homes built under the Residential Standards Demonstration Program (RSDP) to current practice have thermal

performance substantially better than that assumed for current residential construction in the development of the MCS standards. The savings realized by imposition of the MCS may, in consequence, be over-estimated, even though the MCS thermal performance targets are realized in the MCS homes.

Supporting this conclusion, thermal analysis of the Residential Base Sample of existing electrically space-heated single-family homes showed that they have lower space heating requirements than is currently estimated for the regional stock (Section 5.0). This is despite the rather high inside air temperatures at which these homes are operating over the heating season (69°F), and the fact that effects of wood use are excluded in the analysis. Comparison of theoretical heat loss rates^(a) with apparent values^(b) determined from the metered data indicate that most homes in the region have lower heat loss rates than expected. This underlines the possibility that the current forecasts of space heating for the entire existing housing stock may be high.

The thermal analysis of the Base sample also indicates that heating system types and foundation types have significant impact on residential heating loads. The heat and air losses from the ducts in central heating systems, and the lesser capability for zoning inherent in them, apparently significantly detract from overall residential thermal performance. This is important for heat pump systems, since these same factors must reduce overall performance of heat pump homes in a similar fashion.

Another important conclusion of the thermal analysis of the Base homes is that the space heating response to temperature conditions of over half the homes in the ELCAP sample is not characterizable, apparently because of extensive wood use, use of other fuels in homes that are reportedly electrically heated, and other unmetered behavior on the part of some

(a) Rates as determined by standard engineering calculations. Will be referred to as "nameplate" values.

(b) Rates that include aspects of internal gains and occupant effects that are not incorporated in standard engineering calculations. Will be referred to as "as-operated" values.

residents. Of the approximately half that are characterizable, half again show strong nonlinear behavior in the region of low outdoor temperatures.

The Hood River end-use metered data have been integrated with the ELCAP data base. The analysis of the Hood River data confirms previous findings that less than 50% of the predicted annual savings were achieved, even when the effects of wood burning were eliminated (Section 6.0). The magnitude and cost-effectiveness of the conservation resource in existing buildings is indicated to be much less than predicted by the engineering models as used for the prediction.

The discrepancy between theory and practice in retrofit savings estimates is commonly attributed to "takeback" effects. The Hood River analysis suggests that there is no intentional behavior on the part of the occupants to use some of the savings for increased comfort and convenience by increasing room temperatures, the traditional definition of "takeback". There is evidence of a disproportionate level of savings in wood instead of electricity in wood-burning homes. However, it is possible that at least part of this is also unintentional on the part of the occupant. Thus the existence of "takeback" effects are either unsupported or inconclusive (in the case of wood heat) by the Hood River data.

In load forecasting, conservation planning, and other utility planning work it is necessary to make assumptions regarding the strategy by which occupants operate their houses. The median room temperature observed in 54 RSDP homes metered by ELCAP is 70°F for a period from December through February (Section 7.0). These indoor temperatures are similar to those of the ELCAP Base homes (69°F). This is significantly higher than the assumptions in the Northwest Power Plan (Northwest Power Planning Council 1986), typically 65°F. The estimated resulting increase in space heating ranges from an increase of about 35% in Seattle to 20% in Great Falls.

The indoor temperature data also indicate that temperature differences between the living areas of homes and bedrooms are around 4°F in the median, indicating extensive zoning behavior that reduces space heating loads considerably (as much as 45% in Seattle to 28% in Great Falls), more than offsetting the effects of the higher-than-expected living area temperatures.

The analysis of zoning behavior confirms that zoning is a widespread effect of sufficient magnitude to explain why the performance of ELCAP metered homes exceed theoretical expectations. Room closure (zoning) also becomes a primary candidate as an explanation of both reduced preretrofit consumption and lower-than-expected benefits in Hood River.

Section 8.0 summarizes the analysis of the frequency of wood burning in homes equipped with wood stoves. Frequency of wood use increases dramatically in the colder months and on the colder days within given months. Thus, electrical displacement by wood heating increases as the demand for space heating increases, and is greatest on days that tend to have the highest system loads. Wood-burning behavior for the sample as a whole is characterized by a relatively predictable number of hours of wood use as a function of outdoor temperature, suggesting the possibility of incorporating such behavior into hourly demand forecasts and weather adjustments when comparing actual regional loads to load forecasts.

The population of wood users is strongly bimodal, with large groups either burning wood almost every day or quite rarely, indicative of a potential for large and sudden shifts in wood usage should the motivating factors for either of these two groups change. Analysis of the data from two heating seasons suggests, in fact, that wood use is increasing in the region, despite the fact that outdoor temperatures were the same or warmer in the second season.

Section 9.0 illustrates the use of ELCAP data to analyze the performance of new technology, in this case air-to-air heat exchangers. This study indicated that these devices, as installed, are only used sporadically by the residents. They therefore fail to provide air-exchange rates to maintain indoor air quality at normal levels.

Analysis of data from the commercial sector is just beginning. Examples of two early analyses are included in this report. Section 10.0 indicates that energy conservation techniques (in this case thermostat setbacks) can have significant adverse impacts on peak loads. Section 11.0 is an early comparison of baseline loads predicted by commercial audits with actual metered loads. The magnitude and range of errors in baseline estimates of

lighting and plug loads (standard deviations of $\pm 57\%$ and $\pm 33\%$, respectively) indicates that significant uncertainty exists for audit-based conservation predictions in individual buildings.

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The material contained in this document is a tribute to the various project managers at the Pacific Northwest Laboratory that have served ELCAP. Without their continual encouragement, overwhelming interest in the success of all ELCAP activities, and devotion to produce quality products this report would not be possible. Those project managers include in order of succession, Dr. Robert A. Stokes, George J. Schuster, Dr. Gerald M. Stokes, Steven G. Hauser, and William F. Sandusky.

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1.0 ELCAP DATA COLLECTION AND MANAGEMENT

1.1 INTRODUCTION

The End-Use Load and Conservation Assessment Program conducted by Pacific Northwest Laboratory (PNL) for the Bonneville Power Administration (Bonneville), was initiated in August 1983 in an effort to support Bonneville's conservation assessment and load forecasting missions. This project involves the collection and analysis of hourly end-use electricity usage data together with detailed characteristics of the participating structures and occupants. In the spring of 1988 the name of the program was changed to the End-Use Load and Consumer Assessment Program (ELCAP) to reflect the fact that conservation assessment is only one part of program objectives.

Several reports and presentations provide an overall discussion of the study objectives of ELCAP (Windell 1985, Stokes 1985, Parker and Stokes 1985). These documents provide information on participating projects that later became an integral part of ELCAP, related simultaneous studies, and the ELCAP data management and computational environment. In addition, the report by Windell (1985) explains how ELCAP is related to the Public Utilities Regulatory and Policy Act of 1978 (PURPA) and the Pacific Northwest Electric Power Planning and Conservation Act of 1980.

This chapter discusses the operational aspects of ELCAP from the initial selection and recruitment of sites through the installation of metering equipment and the verification and data processing necessary for the data to be archived for analysis. This discussion is organized by activities such as site selection and recruitment, installation and hardware, verification and data processing, and preaggregated data set. Each of these activity sections is further subdivided as appropriate into residential and commercial sections.

1.2 SITE SELECTION AND RECRUITMENT

It was recognized at the start of the project that careful selection of sites would be necessary if the results of ELCAP were to be applied to the entire region. Metering a random number of sites would not provide the information necessary to generalize the results for the region. Ideally, a

"representative" sample of all building types would be metered. In reality, it is difficult to characterize all building types and then choose a "representative" sample for each type. From the point of view of an electrical utility in the Northwest, homes with little or no electrical space heat have less impact on load forecasting, and so relatively few homes with primarily gas-fired space heat were included in ELCAP for case study purposes only. No similar distinction was made in the commercial sector on the basis of fuel type.

1.2.1 Residential Sector

The residential portion of ELCAP consists of the Residential Base study, four case studies, two studies of new energy-efficient single-family homes, and a study of new energy-efficient manufactured homes. Each of these studies had a different target population and different selection criteria. For example, the base study home is considered to be representative of the existing housing stock of owner-occupied, single-family, electrically heated homes in the Bonneville service region. The representative criteria used in selection of the sites for each study were:

- vintage
- utility type (investor owned versus publicly owned)
- climate zone
- income
- presence of wood-burning equipment.

The four case studies represent variations on the sample definition of the Base sample. Table 1.1 shows the differences between the base and the four case studies. Once the target population and sample criteria were chosen, a stratified random sample of the Pacific Northwest Residential Energy Survey homes were chosen for inclusion in ELCAP. The selection and stratification process is described in detail by Windell (1987). Each of the sample criteria discussed above were stratified into several levels and a series of sample cells created. For example, the region was divided into three climate zones, the existing housing stock was binned into three different vintages, and three categories were used for occupant income. The complete stratification is a matrix of 192 cells. After the initial sample

TABLE 1.1. Comparison of Base and Case Study Sample Definition

<u>Study</u>	<u>No. of Sites</u>	<u>Owner-Occupied</u>	<u>Single-Family</u>	<u>Site-Constructed</u>	<u>Electrical Space Heating</u>
Base Sample	289	Yes	Yes	Yes	Yes
Case Studies:					
Manufactured	19	Yes	Yes	No	Yes
Attached (in Base)		Yes	No	Yes	Yes
Renter	14	No	Yes	Yes	Yes
Fossil Fuel	21	Yes	Yes	Yes	No

selection it became apparent that some of these cells were empty or had few entries. Complete statistics on the final contents of each group of cells are found in a report by Windell (1987).

Associated with the residential sector of ELCAP are three additional studies of energy-efficient new homes. The first group involves homes constructed as part of the Residential Standards Demonstration Program (RSDP). This group of homes were built to test and evaluate the Model Conservation Standards (MCS) outlined in the 1983 Regional Power Plan (Northwest Power Planning Council 1985). The second group involves homes constructed under the City of Tacoma's "Early Adoption" program, also as a trial of the MCS. ELCAP metering equipment was installed in 70 of these homes representing the MCS, and in 30 of the Control homes built to current practice as a control sample for the evaluation. A subset of the ELCAP Base sample homes built after 1978 are also used as controls for the MCS test. Complete details on the RSDP sample selection and recruitment are found in a report by Parker and Foley (1985).

The third group of residences is a group of five energy-efficient manufactured homes constructed as part of the Energy-Efficient Manufactured Homes Demonstration Program (EEMHDP). The mission of this program was to demonstrate the capability of the industry to produce energy conserving manufactured homes. A report by Lee et al. (1986) outlines the objectives of the metering and data collection work and provides results of this study.

Before beginning the actual process of recruiting participants, installing metering equipment, and initially acquiring the data, a pilot study was completed. The objective of this pilot study was to test the initial procedures that had been prepared to complete these activities. The experience gained from the pilot study is documented in a report by Parker et al. (1985). With that knowledge, some procedures were modified and recruitment activities began. Documentation of those activities for the residential base and case study sample is available in a report by Parker and Foley (1985).

1.2.2 Commercial Sector

The commercial base study contains a sample of buildings chosen to represent the entire population of existing commercial building stock in the region. The sample is confined to buildings in the Seattle City Light service area since the buildings in that area were considered to be representative of the region. By confining the geographic area of metering activities, tasks related to recruitment and maintenance also were simplified.

A two-stage stratified random sampling procedure was used to identify potential sites (Baker 1984). The two criteria used for selection were building type and building size. A subset of this sample was chosen specifically on the basis of age. These buildings were constructed after January 1, 1980 and comply with the City of Seattle Energy Code. The Seattle Energy Code is similar to the Power Planning Council's proposed model conservation standards for new commercial buildings. The commercial base sample thus provides both the control and the test sites for evaluating the pending commercial standards.

As was the case for the residential study, a pilot study was completed to evaluate procedures that had been prepared for recruiting participants, installing metering equipment, and obtaining characteristics data (Mazzucchi 1985). The pilot study indicated a need for more detailed procedures regarding installation of the metering equipment and more elaborate means to verify the installation was correct before the installation team left the site. Experience from the pilot also indicated that some of the sites

selected in the sample were unsuitable for metering because of the poor condition of their electrical distribution system. With the knowledge gained from the pilot study, full recruitment activities began. Documentation of that activity is available in a report by Mazzucchi and Craig (1985).

In conjunction with the commercial base sample are two other metering studies. The first study involves buildings from Bonneville's Commercial Audit Program (CAP). This program was established to evaluate Bonneville's specifications of minimum requirements for energy audits in commercial buildings and facilities. It was determined that this evaluation could be enhanced by metering a subset of the buildings participating in CAP. First, load data would be obtained to compare audit results regarding the existing loads in the buildings. Next, once the participants had installed conservation measures recommended by the audits, the metered data could be used to determine how much the load was reduced as the result of implementing the conservation measures.

The second study involves buildings from Bonneville's Purchase of Energy Savings (PES) Program. The goal of the PES program was to evaluate the use of financial incentives for acquiring the energy conservation resource in commercial buildings. Participants in the program were given funds in relationship to the amount of electrical load reduction that occurred. Again, with the use of metered data, the baseline consumption could be documented along with the actual reductions after measures were implemented. In general, the PES buildings represent some of the largest commercial buildings in ELCAP of the various building types.

The distribution of building types in the commercial base and CAP/PES samples is shown in Table 1.2. Whereas the commercial base sample is concentrated in Seattle, the CAP and PES sites have a broad geographic and climatic distribution throughout the region (Table 1.3).

1.3 INSTALLATION AND HARDWARE

After sites were selected and recruited into the program, installation of metering equipment began. Results of the two pilot studies indicated carefully planned and executed measurement strategy, along with proper

TABLE 1.2. ELCAP Sample of Commercial Buildings

<u>Building Type</u>	<u>Com Base</u>	<u>CAP/PES</u>	<u>Total</u>
New Warehouse	3	0	3
New Retail	4	0	4
New Grocery	4	0	4
New Restaurant	7	0	7
New Office	11	1	12
Old Warehouse	11	1	12
Old Retail	18	9	27
Old Grocery	10	5	15
Old Hotel	1	10	11
Old Restaurant	6	6	12
Old School	4	0	4
Old University	4	0	4
Old Office	13	8	21
Old Other	5	0	5
Total	101	40	141

attention to the actual installation process, which is required if the metering program is to be successful. This section on installation and hardware discusses such a strategy. Installation is considered in conjunction with the hardware because there is an intimate relationship between what is being measured and how it is measured. Associated with the hardware and installation procedures is the ELCAP metering protocol. This section will start with a discussion of the ELCAP metering hardware and proceed to the ELCAP metering protocol. A final section on the installation process itself will follow, although the metering protocol and installation process are very closely tied together.

TABLE 1.3. CAP/PES Study - Geographic Distribution of Buildings

	<u>Newport</u>	<u>Eugene</u>	<u>Everett</u>	<u>Idaho Falls</u>	<u>Richland</u>	<u>Seattle/Olympia</u>	<u>Spokane/Sandpoint</u>	<u>Total</u>
Office	0	2	2	1	2	2	0	9
Grocery	0	1	1	3	1	0	1	7
Retail	0	2	2	2	2	0	0	8
Motel/Hotel	4	0	0	1	1	1	2	9
Warehouse	0	0	0	0	0	0	1	1
Restaurant	0	1	1	2	2	0	0	6
Total	4	6	6	9	8	3	4	40

1.3.1 Metering Hardware

The basic hardware used in ELCAP consists of a series of sensors connected to a field data acquisition system (FDAS). The sensors may be current transformers (CTs) used to monitor building energy loads, temperature sensors monitoring indoor or outdoor temperatures, or they may be other sensors that provide either an analog or digital output. The design strategy and technical specifications of the FDAS are described in a report by Tomich and Schuster (1985). The FDAS has essentially three functions: 1) to collect data from the sensor channels, 2) to store the data, and 3) to provide the data to a central data acquisition system on demand. All functions are controlled by the central processing unit of the FDAS. The sensor channels are scanned once per second, and any number of seconds may be aggregated to produce an individual data record. Typically, data records corresponding to 5-minute, 15-minute, or hourly intervals are collected.

A data record containing the date, time, and values for all active sensors is produced at each interval. These data records are stored in memory until retrieved by the central data acquisition system. The configuration of the active channels and the data collection interval are all remotely programmable from the central data acquisition system. The configuration of the sensors is not remotely controllable and the site must be visited to make any changes to the sensors themselves. Communication with the central station is accomplished with a modem and a dedicated phone line. Data are stored and transmitted as a series of eight binary digits.

Several different versions of the ELCAP FDAS are available. The main differences are in the number of allowable active channels and the amount of memory. Units used in commercial building are designed to allow a greater number of active channels than those units used for residences. A recent version developed for use in multifamily dwelling units is not only smaller and contains more memory, but also has capabilities that allow many loggers to be linked together with communication from only one phone line.

The CTs used to monitor the electrical currents in the building's electrical system are available in three sizes (30, 100, and 400 amps), as shown in Figure 1.1. By using a minimum number of CT sizes and a series of

scaling resistors, a wide variety of maximum loads can be handled without a large inventory of different CTs. Proper scaling of the CT size to the maximum load on each breaker is necessary to maximize data resolution. The voltage from each phase of the electrical service to the building is integrated in real time with the current signal from the CTs to produce a power signal. The power signals are then averaged over the data collection interval by the set of calibrated watt-meter cards in the FDAS. Internally, the data records are stored as binary representations of some fraction of the maximum expected load on each channel. Once the data are sent to the central data acquisition system, a conversion process must transform this fractional load number to real engineering units.

Each FDAS has dedicated channels for metering weather, indoor temperatures, and wood stoves. A network of weather stations are installed at carefully selected geographic sample sites (Hadley 1986). Temperature measurements are made with thermistors and solar data are gathered from pyranometers. Additional sensors include wind speed and relative humidity. The wood stove sensors are thermocouple junctions to indicate stove operation by sensing relative flue gas temperatures.

1.3.2 Metering Protocol

The metering protocol provides for the correct installation of sensors, for consistent definition and means of identification for end-use loads within buildings, and for allocation of the various data channels that comprise specific end-uses. These activities must be completed within the constraints of institutional requirements, such as electrical inspection and proper quality control activities. A complete discussion of the metering protocol is available in a paper by Mazzucchi (1985).

The metering protocol requires that each phase of the main feeder wires to the breaker panel be monitored independently, and for each wire leading from a circuit breaker to a load be monitored (singly or in combination with other circuits of the same end-use and electrical service phase). An energy balance (termed a sum-check) can then be calculated for each phase, comparing the power entering with the sum of that leaving the panel. This provides a robust and continual indicator of data quality as well as a means of diagnosing installation errors and sensor failures when they occur. In large

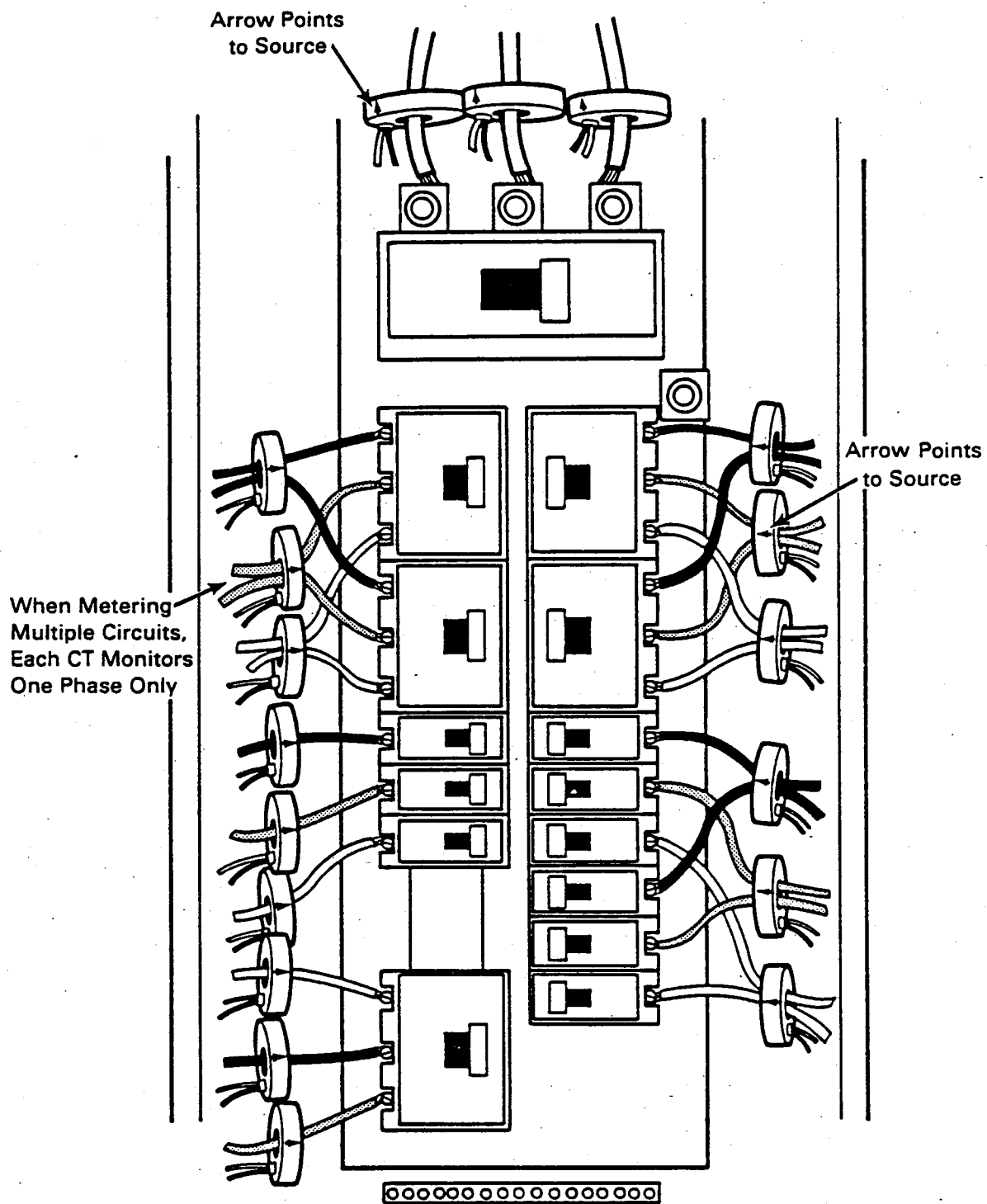
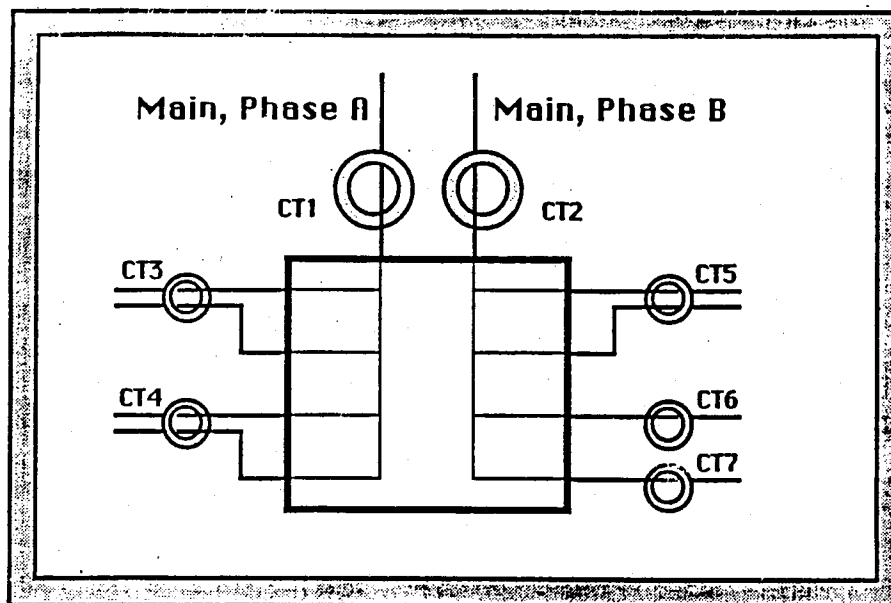


FIGURE 1.1. Typical Circuit Breaker Panel with CTs Installed

commercial buildings, metering is often conducted partially or wholly at the level of the service entrance switch gear and the wires that feed the breaker panels, when the panels are essentially dedicated to specific end-uses. The sum-checking protocol is then applied at that level. Basically, every power measurement in ELCAP has a control total against which it is matched in a sum-check. Figure 1.2 shows a typical breaker panel metered according to the ELCAP protocol.

The load for a specific end-use is obtained by adding the various data for the end-use by phase. For example, in residential sites the large end-use loads, like space heating or water heating, are two-phase devices. The consumption for that end-use is the sum of the consumption for the individual phases. Initially it was planned to meter only one of the phases serving certain two-phase loads such as water heaters and double the value to obtain the end-use consumption. However, it was discovered through the sum-checks that many of these two-phase loads are not balanced, and metering of both phases is required.



$$P1 - P3 - P4 = 0$$

$$P2 - P5 - P6 - P7 = 0$$

FIGURE 1.2. Circuit Breaker Panel Schematic Illustrating Sum-Check Protocol

1.3.3 Installation

The first step in any installation, commercial or residential, is to gather information about the building electrical system. A measurement plan documenting the location of all switch gear, transformers, and panels must be made. The plan provides a detailed estimate of the number and location of sensors that will be needed to provide the full end-use disaggregation according to the ELCAP metering protocol. The plan also provides the information necessary for the aggregation from the channel level to the end-use level.

The next step is the actual installation of the FDAS, CTs, and other sensors. This involves removing the electrical panel covers, detaching wires from individual breakers, installation of the CTs, and connecting the leads from the CTs and other sensors to the FDAS. Connecting the CTs to the FDAS generally requires installing conduit since the CTs are installed within the electrical panels. Once the installation has been completed the installation team performs a test of each electrical power channel with a known load to ensure the CTs are installed and operating properly. Then the "as-installed" measurement plan is generated, noting any changes from the original measurement plan including the results of the load test. For large commercial sites, installation of additional FDAS units is often required.

1.4 VERIFICATION AND DATA PROCESSING

Verification and data processing are the two major data management activities that take place within ELCAP. Verification is concerned with the correctness of the installation and the quality of the data. Data processing describes the entire process of collecting the data from the field, performing the appropriate conversions on the raw data, updating the control information as the installation is modified, and archiving the data for use by analysis. Much of the aggregation and data quality checking needed for analysis is also performed as part of data processing. This section discusses the data processing aspects first, followed by data verification.

1.4.1 Data Processing

After a site has been installed according to the metering protocol and all documentation has been transmitted to the project records office, data collection and processing activities begin for the site (Pearson 1985). Once the site is instrumented and all documentation properly digitized, the FDAS is remotely configured from PNL and data collection starts. This ensures that all data in the archive are fully documented and there are no uncertainties about the channel definitions. At present, data collection is controlled by a Hewlett Packard microcomputer. This computer controls most of the polling activities without operator intervention. Data are collected from each FDAS after a preset amount of the FDAS memory has been filled. For a residential FDAS, this is typically every 6 days. For a commercial FDAS, the period is typically every 3 days.

After the raw data are collected from the field, they are converted to engineering units. The information in the measurement plan provides the key to this transformation. Following conversion, the data are transferred from the HP system to the MicroVAXII system for further processing and completing verification activities. Additional data processing of the measurement plan takes place on the MicroVAXII system. The correct sum-check equations (Section 1.4.2) are developed on this machine and the proper end-use aggregation equations are also entered from information contained in the measurement plan. Further processing involves getting the data in the proper format before being archived on a VAXII/780 computer. A series of data quality checks are run on every record of data and a data quality flag is encoded for each record. Sites with poor data quality are sent back to verification for additional checking. Finally, the data are aggregated up to the end-use level and run through a final series of data quality checks. The end-use data are then preaggregated to form a variety of data sets used by the analysts.

1.4.2 Verification

The process of the initial data verification in ELCAP is a separate function from analysis. Since the amount of data collected in ELCAP is so large, the verification activity is completed before making the data available

to the analyst (Parker et al. 1985; Pearson et al. 1985). Each installation goes through a rigorous sum-check test before being accepted, as does each site after a maintenance visit. The data are also examined for reasonableness. This involves subjective, but skilled, knowledge of expected values based on the type of equipment in and operation of the building. Once these tests have been completed, the site is considered "online" and routine data collection begins.

As data are being collected an automated sum-check process is used to examine the data before they enter the archive. If any problems are identified, the data are excluded from the archive and the verification process begins again to diagnose the problem. Typical problems that are found are failure of components due to age, owner modifications or additions to the site electrical system, or problems that did not show up in the initial verification process because they were sporadic in nature.

1.5 PREAGGREGATED DATA SET

Preaggregated data sets (PADS) are the final analysis-ready archive of the ELCAP metered data. These sets are assembled and then aggregated across the time domain of days and months and then subjected to extensive quality assurance activities. These sets are those most useful for the existing, or planned, ELCAP analytic tasks and provide the user with all the information needed to analyze the data with a minimum of preliminary work. The primary quality assurance activities consist of a procedure to check that the hourly end-use value for total energy consumed at the site is equivalent to the sum of the end-use loads. The differences found in these checks are close to but rarely zero because truncation errors are incurred in converting from analog to digital values. These differences are compared to established limits to determine if the data record has "passed" the quality assurance process. Detailed sum-checking has already been done at the channel level, so these end-use sum-checks are used primarily for catching data processing errors such as assigning a channel to two end-uses.

Along with checks on the energy data, a series of checks on the meteorological data are performed. Range and limit tests are performed on temperature sensors to check for not only abnormally high or low readings, but

also abnormally constant readings. A detailed range test was developed for pyranometer data that compares the measured hourly values to the expected values for that time of year and location. Values that fail these checks are not incorporated in PADS.

As the hourly data are read into PADS, a series of temporal aggregations are performed to create daily values, monthly values, and monthly profiles. These temporal aggregations were deemed most useful to the majority of analysts and so are produced automatically. Other aggregations can be made by an interested analyst using the S analysis software. For example, there might be a reason to look at weekly values, quarterly values, or annual values. All of these can be easily produced outside of PADS using the information in PADS.

In addition to the variation in temporal aggregation, up to six types of summary data are presented for each end-use in the ELCAP daily, monthly, and monthly profile data sets. The types of summary data stored with each end-use depends on the end-use category, such as energy, meteorological, or wood-stove sensors. Two types of summary data stored with energy end-uses are mean power and total energy. For end-uses which represent a specific piece of hardware, a third type of summary data, the "on-count" (a count of the number of hours of use in the aggregation period) is calculated. A device is considered "on" only when the hourly value exceeds a predetermined minimum. Therefore, the on-count does not include periods of low power. For example, in the case of a range, low power use below the threshold might be represented by a clock on the range.

The fourth data type is an indicator of aggregation periods in which a device uses zero power. The fifth data type is a count of the number of valid observations that went into making up that data value. For instance, a particular month of data might have 744 hours in the month, but the monthly total may contain only 740 valid hourly observations. The sixth data summary type is again a mean value, but is only present if a minimum number of valid observations for the aggregation period are present. Criteria have been set for each level of aggregation to specify the percent of missing values allowed in this mean value summary data. For example, a monthly value would be produced for a specific month only if more than 90% of the data are present. Threshold values are also set for the total energy summary data at each level

of aggregation. Experience has shown that analysts prefer the standard aggregations with its missing value criteria because of the ease of use.

The final part of PADS are two "behavioral" data sets derived from the information content of the load data. These data sets indicate vacancy and wood stove use. The vacancy data set is created by an examination of selected daily end-use loads, giving an indication of whether or not the occupants were home on a certain day and some information about the certainty of that result. The wood stove use data indicates whether or not a wood stove was in use for a particular hour.

1.6 CHARACTERISTICS DATA COLLECTIONS

To properly interpret the end-use load data, characteristics data are required. The characteristics data also are used for demographic and sociological analyses and for evaluating the potential for marketing conservation devices and activities. Characteristics data collected for use in ELCAP included both information on the building structure, electrical devices in that structure, and survey information regarding the occupants. A discussion of how these data were obtained is presented below.

1.6.1 Residential Characteristics

The procedures used to obtain the building structure data are contained in a report by Taylor et al. (1985). These procedures were used by trained surveyors who conducted field interviews with each owner/occupant. A summary of the information collected during the survey can be found in a report by Weakley et al. (1990).

Residential occupant data was obtained by mail and telephone (Darwin et al. 1986). Questions were limited to those that occupants would likely be able to answer, such as opinions, personal data, and whether any particular changes had been made to the structure. Another occupant survey comparable to the mail and telephone survey was carried out in 1987 for the entire ELCAP residential sample (Windell 1988). A similar survey is planned for 1988.

The homes in the EEMHDP are considered special cases and were not included in these surveys. Detailed information on these homes is not available in an electronic form, only on paper.

The information included in all these surveys are voluminous. A report by Windell (1987) compares the survey methods and some of the results. Information is sparse or nonexistent for some sites, but complete for the others. Most sites contain at least some missing values, and there may be apparent conflicts between data collected by one survey and data collected by another. This is the nature of survey data. Attempts are being made to condense the vast bulk of characteristics data into a user-friendly, analysis-ready data set. This effort will also reconcile many of the apparent conflicts between survey instruments, but will not eliminate them entirely. Table 1.4 gives a partial listing of data available in the archive.

1.6.2 Commercial Characteristics

The commercial sites in ELCAP were surveyed with regard to building structure data. This survey encompassed only the commercial base sites. Those CAP sites that were metered were audited under a separate agreement outside of the ELCAP. Sites in the PES study were never fully surveyed because of changing priorities within the PES program.

A partial list of information available for commercial buildings is given in Table 1.5. These data are presently available only in raw form until a more analysis-ready form can be made available.

TABLE 1.4. Data Available in ELCAP Characteristics Database for Residential Sites

- | | |
|-----------------------------|---------------------------|
| - Vintage | - Conditioned Floor Space |
| - Primary Heating System | - Other Heating Systems |
| - Number of Occupants | - Occupant's Income |
| - Occupants Education | - Ages of Occupants |
| - Number of Appliances | - Window Areas |
| - Appliance Specifics | - Billing Data |
| - Hot Water Tap Temperature | - Insulation R-Values |

**TABLE 1.5. Data Available in ELCAP Characteristics Database
for Commercial Sites**

- | | |
|-------------------------------|----------------------------------|
| - Gross Floor Space | - Vintage |
| - HVAC System Types | - Billing Data |
| - Fuel Types | - Structural Information |
| - Envelope Areas and R-Values | - Tenant Business Types |
| - Glazing Types | - Tenant Business Hours |
| - Lighting Types | - Plug Load Equipment Types |
| - Lighting Capacities | - Plug Load Equipment Capacities |

2.0 RESIDENTIAL END-USE LOADS AND SHARES

2.1 INTRODUCTION

This section reports on end-use loads and shares for the End-Use Load Consumer Assessment Program (ELCAP) Residential Base Sample for the period September 1984 to March 1988 (Pratt et al. 1989). It provides an overview of the electricity consumption by existing single-family, owner-occupied homes with permanent electric space heat. The analysis developed basic information used as input or background for several other ELCAP and Bonneville analysis tasks. This report had several goals:

- compute the mean load and share of the major residential end-uses on both an annual and monthly basis
- show the distribution of loads and shares
- show annual loads and shares when partitioned on demographic and site characteristics
- show the monthly variation in the major residential end-uses.

2.2 METHODOLOGY

The annual and monthly values used in this report were calculated from hourly measurements using a four-step process, as outlined here.

- A 24-hour-average load profile was created for each site, for each end-use, and for each month. Each hour of the profile was the mean of available data for the hour of that particular month. A minimum of 15 observations for each hour were required for a given month to be used.
- Monthly loads were computed by summing the 24 hourly mean values in each profile and multiplying by the number of days in the month. This implicitly fills missing hourly data with the average values for that hour of the data actually present.
- Annual loads were computed as the sum of all the monthly loads, with the requirement that data be present for all 12 months for each site.
- Shares for each end-use were computed as the ratio of the end-use to the total building energy use for each site.

The ELCAP end-uses are metered by measuring power for individual circuits at the circuit breaker panel in the homes. Therefore the ELCAP end-use definitions correspond to the type of circuits used in home wiring systems. These end-use definitions differ somewhat from those used in Bonneville residential forecasting models. An outline of Bonneville's forecasting end-uses and their relationship to corresponding ELCAP definition of end-uses is given in Table 2.1.

For purposes of comparison with forecasting models, a set of comparable end-use categories have been developed. The forecasting end-uses, which are lighting, other, and freezer, can be combined to correspond to the combination of ELCAP end-uses: lights and conveniences, kitchen lights and conveniences, dishwasher, clothes washer, small major appliances, and freezer. The resulting end-use categories are space heat, air conditioning, water heat, refrigeration (pure and mixed), clothes drying, food preparation, and a remainder that forms a redefined Other. The most important issue not resolved by this aggregation of end-uses is that most of the refrigerators in the ELCAP sample are on circuits that additionally serve plug outlets and lighting in the kitchen and/or adjacent areas. A specific effort will be undertaken to formally disaggregate mixed refrigerators.

Eight end-uses were included in the end-use report. The total load was divided into the triple metered end-use categories of heating, ventilation and air conditioning (HVAC), water heating, and Other. Other was subdivided into refrigeration (including mixed refrigeration), food preparation, dishwasher, clothes washer/dryer, and lights and conveniences (wall plugs).

Only data from the period of September 1984 to March 1988 were included in the report. The results reported here include data for 214 sites from the ELCAP Base Sample.

TABLE 2.1. Comparison of Bonneville's Forecasting and ELCAP End-Use Definitions

<u>Bonneville Forecasting End-Uses</u>	<u>Corresponding ELCAP End-Uses</u>	<u>Notes on ELCAP End-Uses</u>
Space heating	Heating	Used when pure (76% of sites)
Air conditioning	Air conditioning	Used when pure (A/C)
Heat and A/C	Heat, vent, and A/C	End-use is the sum of Heat & also used for mixed heat and A/C when not pure (as in heat pumps) (10% of sites)
Water heating	Hot water	End-use is pure
Cooking	Food preparation	ELCAP and Forecasting are both purely ranges & ovens
Clothes drying	Clothes drying	End-use is pure
Refrigeration	Refrigeration and mixed refrigeration	Used when pure (25% of sites) Used when mixed with plug circuits (75% of sites)
Freezer	Freezer	Used when pure (10% of sites)
Lighting	(No direct ELCAP counterpart)	See Other
Other	Lights and conveniences, kitchen lights and conveniences, clothes washer and dishwasher	Used for all plug circuits not dedicated to a single end- use. Includes lights, some room A/C units, most bathroom and some portable heaters, and most freezers. Purely lighting in forecasting.
(No direct forecasting counterpart)	Special major appliances	Used for hot tubs, kilns, etc. when pure. Included in Other in Forecasting.
(No direct forecasting counterpart)	Outside lights and conveniences	Garages, etc.

2.3 RESULTS

For the approximately 200 ELCAP Base Residential sites on line at the time of the analysis (July 1989), the mean end-use loads and shares for the homes (when the end-uses are present) can be summarized as shown in Table 2.2.

The largest end-use was HVAC, followed by water heating, lights and conveniences (plugs), and refrigeration. It is important to note that the standard deviation for the end-use shares is almost uniformly about half the mean share, indicative of the large variation in end-use consumption exhibited by the homes in the sample.

Figures 2.1 through 2.3 show the ratio of monthly load to average load for each end-use. The seasonality of the end-uses is evident from these two figures. The HVAC load in the summer is non-negligible and appears to consist primarily of space heating on cool days by homes in western regions of Oregon and Washington.

All other end-uses show a monthly variation of less than 10% to greater than 20% above and below the annual mean. All end-uses peak in December except refrigerator, freezer, and mixed refrigerator end use.

TABLE 2.2. ELCAP Residential Base Sample End-Use Loads and Shares

<u>ELCAP End-Use</u>	<u>Mean Annual Load (kWh)</u>	<u>Mean Share</u>	<u>Standard Deviation</u>	<u>Cumulative Share</u>
HVAC	8182	39%	19%	39%
Hot Water	4643	22%	10%	61%
Lights and Conveniences	4581	22%	10%	83%
Refrigeration	1507	7%	5%	90%
Washer and Dryer	666	3%	3%	93%
Food Preparation	508	2%	1%	95%
Dishwasher	106	1%	0.4%	96%

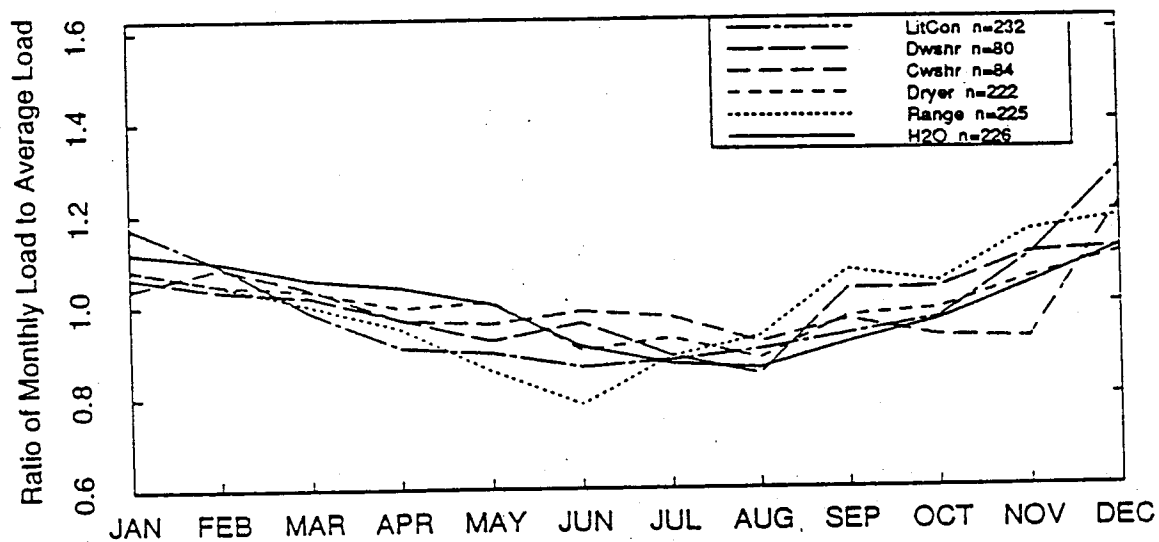


FIGURE 2.1. Seasonal Variation of Hot Water, Range, Dryer, Clothes Washer, Dishwasher, and Lights and Convenience Loads for the Base Study

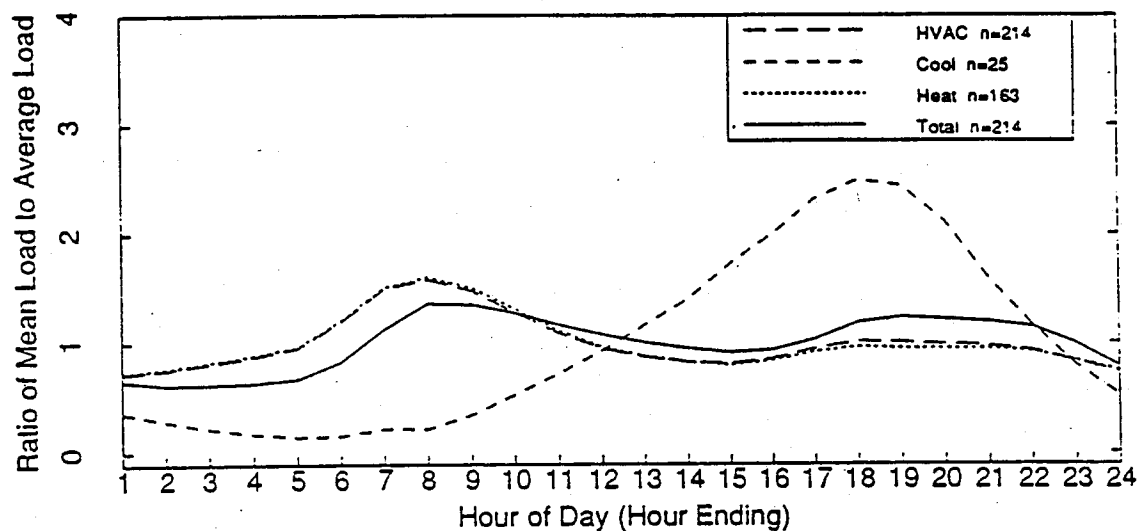


FIGURE 2.2. Mean Annual Total Heating, Cooling, and HVAC Load Shapes for the Base Study

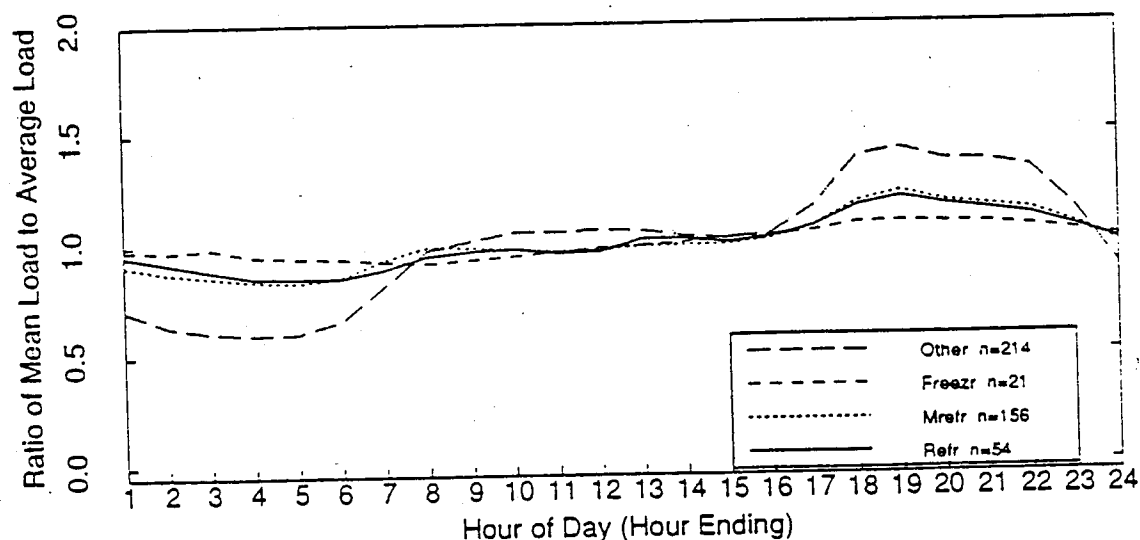


FIGURE 2.3. Mean Annual Refrigerator, Mixed Refrigerator, Freezer and Other Load Shapes for the Base Study

The lights and conveniences end-use has a clear peak in the winter. The winter peak in lights and conveniences can be explained by the increasing number of hours of darkness and level of indoor activities occurring in the winter. Refrigeration peaks, as expected in the months when indoor temperature is warmest, the summer months.

A large portion of the analysis was devoted to partitions or splits of the energy use according to various demographic and site characteristics. Partitions of the Base Sample used were climate zone, electrical heating system (used most), vintage, floor area, number of occupants, occupant income, and utility type. These partitions were applied one at a time rather than collectively, to keep the sample size in each cell of the partition high enough to be meaningful.

Some of the one-dimensional partitions produced results that generally followed expectations, as illustrated in Figure 2.4 where space heating loads decrease for newer homes. An important result, however, was that this

partitioning could produce misleading results. Two examples:

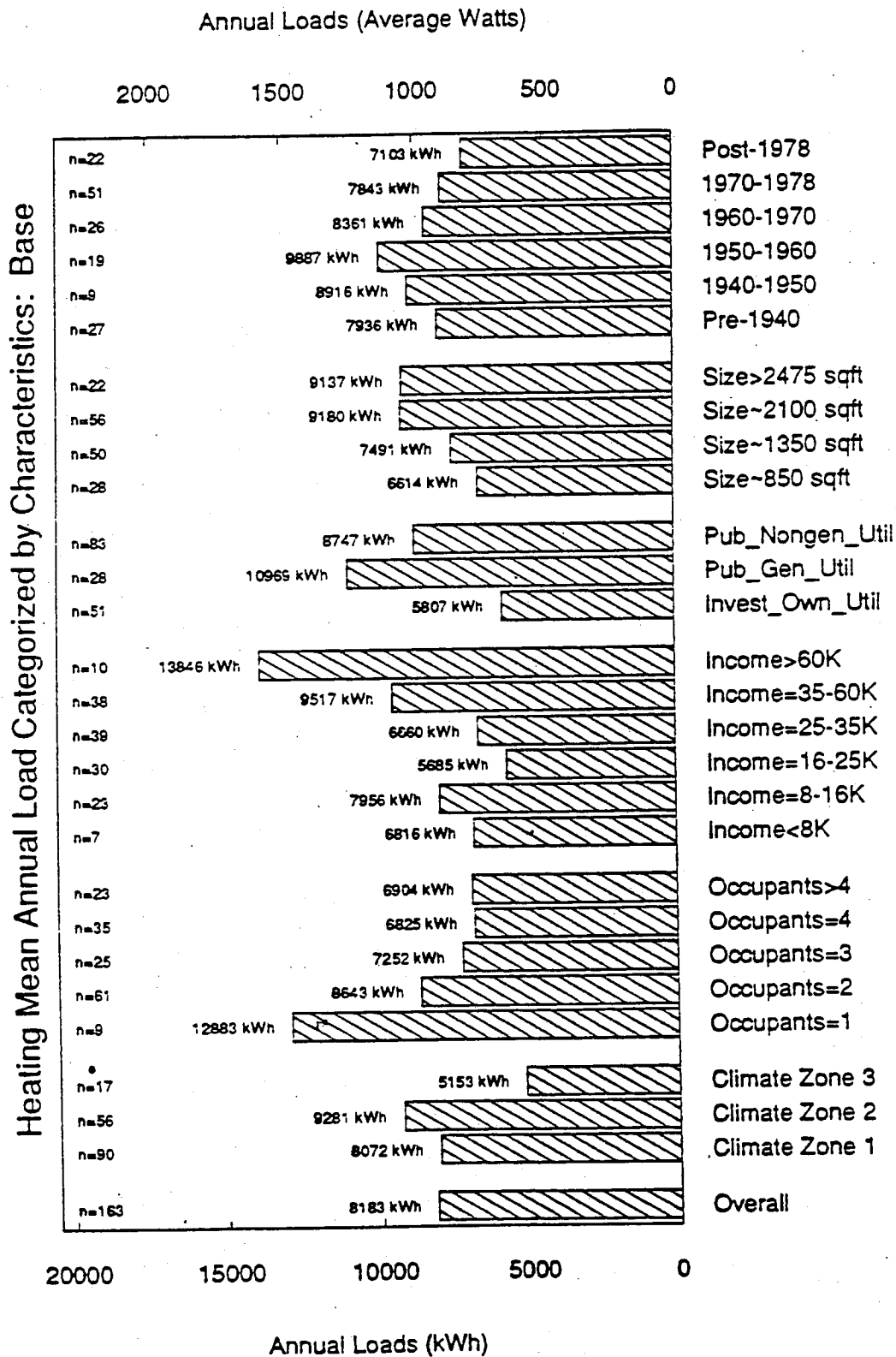
1. homes in colder climate zones use less HVAC energy (see Figure 2.4).
2. homes in colder climate zones use less lighting and convenience energy (see Figure 2.5).

These results are produced by the high correlation between the partition variables. For example, homes in the colder climate zone tend to be better insulated (lower UAs) and have more wood stoves. Similarly, the heat pump homes tend to be larger and hence have higher UAs, while homes with furnace systems have more wood stoves. Both of these misleading results are in contradiction to the results of the thermal analysis of the Base Sample homes reported in Section 5.0, in which climate, UA, wood stove use, and HVAC system type were carefully controlled.

2.4 APPLICATIONS

These reports provide benchmarks for comparison of some of the end-use load values and assumptions imbedded in other work. For instance, the forecasting models use end-use load estimates based on conditional demand analysis of surveyed household characteristics and residential sector total load data provided by utilities. This modeled end-use breakdown can be compared to and potentially improved by using the measured ELCAP end-use breakdown. The impact of any change in technology or consumer behavior, for instance the introduction of more efficient refrigerators, is partly dependent on the size of the load represented by a particular end-use. These basic end-use data can help calibrate projections of future load changes through more accurate estimates of the size of the load.

The results of the one-dimensional splits of end-use loads by widely recognized explanatory variables such as climate zone and number of occupants have led to the exploratory development of physical/demographic models of end-use loads using multivariable regressions to control for the correlation between explanatory variables identified in this analysis. This effort is designed to support analysis of ELCAP end-uses for load forecasting.



Figures 2.4. Heating Mean Annual Load Categorized by Characteristics: Base

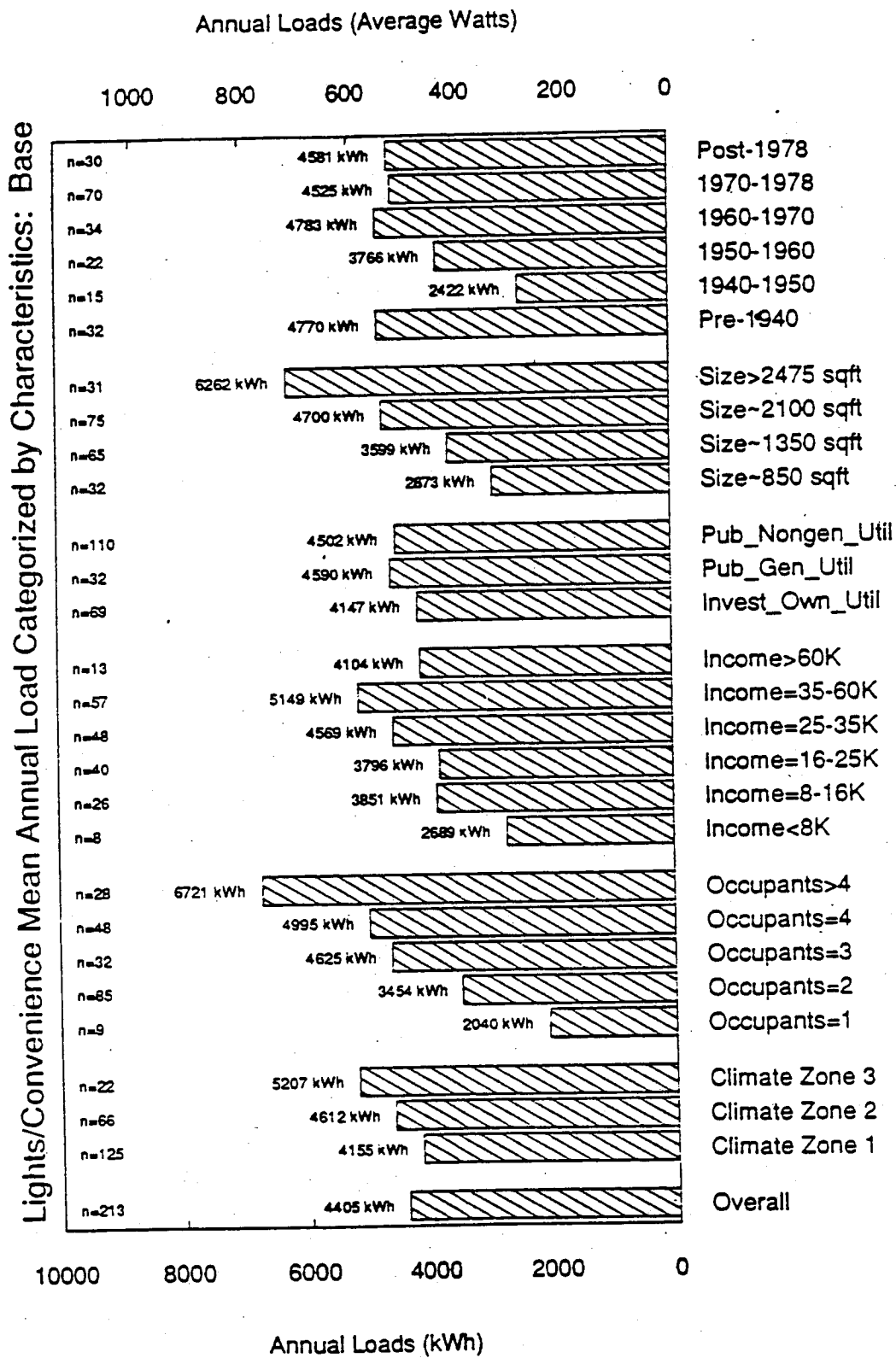


Figure 2.5. Lights/Convenience Mean Annual Load Categorized by Characteristics: Base

3.0 HEAT LOSS CHARACTERISTICS OF THE ELCAP RESIDENTIAL SAMPLE

3.1 INTRODUCTION

The fundamental purpose for this study is to analyze heat loss characteristics of the ELCAP samples of residential buildings to support placement of the samples in a regional context. There are two major samples of electrically heated residential buildings in the ELCAP project: the Residential Standards Demonstration Program (RSDP) sample and Residential Base Samples described earlier in Section 1.0. Briefly, the Residential Base Sample is drawn from the larger Pacific Northwest Residential Survey (PNWRES-83) sample (Lou Harris and Associates 1984), and is roughly representative of the regional single-family electrically space heated housing stock. The RSDP seeks to evaluate the energy savings and cost-effectiveness of the proposed Model Conservation Standards (MCS), a very highly energy-conserving residential building standard proposed by the Northwest Power Planning Council (Council) for new electrically heated homes in the region. The ELCAP RSDP sample of metered buildings is drawn from a large number of new homes constructed by the RSDP, to either the proposed MCS or to current building code as a control group.

The three basic objectives of the analysis are to:

- determine the distribution of insulation levels and heat loss potential among the various building components in existing homes as a function of construction vintage and climate zone
- determine whether the RSDP MCS homes were built to the specifications of the MCS, whether the RSDP Control homes were built to the targeted insulation levels, and whether the target insulation levels in the Control homes are reasonably representative of current construction practices as indicated by the ELCAP homes built after 1978 (the Post-1978 Sample)
- calculate theoretical nameplate residential heat loss rates for use in subsequent analyses.

Unlike other broader but less detailed residential regional surveys such as PNWRES-83, the homes in the ELCAP sample all received extensive on-site inspections of their physical characteristics by experienced energy auditors. As a part of this characteristics data collection effort, each section of each building component (wall, window, door) was separately evaluated for its construction type, insulation, and surface area by the auditor. This provides a unique opportunity to examine in detail the insulation levels and heat loss characteristics of a large sample of homes. The summary presented in this section is based on an ELCAP technical report (Conner et al. 1990).

3.2. METHODOLOGY

The steady-state heat loss coefficient (UA) is the common measure of the heat loss potential of residences, expressing the rate of heat loss through the building shell per degree of indoor/outdoor temperature difference. Building total and component UAs are used in this study to characterize the samples. The total UA is computed as the sum of the component UAs, which are the product of the area and the total U-value for each exterior surface component of the home. The calculation of the UAs are based on the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) standard data and procedures, as implemented in the Standard Heat Loss Methodology used by the Bonneville Power Administration (Bonneville) for residential energy audits (Bonneville 1984). A material's resistance to heat flow is often given as an R-value, which is $1/U$ -value. The total U-value of a building component is the conductance of the entire assembly, taking into account each layer of material, the inside and outside air films, and any parallel heat flow paths caused by studs or joists.

Gaps in reported data are filled with default assumptions about construction, and in cases where a significant part of a building's audit data is missing or where no reasonable default is available, that building is removed from the analysis. It is estimated that less than one-fifth of the houses in the sample have defaulted greater than 20% of the total UA. Although it represents a mechanism for heat loss, infiltration into the heated space is not included in the calculated UA. In practice, infiltration is a strong function of construction quality, climate, and shelter from wind for each

site. Thus the infiltration rate into conditioned zones was judged to vary too much for inclusion in the analysis, except as noted. Average attic and crawlspace infiltration rates are implicitly included in the UA calculation for these components.

Classical residential heating energy and load calculations are based on the UA and the degree-day concept. The space heating energy required can be estimated as the product of the UA and the number of heating degree-days for an appropriate base temperature. To the first order, the heating energy is therefore linearly related to the product of measures of thermal integrity (UA) and climate severity (heating degree-days), assuming wind speed (and hence infiltration) is not correlated with temperature. Similarly, the steady-state heating load is calculated as the product of the UA and the indoor/outdoor temperature difference, minus solar and internal heat gains.

Using the UAs estimated for each residence, the regional distributions of the ELCAP Residential Sample UAs by house construction vintage, and by the regional climate zones used for Bonneville and Council load forecasting are determined. The effects of house size, shape, and foundation type on these distributions are then examined in detail. The distributions of effective insulation values (effective R-values) for the structure as a whole and for the structure excluding the foundation are also calculated, followed by similar analyses of the distributions of effective R-values for each individual building component. The component UAs for the sample are aggregated by climate zone and for the sample as a whole to provide a view of component level target opportunities for energy and load conservation retrofit programs. The MCS homes are included as a distinct vintage in the analysis to place the MCS standards in context with the trend in newer housing for use of increased levels of insulation.

The calculated UAs for the RSDP sample and the Post-1978 homes from the Residential Base Sample are also used to analyze the validity of using the ELCAP samples to test the performance of homes built to the MCS standards. This analysis focuses on several issues specific to the RSDP experiment. These include a determination of how well the ELCAP MCS houses meet the three MCS compliance paths and how well the RSDP Control houses match the Council determined current code. The Control houses are compared with the Post-78

houses to examine whether the assumed current code actually is representative of current building practice in the region. Finally, the MCS houses are compared to the regional building stock.

3.3 RESULTS

3.3.1 Heat Loss Characteristics By Climate Zone and Vintage

The two dimensions explored in this analysis are decade of construction (vintage) and climate zone. These two dimensions are selected as being of particular interest in that they illustrate the extent to which the sample conforms to the common assertions that newer homes in colder climates tend to be better insulated than older homes in warmer climates. These two dimensions also provide a point of reference for interpreting results from two other ELCAP Residential data analyses, characterizing the thermal performance of the MCS and space heating end-use for the Base Sample, described in Sections 4.0 and 5.0.

The distribution of overall UAs in the sample is shown as a function of vintage in the box plot in Figure 3.1. A marked decrease in overall residential UA over time is exhibited, although the change in the medians for the 1970-1978 and Post-1978 vintages is small, indicating a possible leveling off of the trend toward lower heat loss rates in newer homes. The MCS homes clearly have much lower heat loss rates than the Post-78 homes, showing the largest incremental drop in UA between any consecutive vintage categories and clearly exceeding the general trend over time. In Figure 3.2 the distribution of total UAs is shown by climate zone. The median UAs for the three zones are all roughly comparable, although the upper extent of the range is less for Zone 3 than the two warmer zones as indicated by the distribution and the lower mean UA for this zone. This may reflect increased penetration of insulation retrofits in the Zone 3 residences compared to the warmer zones, although it could also be a result of the somewhat smaller and newer sample of homes in Zone 3.

The distributions of occupied floor space as a function of vintage and climate zone are shown in Figures 3.3 and 3.4. There is a clear trend towards increasing median house size over time, although the sample does not include

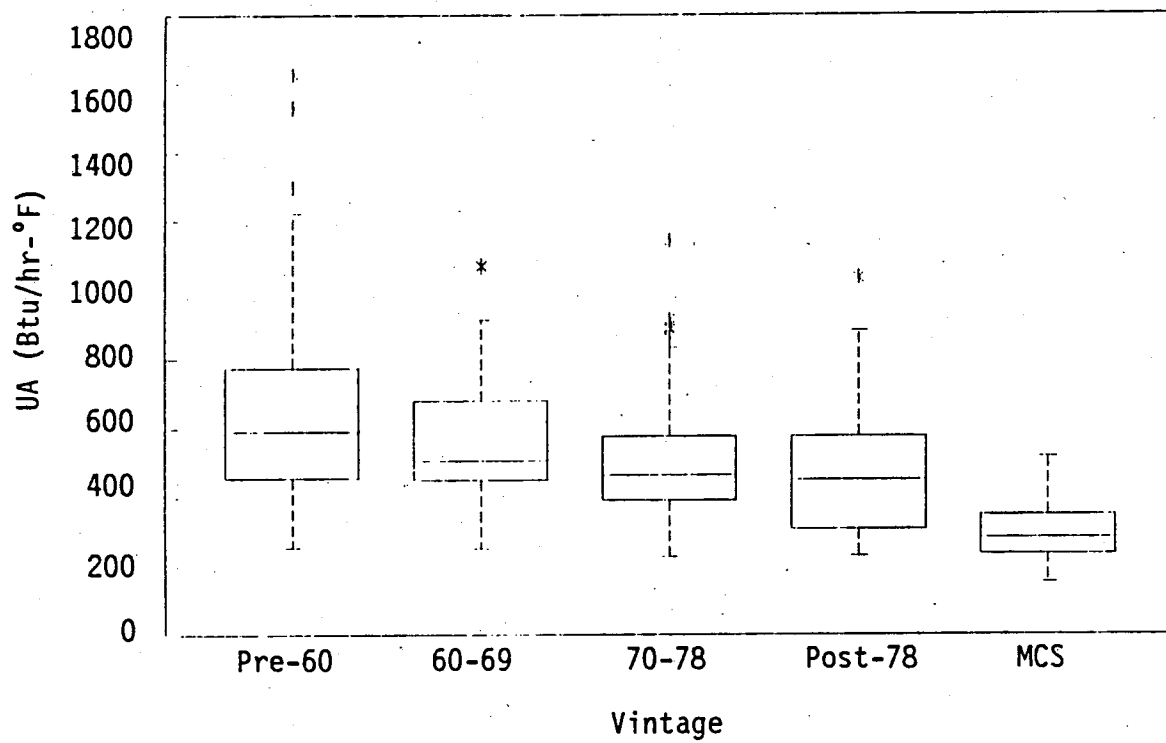


FIGURE 3.1. UA by Vintage

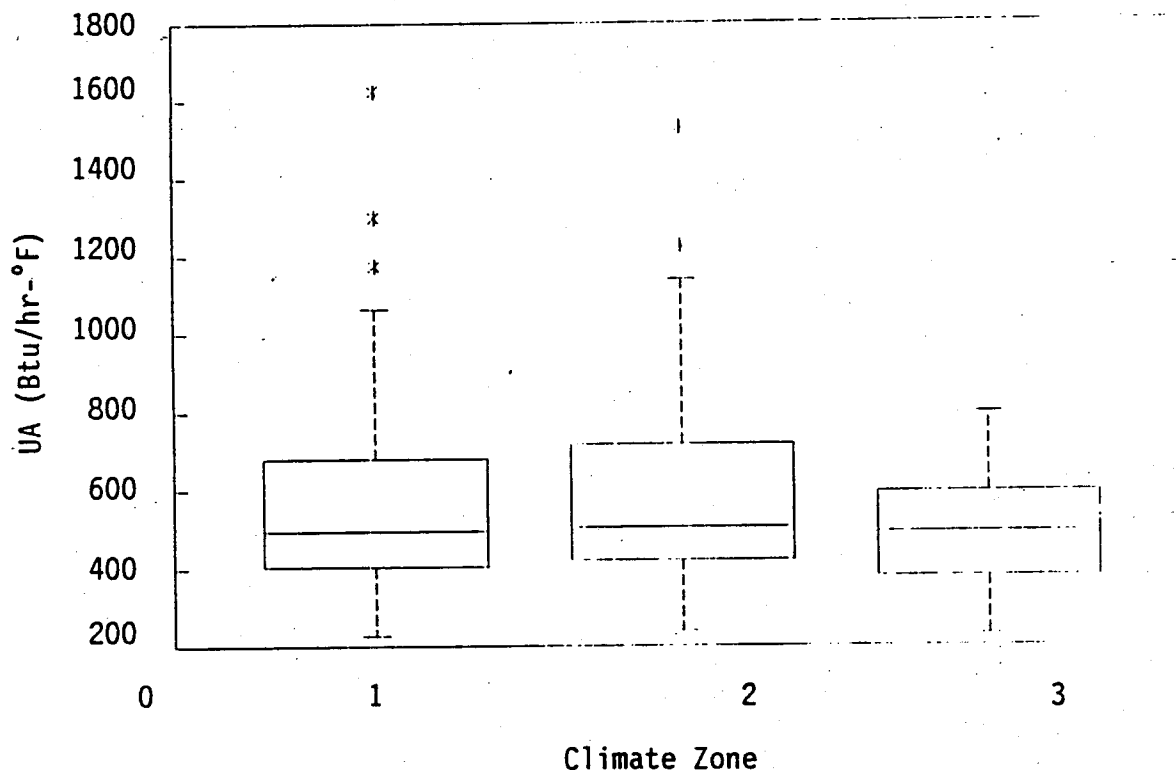


FIGURE 3.2. UA by Climate Zone

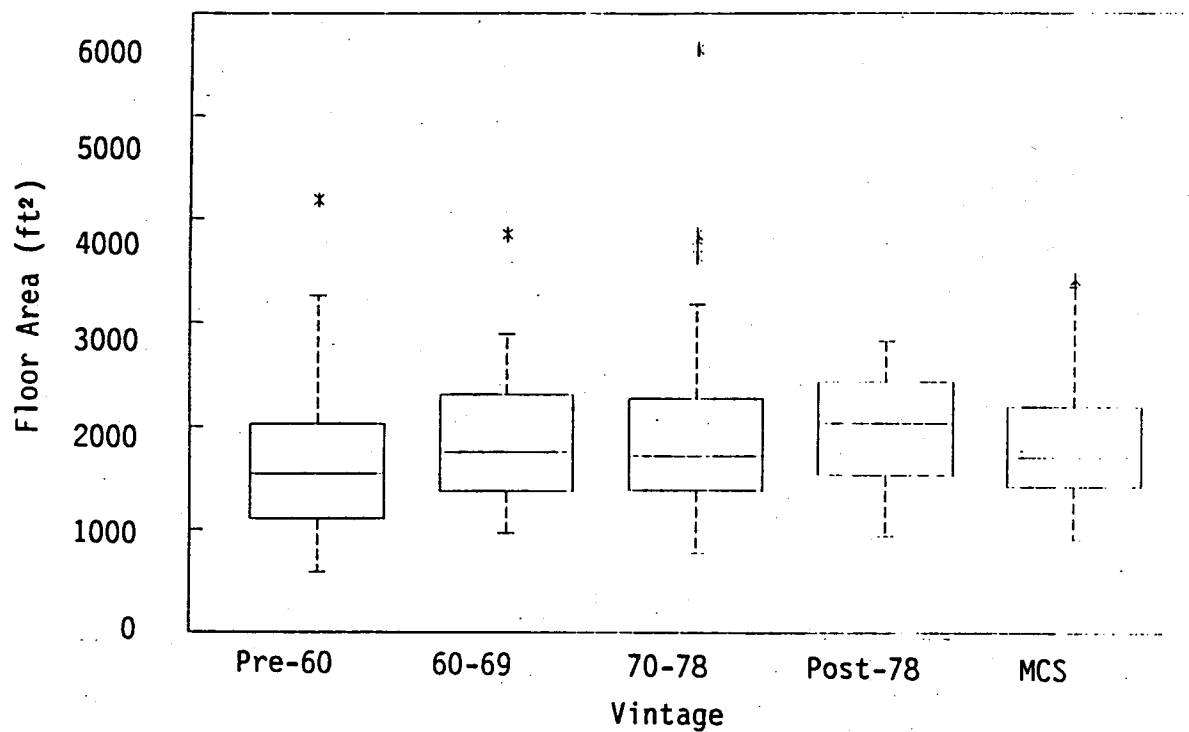


FIGURE 3.3. Occupied Floor Space by Vintage

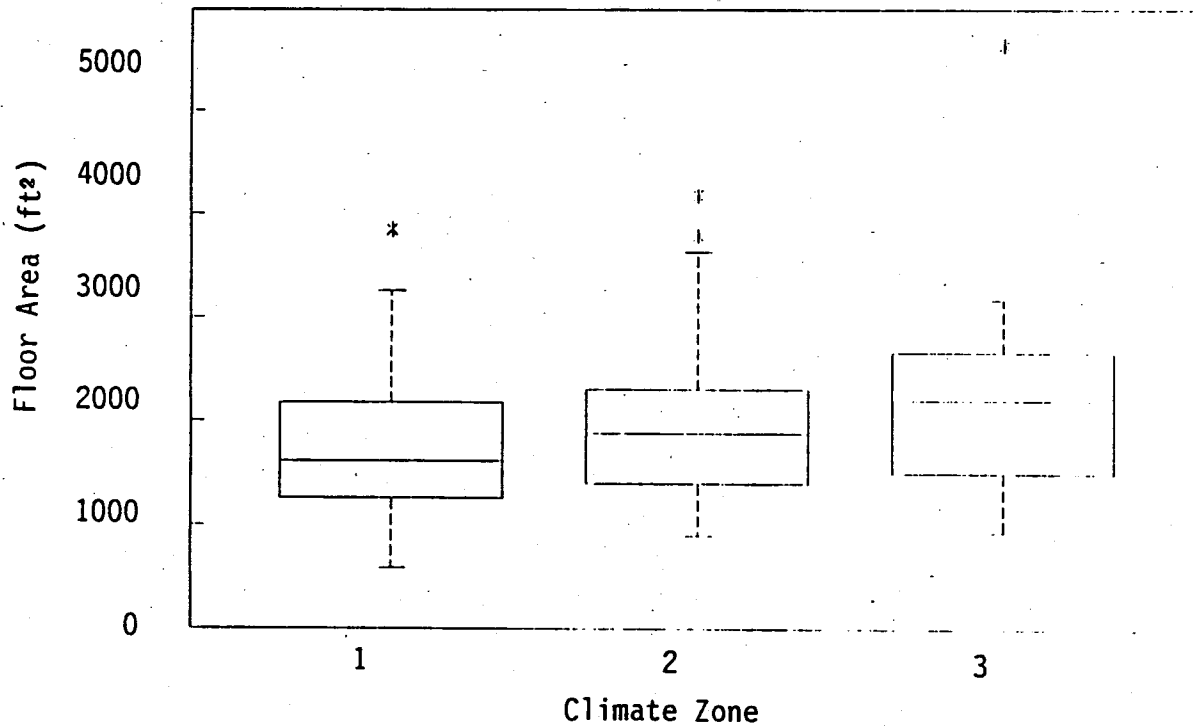


FIGURE 3.4. Occupied Floor Space by Climate Zone

any very large Post-1978 homes. The MCS homes are somewhat smaller than the Post-1978 sample. The data also indicates a trend toward larger homes in colder climates, although this may be largely associated with the distribution of heated basements as described subsequently.

To explore the relative contribution of geometry and insulation levels to the distribution of total UAs, the average level of insulation for each home can be evaluated by calculating an effective overall R-value (R_0) for the house by dividing the total surface area by the UA. Surface area here is defined as the surface area of the "box" or "boxes" enclosing each house, including any heated basement. The distribution of effective R-value by vintage illustrated in Figure 3.5 shows a steady increase in median effective R-values over time. The insulation level of the MCS homes clearly exceeds this trend. The distribution of effective R-value by climate zone is shown in Figure 3.6. Insulation levels appear to increase sharply in Zone 3, but Zone 1 and Zone 2 appear to have similar insulation levels.

As described later in Section 5.0, basement foundations exhibit thermal performance better than predicted by steady-state UA calculations and nonlinear heating requirements as a function of temperature on colder days. The percentage of each foundation type for each climate zone is shown in Figure 3.7, which indicates that heated basements tend to be concentrated in the colder two climate zones, and that there is a steady decline in use of crawlspaces in colder climates. Crawlspaces are by far the predominant foundation in Zone 1, and heated basements predominate in Zone 3. Zone 2 appears to be intermediate with respect to this trend. Slab foundations are relatively rare in the region, and none appear in the coldest climate zone. Foundation types are not observed to vary significantly with vintage, although there are no slab foundations before 1960 and an large number of slabs in MCS homes. Thus the biased geographical distribution of foundation types does not significantly influence the general trend to higher insulation levels in newer homes.

The cumulative UAs of individual building components in the ELCAP Residential homes (excluding the RSDP sample homes) are shown in Figure 3.8. The stacked bar plot shows the component UA aggregated across the sample for each climate zone and for the entire region. An estimate of the infiltration

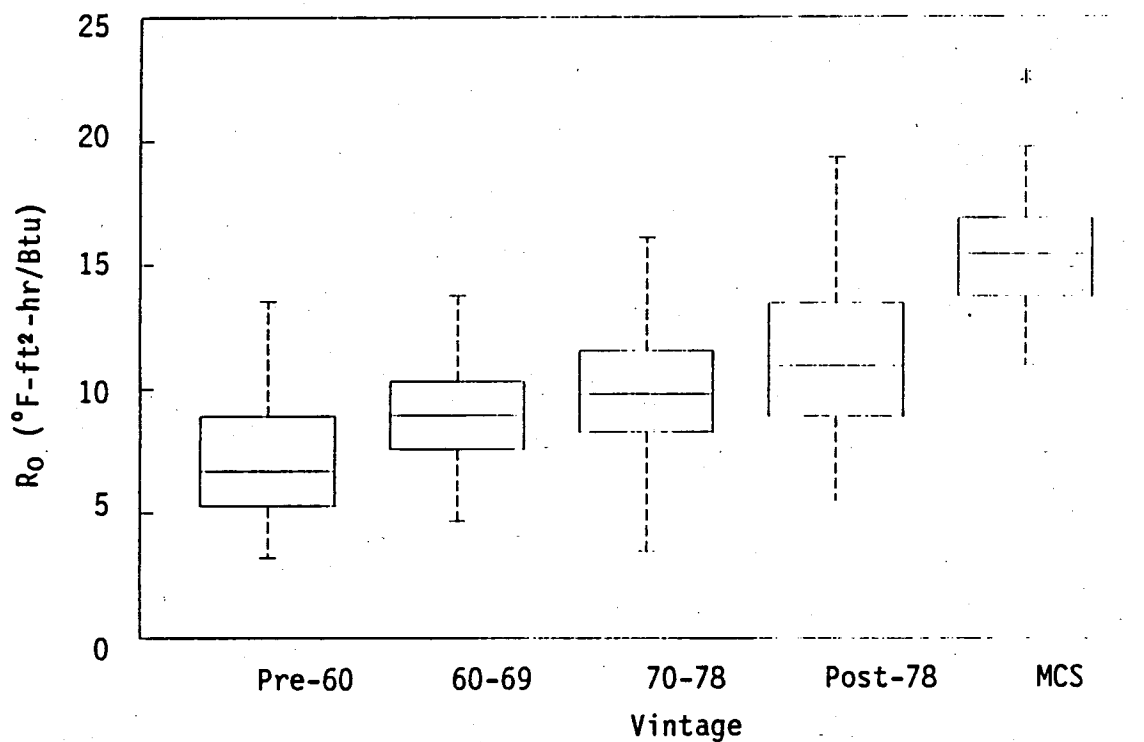


FIGURE 3.5. Total Effective R-Value by Vintage

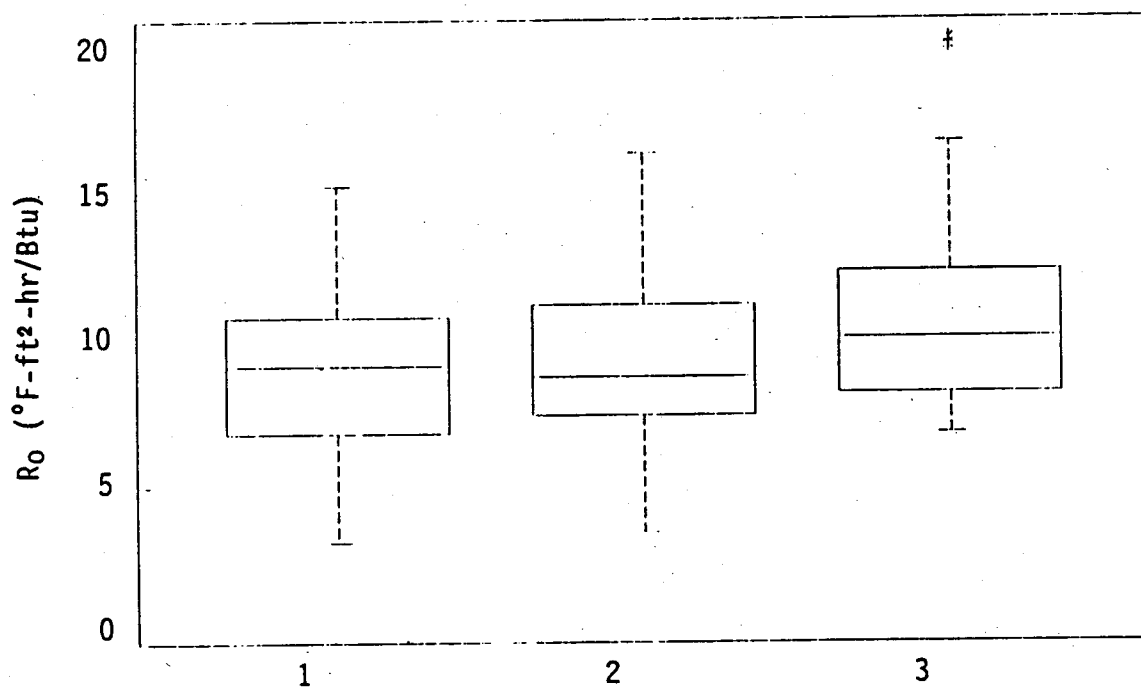


FIGURE 3.6. Total Effective R-Value by Climate Zone

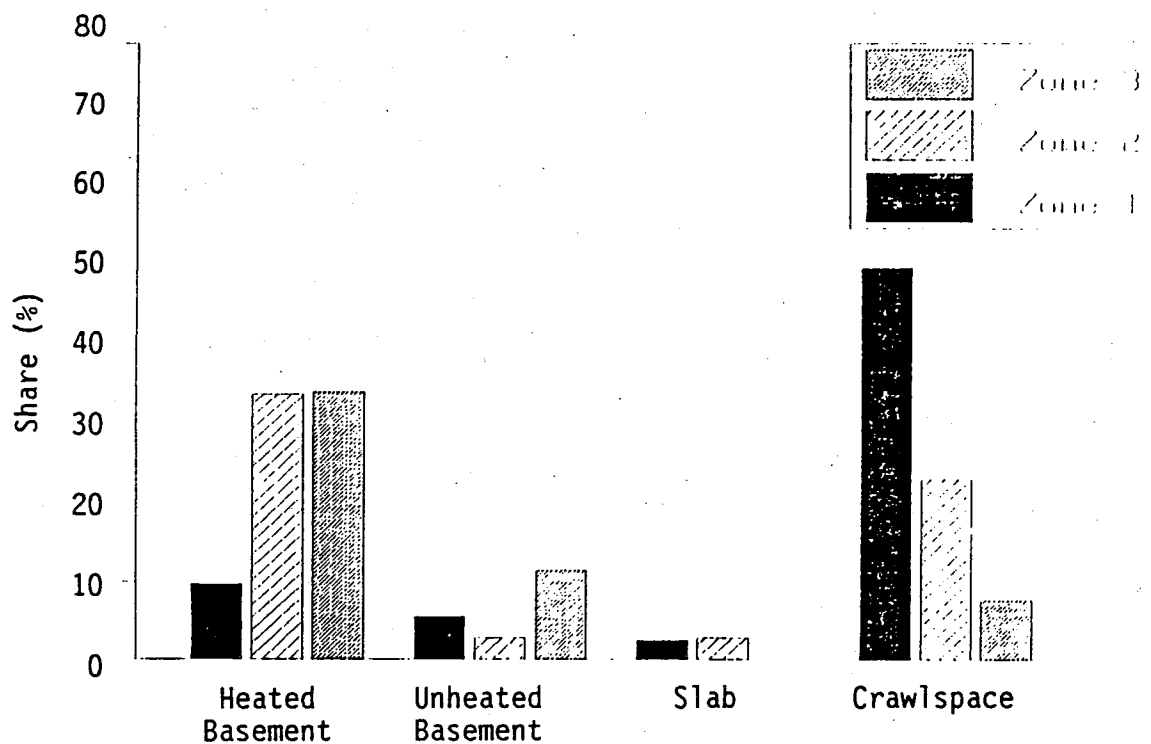


FIGURE 3.7. Share of Single Foundation Types by Climate Zone

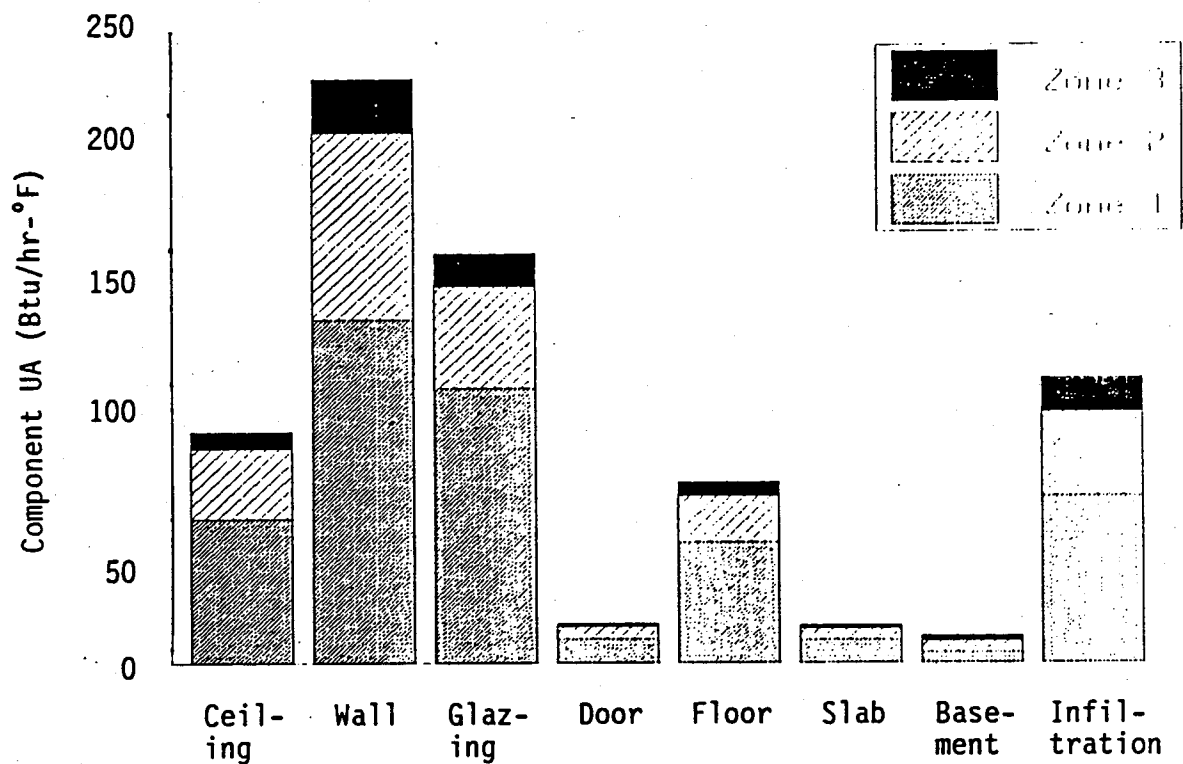


FIGURE 3.8. Average Component UAs for the ELCAP Residential Base Sample with Contributions by Climate Zone

component is also given here for the purposes of comparison, based on an assumed average of 0.4 air changes per hour. The data indicates that heat losses through walls (including basement walls) form the largest component of space heat in all climate zones, followed by glazing, infiltration, ceilings, and floors. The floors total includes floors over crawlspaces, unheated basements, and other unheated areas such as garages. Doors, slabs, and basements floors are minor regional space heat loss components.

The ceiling and wall component R-values generally exhibit the trend of increasing insulation levels over time but not climate zone, as illustrated in Figures 3.9 and 3.10 for walls. The median levels of effective wall R-value climb steadily with time, and the interquartile range also decreases dramatically. The median and mean R-values roughly double from Pre-1960 homes to Post-1978 homes. The distribution of effective ceiling R-values with vintage is similar to that for walls, although the median and mean values increase by about 50% over this period. This reduced change with time may be an effect of insulation retrofits, given the relative cost effectiveness of adding insulation in attics as compared with walls. Doors, floors, and slab foundations show sharply increased insulation levels under MCS, but little relationship otherwise to vintage or climate zone.

By contrast, windows exhibit a strong trend with climate zone but not with vintage, as shown in Figures 3.11 and 3.12. The median R-values rise from R-1.51 in Zone 1 (low-quality double glazing), to R-1.73 in Zone 2 (high quality double glazing or storm windows), to R-1.95 in Zone 3 (very high-quality double or low-quality triple glazing). Window areas were not found to be strongly related to climate zone or vintage.

3.3.2 Comparison of RSDP Sample UAs with Design Targets

The residential MCS primarily define insulation values for a building shell. That is, they specify insulation R-values and component U-values. In particular they do not limit the area allowable for each component, except in sometimes specifying a limit on window area. Therefore, for each building there is a target MCS UA specific to that building that is a function of both the MCS and that building's size and shape. This analysis compares the as-built UAs for the ELCAP MCS houses to three of the possible methods of meeting the

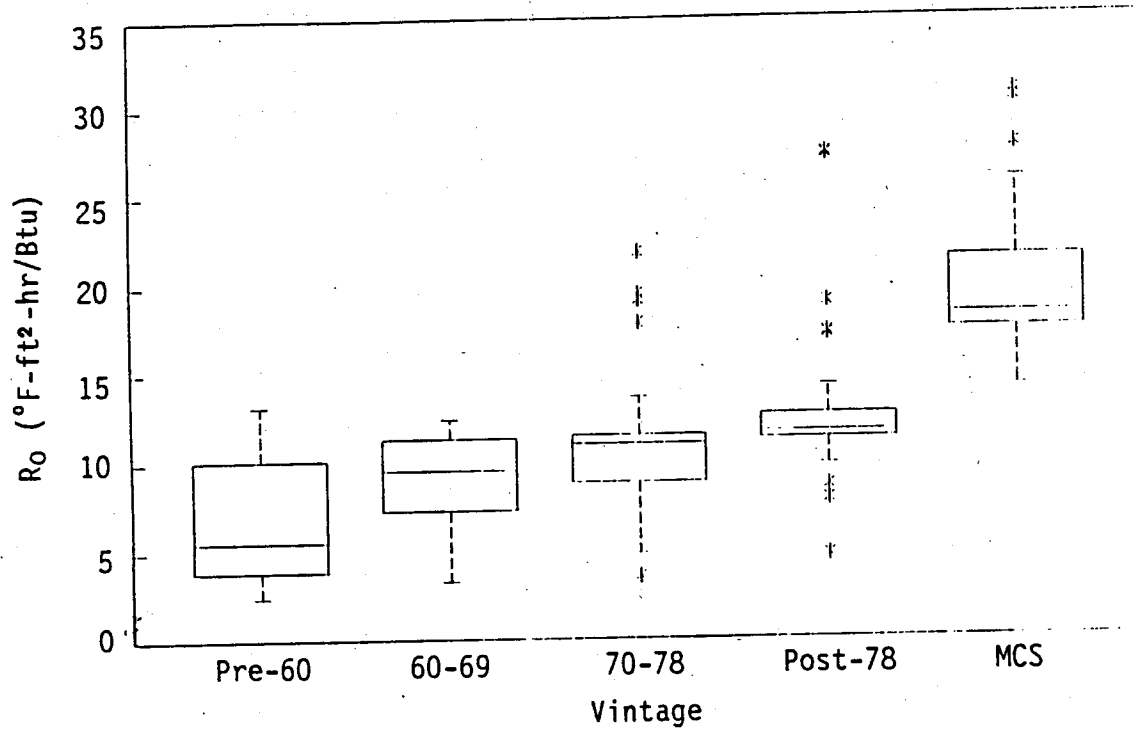


FIGURE 3.9. Effective Wall R-Value by Vintage

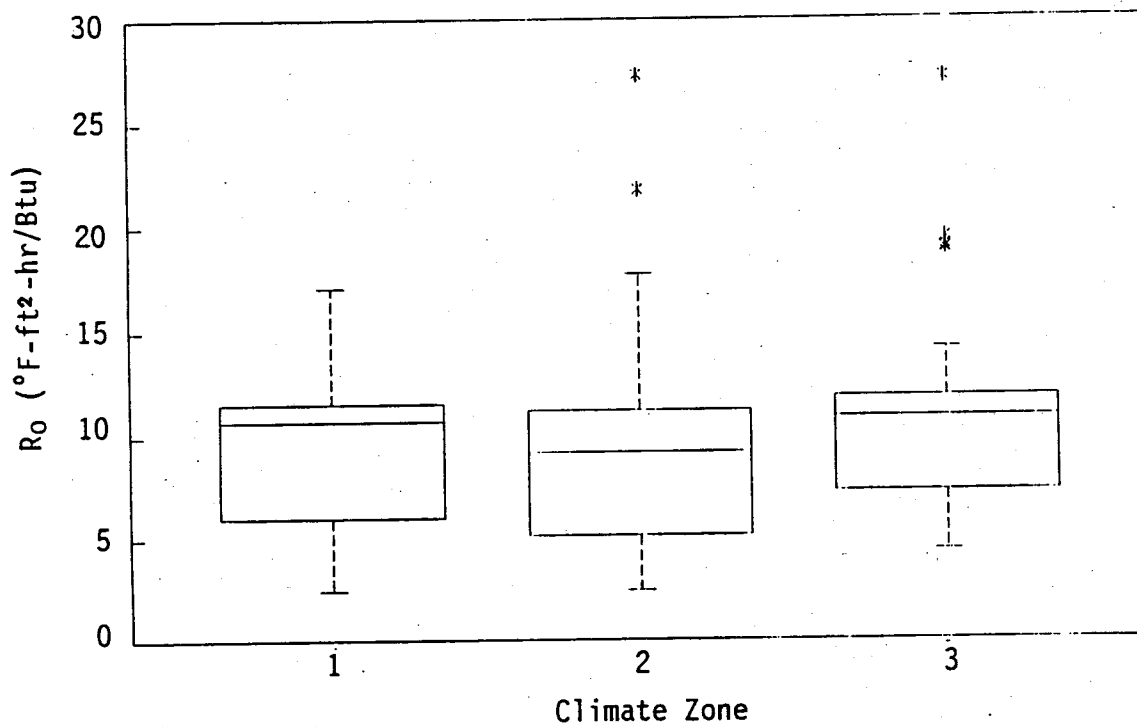


FIGURE 3.10. Effective Wall R-Value by Climate Zone

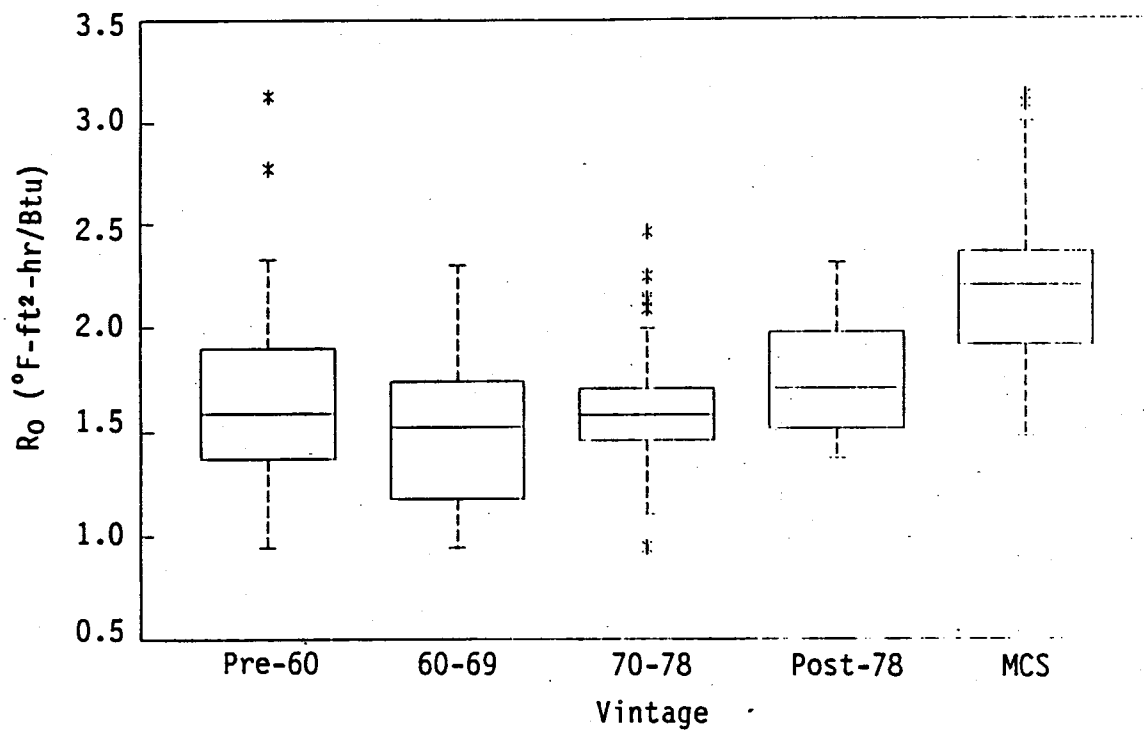


FIGURE 3.11. Effective Window R-Value by Vintage

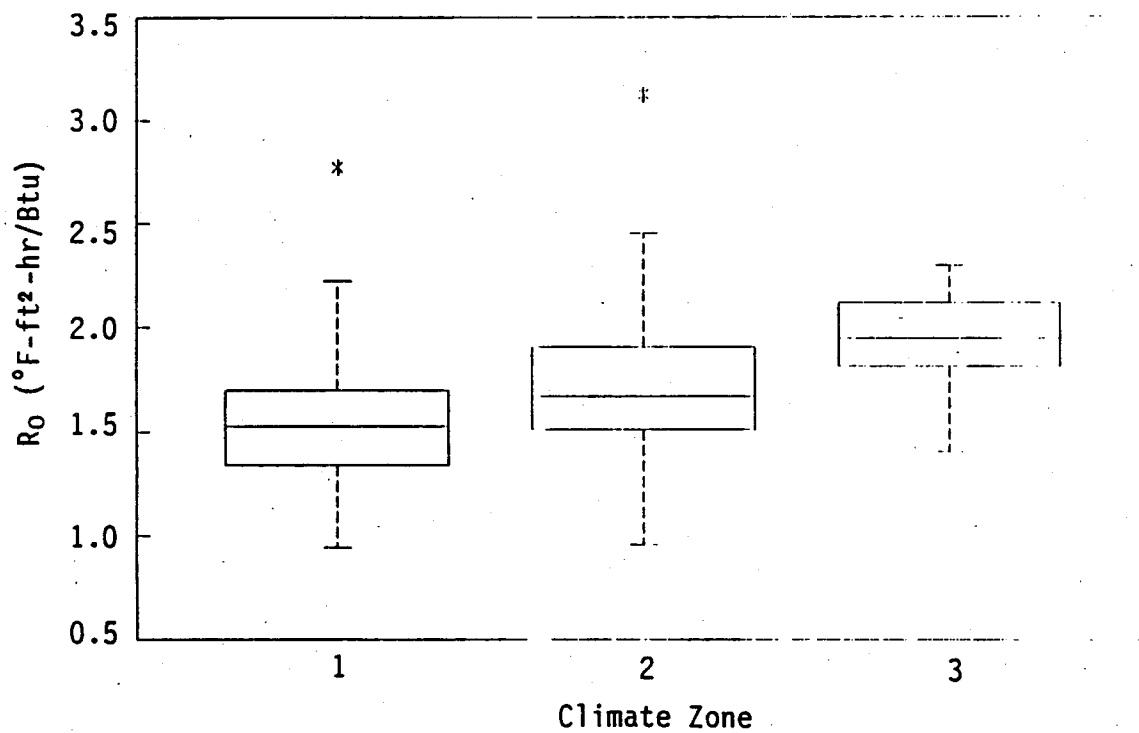


FIGURE 3.12. Effective Window R-Value by Climate Zone

standard, compliance paths A, B, and C of the Prescriptive Requirements Method. Therefore, three standard UAs are computed for each house.

Figures 3.13, 3.14, and 3.15 compare the as-built UAs for the MCS homes to the UAs they must meet using compliance paths A, B, and C respectively. Each point represents one MCS house. All ELCAP MCS houses are included on each graph. Any houses falling on the diagonal line in each figure have as-built and MCS UAs that are exactly the same. Figure 3.13 shows that the ELCAP MCS houses are near the MCS UA for path A, although there is a tendency for the as-built UAs to be somewhat over the UA allowed by path A. Figures 3.14 and 3.15 show that the MCS houses are closer to path B and C. The mean of the as-built UAs exceeded the MCS UAs by 11%, 9%, and 4% for paths A, B, and C, respectively. The tendency for the as-built UAs to be slightly higher than those allowed by the three paths is reasonable because some of the MCS paths had energy-saving features (like heat pumps or properly oriented glazing), which are not reflected in the UA but that allow a higher UA in compensation. Therefore, the thermal integrity of the MCS portion of the ELCAP RSDP sample is roughly as targeted in the MCS.

Figure 3.16 compares the Control homes' as-built UAs to their target, the current code UA. Although the Control homes show some variation from the current code, the points are generally grouped around the line; in fact the average values for the Control's as-built UAs and the Control's current code UAs differ by less than 3%. Therefore the ELCAP Control homes in the RSDP study are a good representation of the current code targeted by the RSDP. A comparison of the as-built UAs for Post-78 homes (the non-RSDP ELCAP homes built after 1978) with the current-code UAs for the same houses again shows most of the points group around the line where the two UAs would be equal, with a mean difference of 8%. The tendency for the Post-78 as-built UAs to be similar to the RSDP Control home UAs suggests that the RSDP current code is indeed representative of new construction in the region.

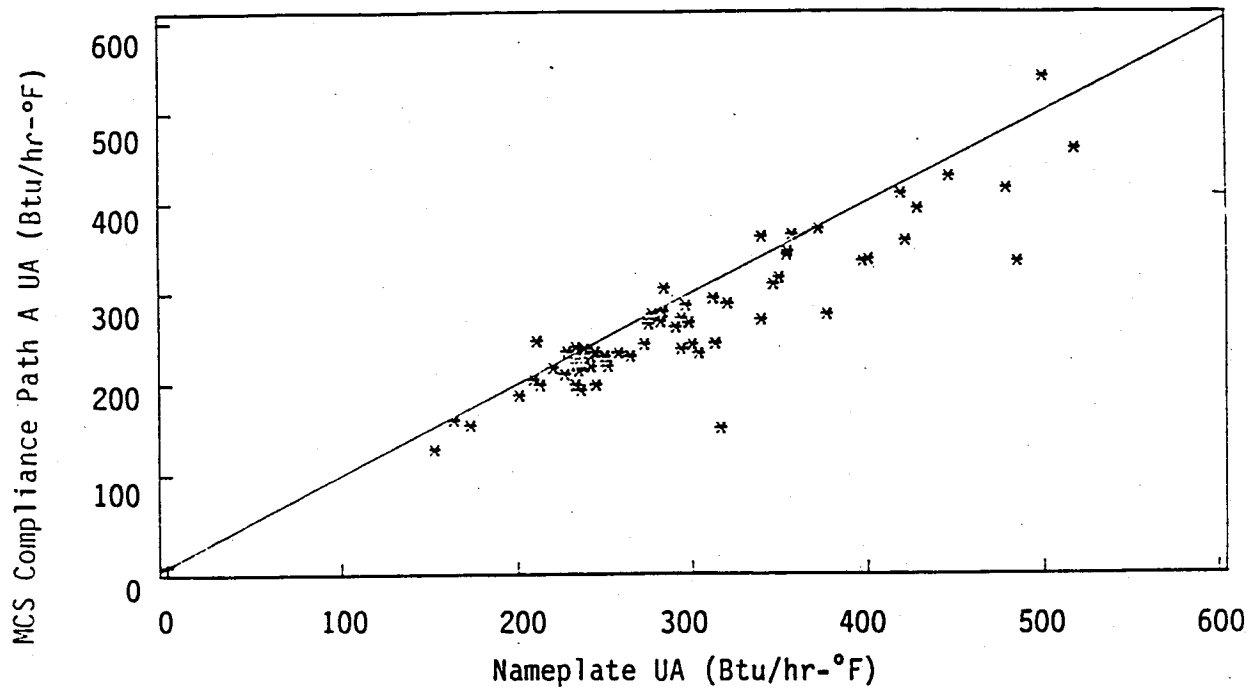


FIGURE 3.13. MCS House Nameplate UAs vs. Compliance Path A UAs

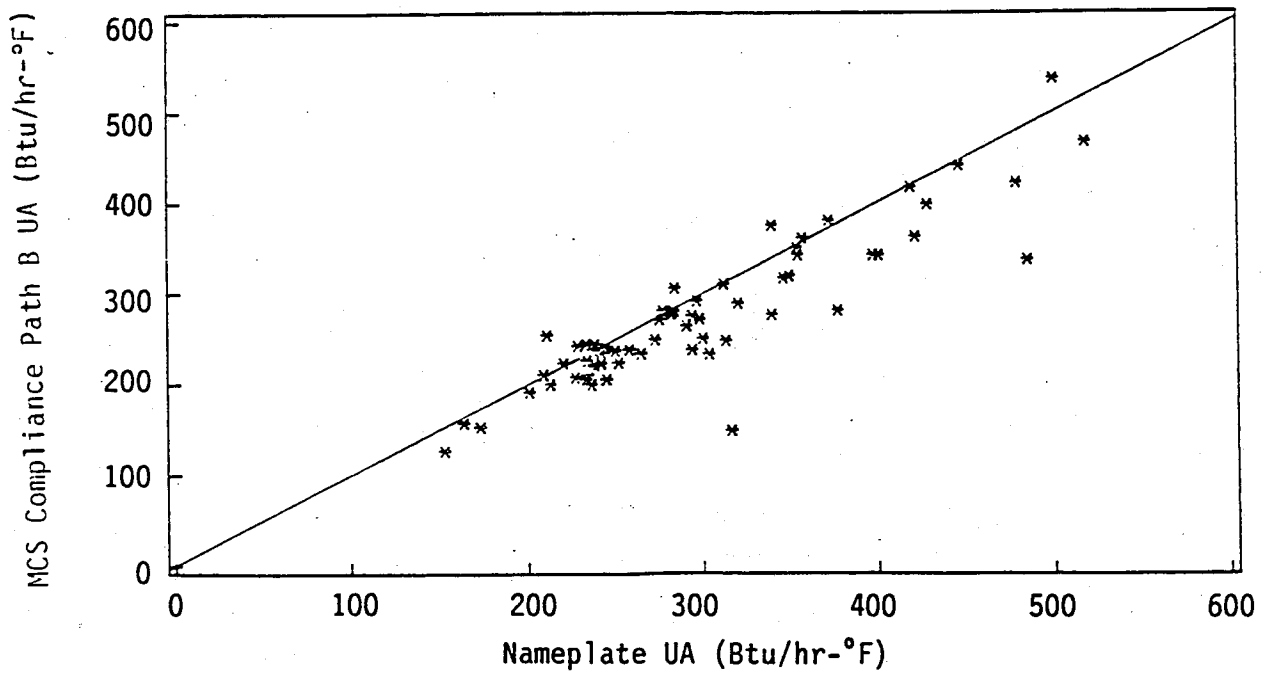


FIGURE 3.14. MCS House Nameplate UAs vs. Compliance Path B UAs

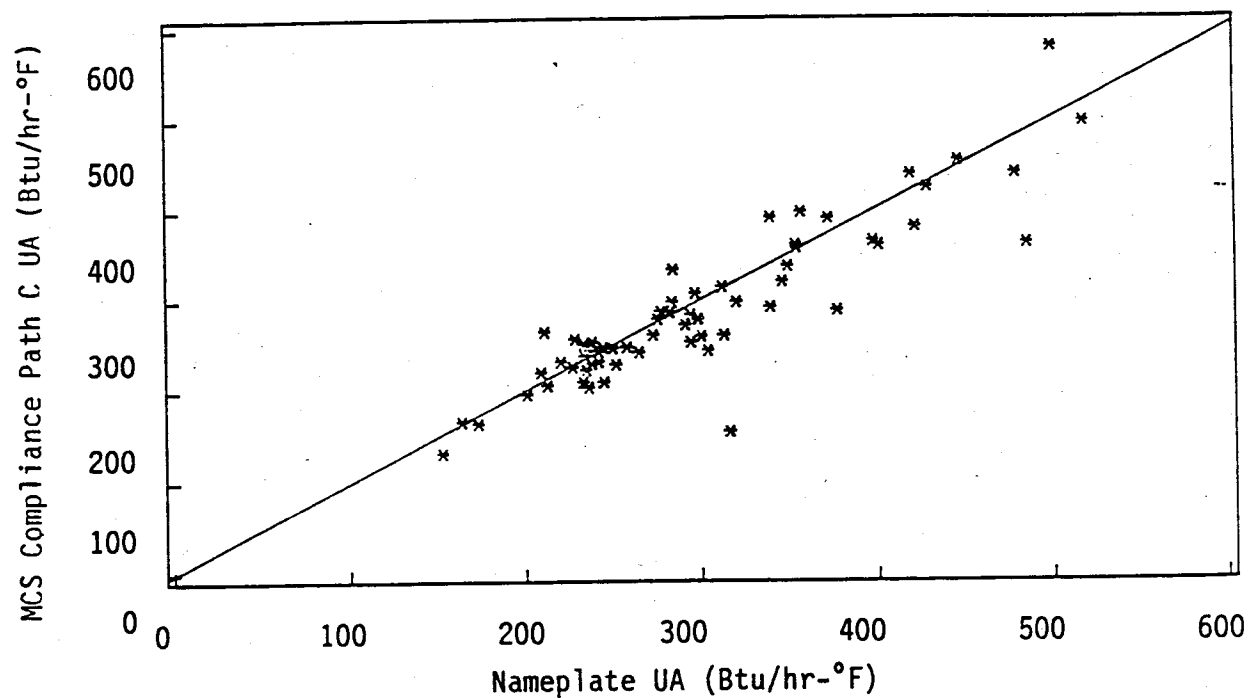


FIGURE 3.15. MCS House Nameplate UAs vs. Compliance Path C UAs

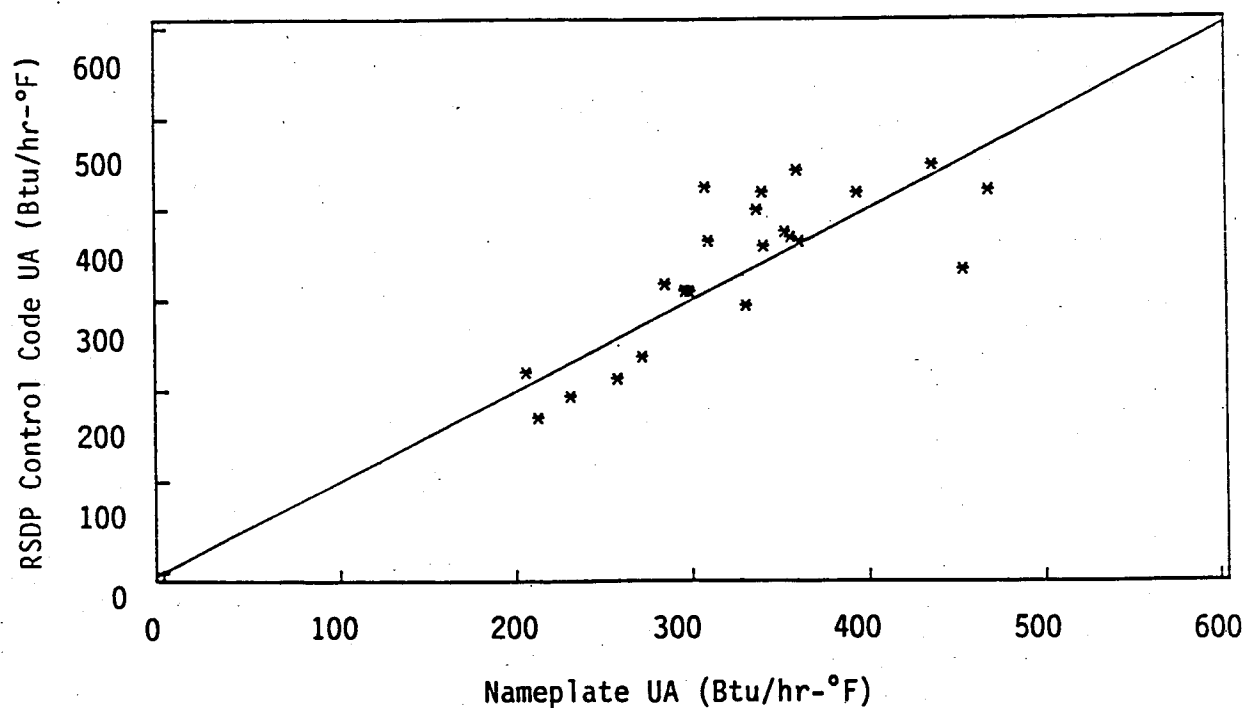


FIGURE 3.16. RSDP Control House Nameplate UAs vs. Control Code UAs

3.4 APPLICATIONS

A principal result of this analysis is that home insulation levels are primarily related to vintage rather than climate severity, at both the whole house and component levels. The sole exception to this trend is windows, which exhibit a trend in climate zone but not vintage. The general trend toward vintage as a determinant of thermal integrity of residences can be interpreted as a consequence of a lack of climatically appropriate energy standards. The lost opportunities for achieving an energy-efficient housing population can be large in the face of a tendency to build to common practices that are not adapted to particular climates. It should also be noted that the historical trend toward larger homes does result in higher UAs, but this is more than compensated by the trend toward increased insulation levels. The MCS homes clearly exceed the historical trends when they are viewed as representative of the next decade of construction.

Some impact of retrofit programs appears to be evident in the data, as indicated by the relatively smaller increase in insulation levels in ceilings compared to walls. The complete lack of dependence of window R-values as a function of vintage may also be the result of program or owner sponsored retrofits, but it is also possibly related to the problem of condensation in colder climates. The magnitudes of the heat losses through the region's residential walls, windows, and outside air infiltration indicate that they remain targets for conservation if cost effective measures can be developed and utilized.

The distribution of foundation types across climate zones, particularly basement foundations, has consequences for regional forecasting and conservation resource assessment. Basement foundations are shown to be associated with better than predicted overall household thermal performance, and with nonlinear behavior with temperature (see Section 5.0).

The UAs of the ELCAP RSDP homes support the validity of using the ELCAP metered data from the RSDP sample to analyze the effectiveness of the MCS. The compliance of the MCS and Control samples' as-built UAs with their targets indicates that designers and builders in the Pacific Northwest region can and do construct homes to standards with reasonable accuracy, in the aggregate. The control homes are also shown to conform to current practice as exhibited by the Post-78 homes.

4.0 RSDP THERMAL ANALYSIS

4.1 INTRODUCTION

Bonneville initiated the Residential Standards Demonstration Program (RSDP) in 1983 in order to determine the costs and thermal performance improvements associated with increased levels of weatherization in new residences as proposed by the Northwest Power Planning Council (Council) in the Model Conservation Standards (MCS). The program resulted in the construction of approximately 500 new residences built to thermal performance standards as dictated by the MCS in each of three climate zones in the region. One of the goals of the RSDP study was to compare the thermal performance of the structures built to the MCS to that of structures built to current code requirements.

A subset of the residences constructed under the RSDP program was included in ELCAP. These structures were metered to record hourly energy consumption on 10 to 20 channels, permitting disaggregation of electrical loads at the end-use level. Two types of structures were included in the study: homes built under the RSDP to MCS standards, and Control homes built under the RSDP to meet current building code requirements for thermal performance. The data from these structures were used to assess the thermal performance of both MCS homes and homes built to current standards. This section summarizes the results of that comparison from an ELCAP technical report (Drost et al. 1987).

This research had two objectives:

1. Comparison of the performance of homes built to the MCS with Control homes in each of three climate zones.
2. Comparison of the performance of Control and MCS structures analyzed in this study with the performance assumed in by the Council.

4.2 METHODOLOGY

The thermal performance of the structures was characterized by several figures of merit, as listed here. Details of the methodology used in determining the figures of merit follow.

- The slope of a robust linear fit to daily space heating load as a function of inside/outside temperature difference, interpretable as the overall as-operated heat loss coefficient (as-operated UA), of the structure.
- The intercept on the temperature axis of the robust linear fit to daily space heating data as a function of inside/outside temperature difference, interpretable as the inside/outside temperature difference which the structure can support (given typical levels of internal activity and solar gains) without requiring use of space heating equipment. This characteristic is the balance temperature difference of the structure.
- The predicted space heating electrical consumption for a standard reference climate, assuming the house was operated at the observed average internal temperature. This provides a "weather-normalized" estimate of space heating consumption on an as-operated basis, and is termed the as-operated annualized estimated consumption (as-operated AEC).
- The predicted space heating electrical consumption referred to a standard reference climate, assuming the house was operated at an average internal temperature of 65°F, providing a "weather-normalized" estimate of space heating consumption adjusted for one of the principal sources of occupancy induced variation. This is termed the 65°F reference annualized energy consumption (reference-65 AEC).

This study took a strictly empirical approach to thermal performance analysis. The monitored performance of a structure is used to develop relationships that can be used to predict thermal performance with arbitrary conditions of internal temperature and external weather. The variable with the most significant impact on space heating energy consumption is the temperature difference from inside to outside the thermal envelope of a structure, because the daily average space heating energy consumption is strongly correlated with this daily average indoor/outdoor temperature difference (ΔT). In order to account for variations in size between structures, the energy consumption can be divided by floor area.

Often, the plot of daily space heat consumption versus ΔT has a linear region at intermediate and high values of ΔT , and a nonlinear region at low values of ΔT . In addition, a significant number of sites were found to exhibit nonlinear behavior at high values of ΔT . This suggests two approaches to modeling a structure's thermal performance. First, a linear fit can be developed for the linear portion of the data, ignoring the nonlinear region at either low or high ΔT . Second, a smooth nonparametric curve can be fitted to the complete set of data. These two approaches give separate methods of modeling the data. This study used the linear fit to calculate the as-operated UA and balance ΔT . The smooth non-parametric fit is the most complete characterization of the data, and was used to determine the AECs.

The AEC of each structure was determined individually for climate zone in which it is located, using an outside temperature distribution for Power Council's site in the climate zone. These sites are Seattle, Washington; Spokane, Washington; and Missoula, Montana; for Climate Zones 1 through 3 respectively, as defined by the Council. The first step in the procedure was to select the internal temperature for the structure. Two approaches were used. First, the internal temperature was assumed to equal the mean measured internal temperature for the structure. Data on the outside temperature distribution of the comparison site was used to determine the ΔT , which then was used with the smooth nonparametric fit to yield the as-operated AEC. The second approach assumed that the internal temperature was a constant 65°F to estimate the reference-65 AEC.

4.3 RESULTS

4.3.1 Comparison of MCS with Control Structures

The primary goal of this research was to provide a comparison of annual performance of the MCS and Control structures.

The MCS samples have a substantially smaller predicted annual space heating energy consumption than the Control sample. The results, based on measured internal temperature, are summarized in Table 4.1. The MCS sample also demonstrates substantially lower as-operated UAs than the Control sample for all three climate zones. The MCS sample median as-operated UAs are

TABLE 4.1. Comparison of As-Operated AECs/ft² for the MCS and Control Samples (kWh/yr-ft²)

	<u>Climate Zone 1</u>	<u>Climate Zone 2</u>	<u>Climate Zone 3</u>
Median MCS	3.1	3.4	4.2
Median Control	4.6	4.7	5.1
% Reduction MCS Versus Control	33%	28%	18%

between 20% and 50% lower than Control sample median slopes. The reduction of space heating consumption is seen to range from 33% to 18%, with higher savings in warmer climate zones.

4.3.2 Comparison of MCS Structures with MCS Targets

Two questions are central to the comparison of MCS structures with the Council's standards. The first question is whether the MCS structures included in the study are representative of the MCS. Calculation of theoretical nameplate UAs (based on ASHRAE heat-loss calculations) for the MCS homes and comparison with their target levels confirms this to be the case, as discussed in Section 3.0.

The second question is how well the measured performance of the MCS homes compare to the MCS target levels. Table 4.2 compares the "as-built" performance of the MCS structures to the Council's target levels. A review of that MCS structures located in all three climate zones showed thermal performance comparable to, or in excess of, the MCS targets. The comparison is summarized below. These results for MCS performance are based on measured internal temperatures.

4.3.3 Comparison of Control Structures with Power Council Assumptions

The same two questions relate to the comparison of the Control homes with the Power Council standards. First question is whether the Control homes included in the study are representative of current practice. Calculation of the nameplate UAs for the Control homes and comparison with current construction practices in ELCAP Base Post-1978 homes confirms this to be the case, as is also discussed in Section 3.0.

TABLE 4.2. Comparison of MCS AEC/ft² with Council Targets (kWh/year-ft²)

	<u>Climate Zone 1</u>	<u>Climate Zone 2</u>	<u>Climate Zone 3</u>
MCS Target Level (65°F thermostat setting)	3.3	4.3	4.8
MCS mean (reference-65)	2.6	2.6	3.7
MCS mean (as-operated)	3.5	3.3	4.2
MCS mean measured internal temperature (°F)	68.4	69.6	67.6

The "as-built" performance of the control structures is compared to Council assumptions in Table 4.3. A review of Table 4.3 shows that Control homes constructed under the RSDP program have thermal performance substantially better than assumed by the Council in the development of the MCS standards. As these Control homes actually represent current practice (based on the nameplate UA calculations of Section 3.0), the savings realized by imposition of the MCS may in consequence be overestimated, even though the MCS thermal performance targets are realized. This is illustrated in Figure 4.1, where the AECs/ft² from the metered data are compared with the Council assumptions for both the MCS and Control homes.

4.3.4 Nonlinear Relationship Between Space Heating Energy Consumption and ΔT

The results of this study indicated that there is a second nonlinear region at high values of ΔT . The existence of a nonlinear region at high values of ΔT was observed in a significant number of structures in climate

TABLE 4.3. Comparison of Control Home AEC/ft² with Council's Current Practice Assumption (kWh/year-ft²)

	<u>Climate Zone 1</u>	<u>Climate Zone 2</u>	<u>Climate Zone 3</u>
Council Current Practice	7.9	10.8	9.9
Control mean (as-operated)	3.5	3.3	4.2

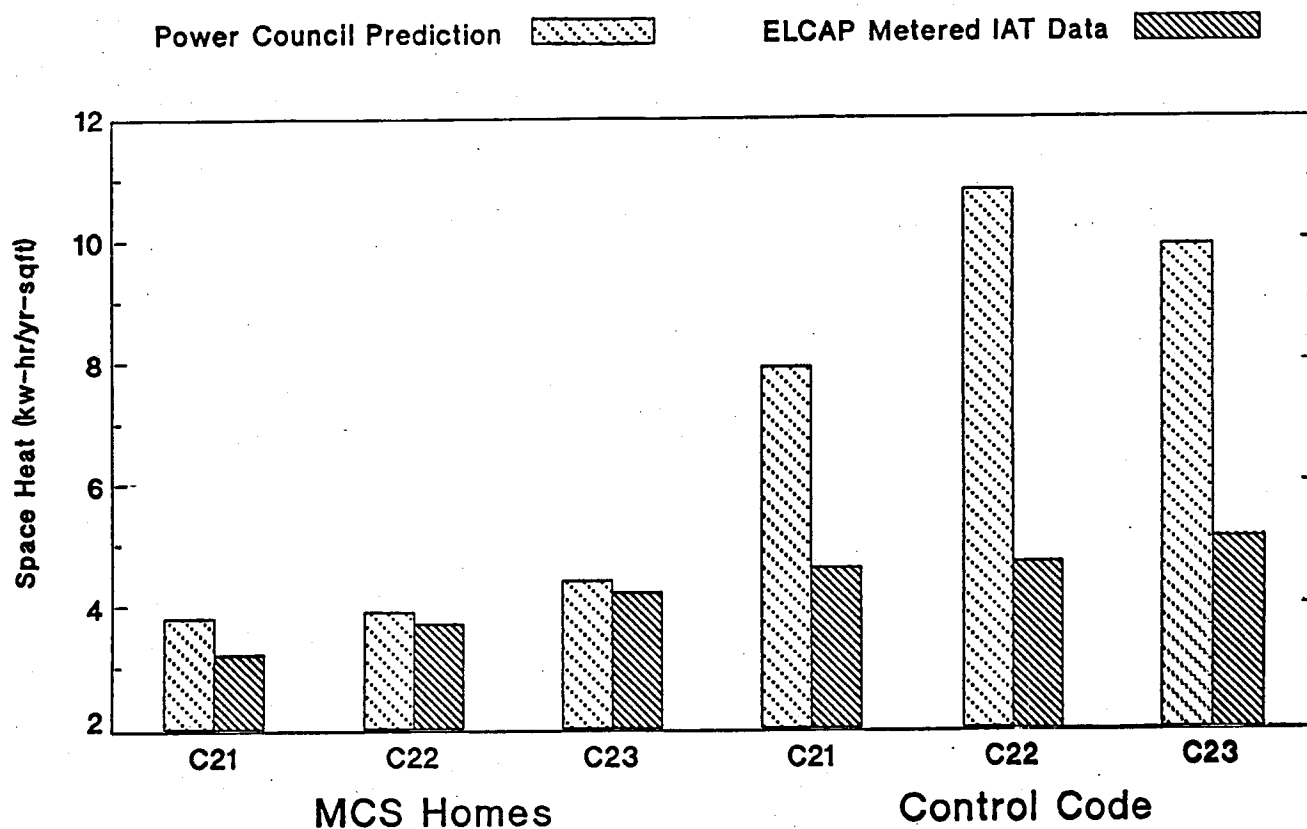


FIGURE 4.1. Predicted and Metered Space Heating Required
MCS and Control Code Homes

Zones 2 and 3. The high ΔT nonlinear region is of particular interest because it can result in a substantial reduction in space heating energy consumption when compared to a more typical linear model.

4.4 APPLICATIONS

Empirical data on the thermal performance of the MCS are important to a wide range of forecasting applications. Some significant results of the study in this context are listed here.

- The MCS homes have substantially improved thermal performance when compared to the Control homes.
- The MCS homes located in all three climate zones have thermal performance that meets or exceeds the MCS.

- Control homes built under the RSDP program to current practice have thermal performance substantially better than that assumed for current residential construction in the development of the MCS standards. The savings realized by imposition of the MCS may in consequence be overestimated, even though the MCS thermal performance targets are realized.

Finally, the thermal analysis techniques developed by this pioneering ELCAP analysis have been improved and used repeatedly in further analyses of metered data, as discussed in the following sections. Also, this work discovered the common nonlinear relationship between space heating energy consumption and ΔT at high values of ΔT , calling into question models that incorporate a linear assumption about this relationship.

5.0 BASE SAMPLE RESIDENTIAL THERMAL ANALYSIS

5.1 INTRODUCTION

In this section the thermal performance of the ELCAP Residential Base Sample of homes is summarized. Annual electrical space-heating estimates for the Base homes are compared to the annual space-heating estimates used to forecast the residential space-heating load for the region (Miller et al. 1991). The thermal performance characterizations for the ELCAP Base Sample of electrically space-heated homes are also combined with those derived for the Residential Standards Demonstration Program (RSDP) sample. For this larger set of homes, the observed conductive heat loss rates are compared to those predicted from engineering calculations. Preliminary results relating heating system type and foundation type to structural space heating requirements are also discussed.

Electric space heating is the largest of the residential end-use loads in the ELCAP Base Sample (Pratt et al. 1989). Consequently, space heating is the chief target of many conservation programs. The residential sector electrical forecast is strongly influenced by assumptions regarding the space-heating requirements for new and existing structures. The large end-use database provided by ELCAP allows a unique opportunity for a detailed study of the space-heating requirements for new and existing single-family dwellings throughout the Pacific Northwest.

The ELCAP Residential Base homes, numbering around 280, are intended to be roughly representative of the stock of detached single-family electrically heated homes in the Bonneville Power Administration (Bonneville) service territory. The thermal performance of approximately half of the ELCAP monitored Base Sample residences has been characterized for the 1985/1986 heating season. In the exploratory work on the determinants of space-heating consumption, the number of homes analyzed is increased to 204. This larger set of homes includes homes built as part of the RSDP program. Section 4.0 reports on the basic performance of RSDP and the Model Conservation Standards (MCS).

Several results are referenced to the three climate zones defined by the Northwest Power Planning Council (Council). Of the characterized sites from the Base Sample, about 70% are located in Climate Zone 1 (less than 6000 base 65°F heating degree-days/year). The balance are located in the more severe Climate Zones 2 and 3, defined as areas having between 6000 and 8000 and more than 8000 heating degree-days/year, respectively. Of the combined set of 204 homes used in the exploratory analysis, 63% are located in Climate Zone 1; the remainder are located in the more severe climate zones. For comparison, the 1986 version of the Council's Northwest Power Plan weights Climate Zone 1 at 84% (Northwest Power Planning Council 1986).

5.2 MEASURES OF THERMAL PERFORMANCE

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 homes with wood-stove sensors, days with diagnosed wood-stove use are removed before the analysis. Periods of extended vacancy are also removed. A detailed explanation on methodology may be found in Volume I of the report by Miller et al. (1991).

Several performance parameters are derived for each residence. Each is briefly explained below:

- **As-Operated UA** - This slope parameter from the robust linear fit of space heat to inside/outside temperature difference can be interpreted as the conductive UA of the home divided by the heating system efficiency. The as-operated UA can be interpreted as a measure of thermal efficiency of the home considering internal gains and occupant effects.
- **Balance Temperature Difference** - The balance temperature difference is derived from the linear fit also. The balance temperature difference may be interpreted as an estimate of the average inside/outside temperature difference that the structure is able to support via internal and solar heat gains without use of the space-heating equipment.

- **As-Operated Annualized Estimated Consumption for Space Heat (As-Operated AEC)** - The as-operated AEC can be viewed as the typical annual electrical space-heating requirements for a structure subjected to a standard climate, reflecting the internal temperature, solar and internal gains actually observed over the period of data collection. Standard climate years allow the thermal performance of homes from various parts of the Pacific Northwest region to be compared. The AEC assumes continuous occupancy and excludes the effects of wood use.
- **65°F Reference Annualized Estimated Consumption for Space Heat (Reference-65 AEC)** - The reference-65 AEC is identical to the as-operated AEC except that an internal temperature of 65°F is assumed instead of the average measured internal temperature.

5.3 RESULTS

In this section the performance statistics derived for the residential base homes are summarized and compared to the 1986 Northwest Power Plan estimates for single-family detached homes. The exploratory results in Sections 5.3.2 through 5.3.4 also include thermal characterizations derived for 77 homes constructed as part of the RSDP program. This exploratory work compares as-operated UAs to those computed from standard engineering methods (see Section 3.0) and looks at the effects of heating system type and foundation type on the heating load. In Section 5.3.5 the observed nonlinear responses of the space-heating load, when daily space heat is plotted as a function of inside/outside temperature difference, are summarized for the Base Sample for homes analyzed.

5.3.1 Base Results and Comparison to the Council Power Plan

The mean inside air temperature over the heating season is used with the appropriate reference Typical Meteorological Year (TMY) weather data for each climate zone to compute the AEC distributions shown in Figure 5.1. AECs for the 127 single-family ELCAP Base homes are displayed in the left panels, while the right panels display those estimates for the subset of these homes built after 1978. The middle (median) consumption estimate for the 17 newer homes

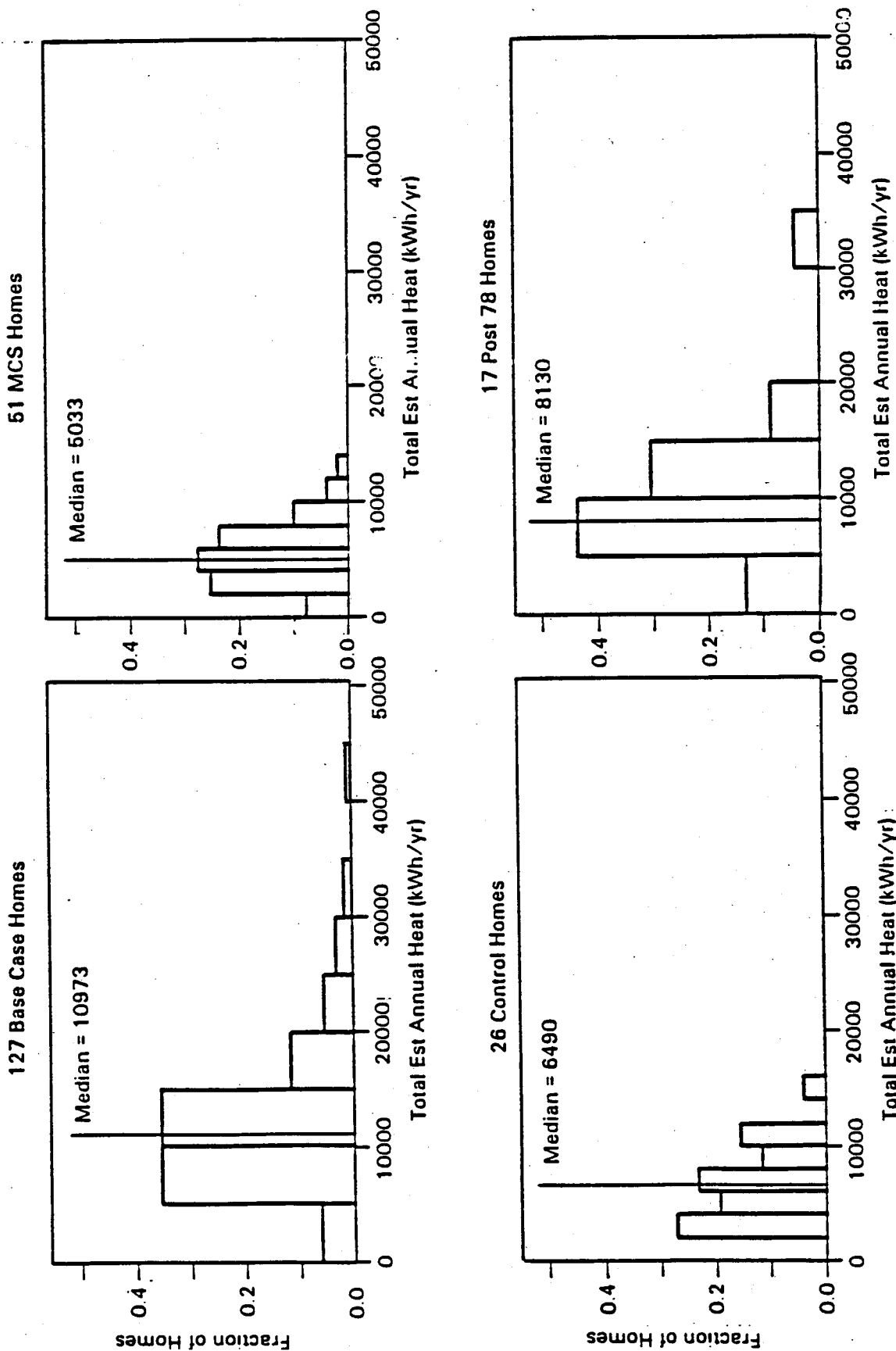


FIGURE 5.1. Annualized Estimated Consumption for Space Heating for ELCAP Residential Base and Post-78 Homes

is between three-fifths and three-fourths of the middle estimates for those homes built predominately before 1979. Clearly, new homes are being constructed with lower space-heating requirements. Although a wide range of AECs is illustrated in Figure 5.1, the bulk of home space-heating estimates tend to cluster around 11,000 kWh/yr, with a few high consumption homes bringing the mean AEC up to about 12,000 kWh/yr.

A summary of performance statistics is given in Table 5.1 for the 127 single-family homes. The average operating temperature over the heating season is approximately 69°F. The average home size is between 1500 and 1700 ft² (depending on selection of mean or median estimate). The average AEC is about 7.6 kWh/yr-ft². This estimate drops by almost 2 kWh/yr-ft² if an assumed inside temperature of 65°F is used instead of the occupant mean measured inside air temperature.

Table 5.2 facilitates the comparison between AECs derived for ELCAP single-family homes and estimates used in the 1986 Northwest Power Plan to characterize space-heating requirements for new home construction and existing housing stock in the Northwest region. The Council's estimate for the MCS homes is also included in Table 5.2.

TABLE 5.1. Summary Performance Statistics for 127 Base Homes

Total AEC	
mean	12,101 kWh/yr
median	10,973 kWh/yr
Normalized As-Operated AEC	
mean	7.66 kWh/yr-ft ² (Uses mean heating season
median	7.64 kWh/yr-ft ² indoor air temperature)
Normalized Reference-65 AEC	
mean	5.77 kWh/yr-ft ² (Uses 65°F
median	5.41 kWh/yr-ft ² indoor air temperature)
Inside Temperature	
Sept. to May	
mean	69.1°F
median	69.3°F
Conditioned Floor Area	
mean	1,690 ft ²
median	1,540 ft ²

TABLE 5.2. Regionally Weighted Council Power Plan Estimates

<u>MCS</u>	<u>New w/Wood</u>	<u>New w/o Wood</u>	<u>Existing w/Wood</u>	<u>Existing w/o wood</u>
Projected Heating Requirements				
kWh/yr	6,431	9,940	11,760	11,477
kWh/yr-ft ²	3.5	7.1	8.4	8.5
Floor Area (ft ²)	1,848	1,400	1,400	1,355

The estimated heating requirements for existing homes (assumed to be built before 1979) are 8.5 kWh/yr-ft². This estimate allows for some supplemental wood use, and yet is still higher than the ELCAP AEC of 7.6 kWh/yr-ft². Recall that the ELCAP AEC is computed for homes predominantly older than 1979 and excludes the effect of wood use. In comparing the ELCAP estimate to that for new homes, the ELCAP estimate is situated between the forecasting estimate and engineering estimates projected for new homes. The forecasting estimate of 7.1 kWh/yr-ft² for new homes assumes wood-stove usage and installation of more efficient appliances. The engineering estimate of 8.4 kWh/yr-ft² for new homes assumes no supplemental wood heat. The Council's MCS estimates are about 75% of the Post-78 homes AECs. All Northwest Power Plan estimates assume a thermostat set point of 65°F.

Given that the ELCAP single-family AEC estimate excludes the effect of wood use, that the sample analyzed is heavily weighted toward the more severe climate zones, and that the estimate most likely represents thermostat set points higher than 65°F, space-heating requirements for new and existing homes may be overestimated in the forecast of space-heating requirements for the region.

5.3.2 Comparison Between As-Operated and Nameplate UAs

The total UA of a home has often been used as a measure of thermal integrity or the tendency for a home to lose heat. For a large number of Base and RSDP residences, total building UAs have been computed from audit data. (see Section 3.0). This total building UA is referred to as a nameplate UA. An as-operated UA is computed from the slopes from the linear fit of daily

space heat to daily inside/outside temperature difference. In Figure 5.2, the as-operated UAs are compared to the nameplate UAs for the combined sample of homes. These nameplate UAs have an assumed infiltration component of 0.4 air changes per hour based on total conditioned floor area for the home.

In Figure 5.2 the majority of residences fall below the line where nameplate UA and as-operated UA are equal, indicating that as-operated UAs tend to be smaller than the nameplate UAs. Even without an assumed infiltration component, two-thirds of the residences lie below the line of equality. Since the as-operated UAs contain the efficiency of the heating system, perfect equality between nameplate and as-operated is not expected. However, it is clear that as a group these homes are performing substantially better than standard the ASHRAE nameplate UA calculations would predict. The effect of zoning (room closure) may be reducing the as-operated UAs from their theoretical values.

5.3.3 Heating System Effects

Comparisons between as-operated and nameplate UAs point to major differences between heating system efficiencies and ways in which the systems are operated. In Figure 5.3, nameplate and as-operated UAs are compared for each of four heating systems: forced air, baseboard, radiant, and heat pumps. For both the baseboard and radiant heat homes, the majority of residences in all climate zones appear to be performing better than expected. Most of the heat pump homes in Climate Zone 1 show much better performance than the nameplate UAs would predict. Only a small number of heat pumps homes are located in the more severe climate zones, but the performance of these home in every case is poorer than a nameplate UA would indicate.

In the box plots of Figure 5.4, the differences between as-operated and nameplate UAs are scaled by the nameplate UA and presented in a form to allow comparisons across heating system types. The notches in the boxes indicate a difference in the heating system efficiency distributions at the 95% significance level. In the median for these residual distributions, the baseboard homes are performing about 35% better than the forced-air homes.

COMPARISON OF UA'S BTU/HR-DEG F

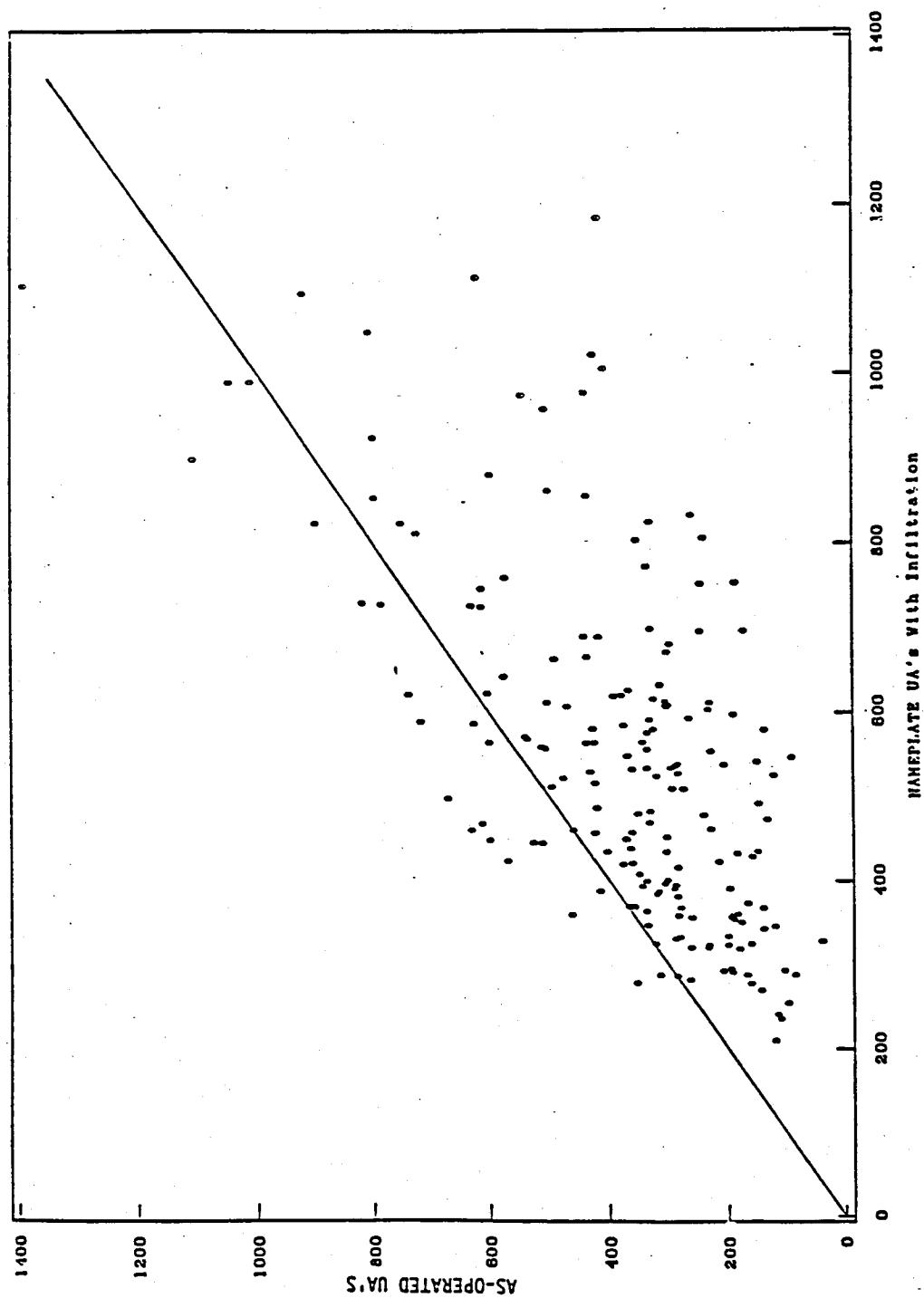


FIGURE 5.2. Comparison Between As-operated and Nameplate UAs for ELCAP Residential Base and RSDP Homes

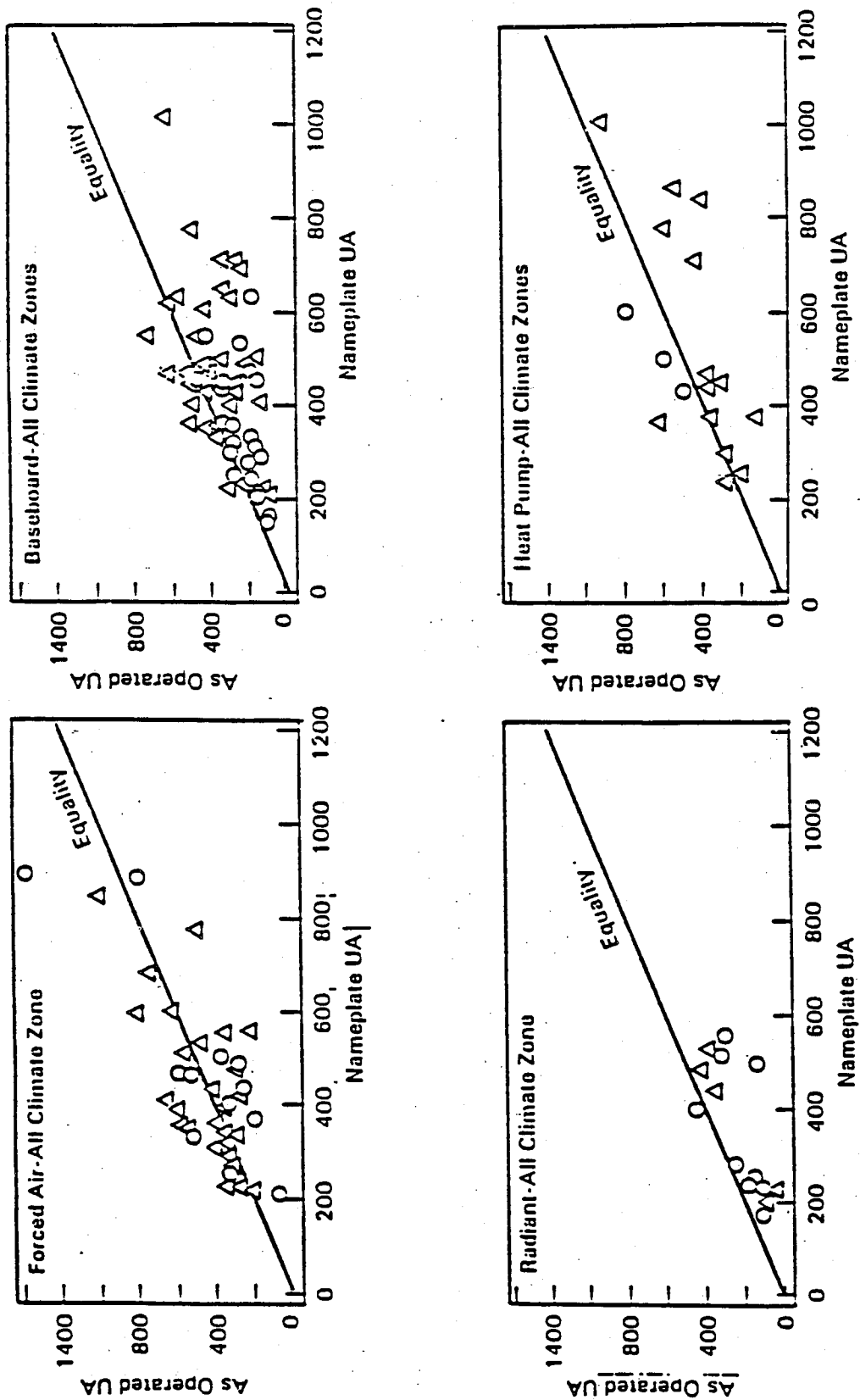


FIGURE 5.3. Comparison Between As-Operated and Nameplate UAs for ELCAP Residential Base and RSDP Homes by Heating System Type (Climate Zone 1 = Δ , Climate Zones 2 and 3 = \circ)

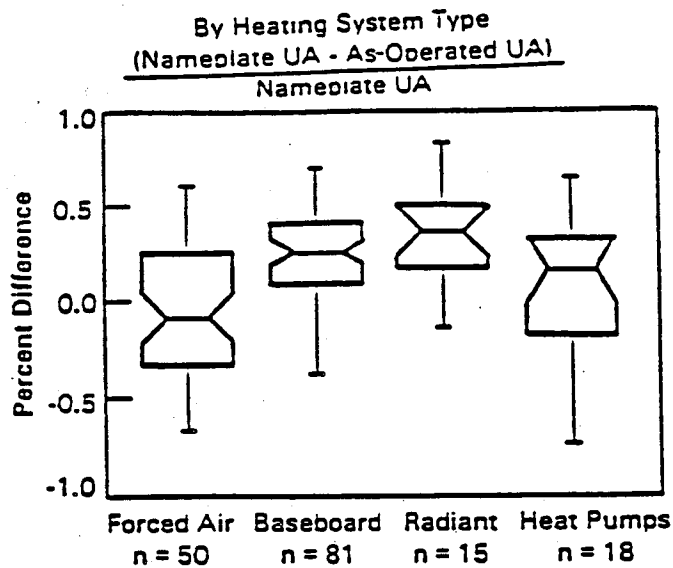


FIGURE 5.4. Residual Distributions from UA Comparisons by Heating System for ELCAP Residential Base and RSDP Homes

This is an indication of the combined magnitude of two effects: heat and air losses from the heating ducts, and lost potential for zoning in central forced-air systems compared to baseboard and radiant systems, which are inherently easy to zone.

5.3.4 Foundation Type Effects

In the box plots of Figure 5.5 the differences between as-operated and nameplate UAs is scaled by the nameplate UA and presented in a form to allow comparisons across the homes with pure foundation types. The heated and unheated basement homes show up as those homes deviating most from nameplate UA-based expectations. The box plot for the heated basement homes implicitly includes any zoning, as the basement space is assumed to be heated in the nameplate UA calculation. However, the performance of the unheated basement foundation type homes still appear somewhat better compared to predictions than that for the slab or crawlspace homes. This result suggests ground conductance and/or mass effects may not be adequately incorporated in the nameplate UA calculations for basement homes. Some "rolloff" or lowering of the space-heat curve as a function of inside/outside temperature difference at high temperature differences appears to be associated with basement homes, as discussed in the following section.

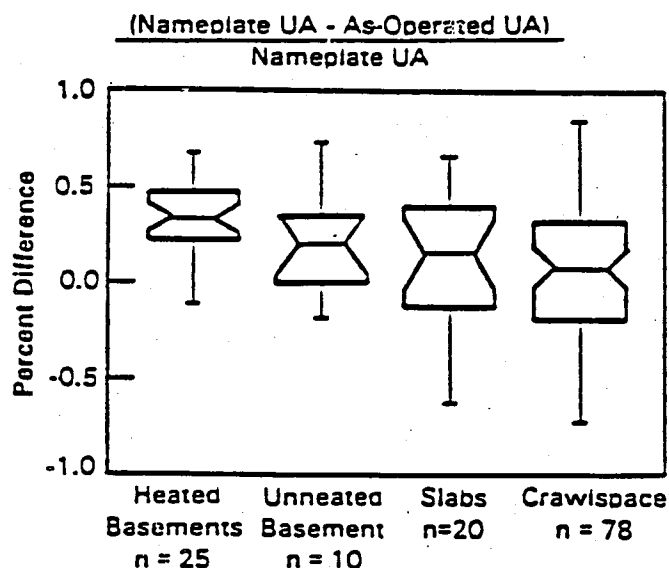


FIGURE 5.5. Residual Distributions from UA Comparisons by Foundation Type for ELCAP Residential Base and RSDP Homes

5.3.5 Nonlinear Character of Heat Load Versus Temperature Difference

It is not possible to characterize many ELCAP Residential Base sites using the methodology discussed in Section 5.2. The predominant reason for exclusion of sites are summarized in Figure 5.6. About 44% of the sites available for analysis are not included in the results of Section 5.3 because of heavy wood-stove use, a high degree of scatter in the data, or little or no space-heating load. The high degree of scatter appears to be associated with wood, some other supplementary fuel source, and in some cases apparently random operation of the permanent space-heating equipment.

For the balance of the homes that were characterized and included in the results of Section 5.3.1, many of these homes had nonlinear shapes associated with the lowess curve fit to the daily heater load versus inside/outside temperature difference. In Figure 5.7 the various typical shapes are illustrated. The basic types for the 127 base homes are linear, linear with a nonlinear foot at the lower delta temperature region, concave upward, and concave downward ("roll off" in the high temperature difference region). In Figure 5.6 the linear and nonlinear foot shapes are defined as the predictable

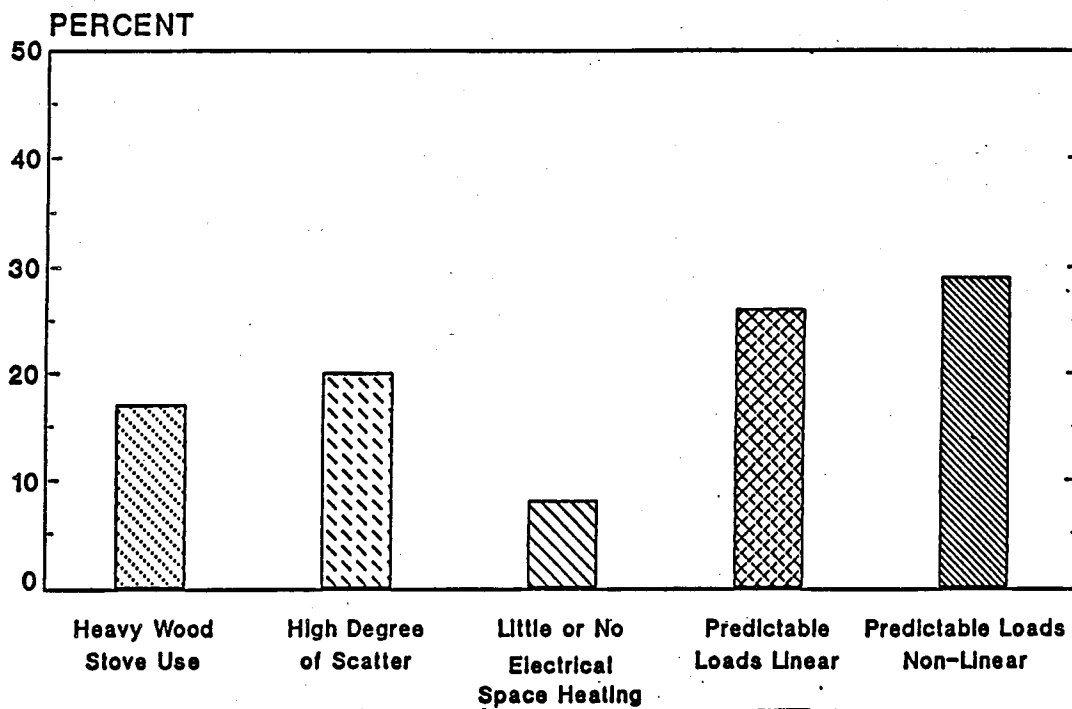


FIGURE 5.6. Disposition of ELCAP Residential Base Sites Available for Analysis

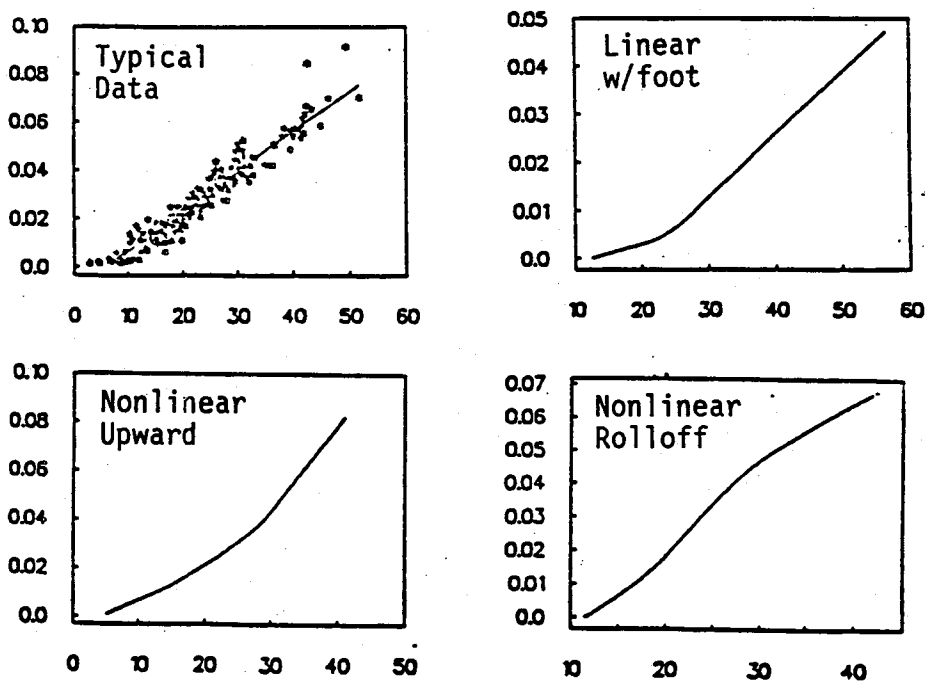


FIGURE 5.7. A Few Interesting Shape Types From the Fit of Daily Heater Load to Inside/Outside Temperature Difference

linear category, and represent a bit less than half the sites characterized. The other portion of homes were the concave upward or concave downward variety. Preliminary work has shown some correlation between the various shapes and both heating system type and foundation type. The upwardly curved shapes are commonly (but not exclusively) associated with heat pumps, as would be expected from the diminished efficiency of heat pumps in colder temperatures. The "rolloff" shapes are similarly associated with heated and unheated basements, and may be due to the thermal lag effect of heat losses through the ground.

5.4 APPLICATIONS

The ELCAP Base Sample of existing electrically space-heated single-family homes have lower space-heating requirements than is currently estimated for the regional stock. This is despite the rather high inside air temperature at which these homes are operating during the heating season (69°F), and the fact that effects of wood use are excluded in the analysis. This underlines the possibility that the current forecasts of space heating for the existing housing stock may be high.

The comparison of theoretical nameplate heat loss coefficients with as-operated values determined from the metered data indicate that most homes in the regions have lower heat loss rates than expected, confirming and the expanding the first conclusion. It is unlikely that an effect of this magnitude is a result of underestimating average infiltration rates (0.4 air changes per hour was assumed). In the first order, the influence of thermostat setback behavior is accounted for by the analysis techniques, and it is unlikely that the second-order effects involved could account for the discrepancy. This points to widespread room closure (zoning) behavior as a likely explanation for the observed discrepancy.

The analysis indicates that heating-system types and foundation types have significant impact on residential heating loads. Basement homes, in particular, are noted to have much better-than-expected performance. This appears to be associated with a "rolloff" in space-heating loads at low

outside temperatures, probably associated with the thermal lag of heat losses from the basement through the surrounding soil.

Similarly, heating-system types showed strong influence on thermal performance. While for heat pumps this is not surprising, the differential between electric resistance central systems and baseboard systems was notable. The heat and air losses from the ducts in central systems, and the lesser capability for zoning inherent in them, apparently significantly detract from overall residential thermal performance. This is also important for heat pump systems by implication, since these same factors must reduce overall performance of heat pump homes in a similar fashion.

Finally, a major conclusion of the analysis is that a linear model falls short of predicting space-heating requirements for most of the homes in the region. The space-heating response to temperature conditions of more than half the homes in the ELCAP sample is not characterizable. Of the approximately half that are characterizable, half again show strong nonlinear behavior in the region of low outdoor temperatures.

6.0 HOOD RIVER THERMAL ANALYSIS

6.1 INTRODUCTION

In this section, the thermal performance of the end-use metered Hood River homes, using techniques developed for End-Use Load and Consumer Assessment Program (ELCAP) analyses, is summarized from an ELCAP technical report (Miller and Pratt 1990). Annual electrical space-heating estimates are compared from the pre- and post-retrofit periods and shown to be reduced by an average of 2432 kWh/yr (24%), in contrast to the audit-based engineering estimated savings of 6100 kWh/yr. No "takeback" effect (taking a portion of savings in increased comfort or convenience instead of energy reductions) is indicated by indoor air temperatures, but a disproportionate amount of wood was displaced in heavy wood-using homes (27% reductions in wood, 17% in electricity).

The objectives of the Hood River Conservation Project, conducted during the period 1983 to 1987, were to fully weatherize as many homes as possible in the community of Hood River, Oregon, and to gather the information required to compare actual and projected costs and savings from that project. As part of the data collection mandate, approximately 300 residences, including single-family homes (80%), manufactured homes (17%), and multifamily units (3%), were end-use metered. Fifteen-minute data were collected detailing total, space heating, and (usually) hot water electrical consumption. In about one-third of the sites the hot water consumption data were replaced by data from a wood-stove sensor, whose magnitude is proportional to the heat output of the wood stove. In addition to the metered energy consumption data, the inside air temperature was also recorded. Weather stations in three locations provided meteorological data. Audit data were collected on structural characteristics pre- and post-retrofit, as well as survey data on occupant attitudes and behaviors.

Between the spring of 1985 and early winter of 1986, various conservation measures were installed in the end-use metered homes. These measures were aimed at improving the thermal performance of the residential envelope and minimizing the heat loss and waste associated with the hot water usage in the homes. End-use metered data were collected for the heating

seasons before and after installation of these conservation measures. These data, along with some audit/survey data, have been used to characterize the end-use metered homes pre- and post-retrofit, omitting the period when the set of measures were installed. Space-heating requirements and shell performance characterizations were derived for all the end-use metered homes when possible.

Previous analyses by others (Hirst 1987) using billing data for all the homes that received retrofits indicate a discrepancy between the mean savings predicted per home, 6,100 kWh/yr, and the estimated mean savings achieved (2600 kWh/yr average, 3,200 kWh/yr for primarily electrically space-heated homes). These estimated savings are substantially less than the predictions which are audit-based engineering calculations based on the Standard Heat Loss Methodology used for regional weatherization programs (Bonneville 1984). Some of this discrepancy is due to the low pre-retrofit consumption, in part resulting from neglecting wood-burning displacement in the audit calculation procedure.

The work reported here uses the end-use metered data and an analysis methodology that uses only days of pure electric space heating to derive annual thermal characterizations as if only electrical space heat was used. The weather normalized mean savings per household for the combined sample of homes characterized is 2,432 kWh/yr overall and 2,899 kWh/yr for single-family homes.

6.2 METHODOLOGY

For this analysis the heating season is defined as September to May. In some cases this heating season window for data analysis is shortened to avoid the time of the retrofit installation. The thermal analysis characterizations for the end-use metered Hood River homes are based on an analysis of daily average inside temperature, daily average outside temperature, and daily electrical space-heating consumption. For homes with wood-stove sensors, days with wood use are omitted from the analysis. For those homes with wood-burning equipment and no wood stove sensor, all days are initially included in the analysis. Exclusion from further analysis occurs if moderate-to-heavy

wood use is indicated by scatter in the data for a site. An inside temperature averaged over the heating season is also computed as a measure of occupant control strategy.

For each structure, several quantities are derived from the inside/outside temperature difference and the heating data. These measures include an as-operated annualized estimated space-heat consumption (as-operated AEC), and a slope and balance temperature difference derived from a robust linear fit of daily space heat to the daily metered indoor/outdoor temperature difference. The slope of this line can be interpreted as the as-operated UA (heat loss coefficient) of the building, recognizing that heating system efficiency is implicitly included in this parameter, as defined. The AEC is derived from a nonparametric curve fit to the daily data, excluding days of wood use. Outdoor temperature data from a typical weather year is then used with the seasonal average metered indoor temperature and this curve to develop the heating season AEC. Note that only the as-operated AEC is used in this analysis (a reference-65 AEC is also used in Sections 4.0 and 5.0), and in this section is termed the AEC.

The sample selected for analysis here contains 113 homes: 82 single-family, 24 manufactured, and 7 multifamily homes. Since this report makes before and after comparisons, only those homes with characterizations for both the 1984/1985 and 1985/1986 heating seasons are selected for final inclusion in the results. Nearly 60 sites with monitored wood stoves that exhibit very heavy wood use are excluded from the results. After deletion of wood-use days for these homes, too few days are left to reliably characterize the heating load of the structure across the appropriate range of temperature differences.

In summary, the derived measures of thermal performance for the end-use metered Hood River homes are:

- not affected by intermittent use of wood-heating equipment, as these days are removed from the analysis
- corrected for weather variations from one year to the next by using a reference weather year to derive the annualized electrical space-heating estimate.

Since all wood-use days are removed before the parameter derivation, the summary numbers produced in this report are not lessened by the rather extensive use of wood in the community of Hood River. Changes in mean inside air temperature for the main living area are directly accounted for in the derived estimates. However, since no multiple temperature sensors are in place for the residences studied, no correction is made for room closures and zoning in this analysis.

6.3 RESULTS

6.3.1 Thermal Performance Characterizations

Weather data from the National Weather Service from the 1976 calendar year and the metered mean indoor air temperature over the particular heating season are used to compute the AECs for each site pre- and post-retrofit. Since no formally defined Typical Meteorological Year is available for Hood River, the 1976 to 1977 weather year, with 5,502 heating-degree days to base 65°F, was found to have the most "typical" weather when compared to outside air temperatures over the last ten years. Figure 6.1 displays the distributions of AEC in kWh/ft²-yr for the various groups of homes. The drop in estimated consumption for the single-family homes is clearly the most dramatic. The mean AECs, before and after the installation of conservation measures, are summarized in Table 6.1, across the single-family, manufactured, multifamily, and combined groups of homes.

From Table 6.1, the combined sample of homes show a 24% reduction in kWh/yr-ft² in the post retrofit heating season. Single-family dwellings demonstrate a reduction from the pre-retrofit consumption per square foot of floor area of 30%. Manufactured homes show the poorest results, with an overall difference of 11%. The small sample of multifamily units shows a change of 31%.

The mean of the total estimated space-heating requirements is also displayed by housing type in Table 6.1. The pre-retrofit mean AEC value of 10,111 kWh/yr for the combined sample drops to 7,679 kWh/yr in the post-retrofit period. This represents a change of 2,432 kWh/yr or a 24% decrease. The change in estimated total space-heating consumption for the single-

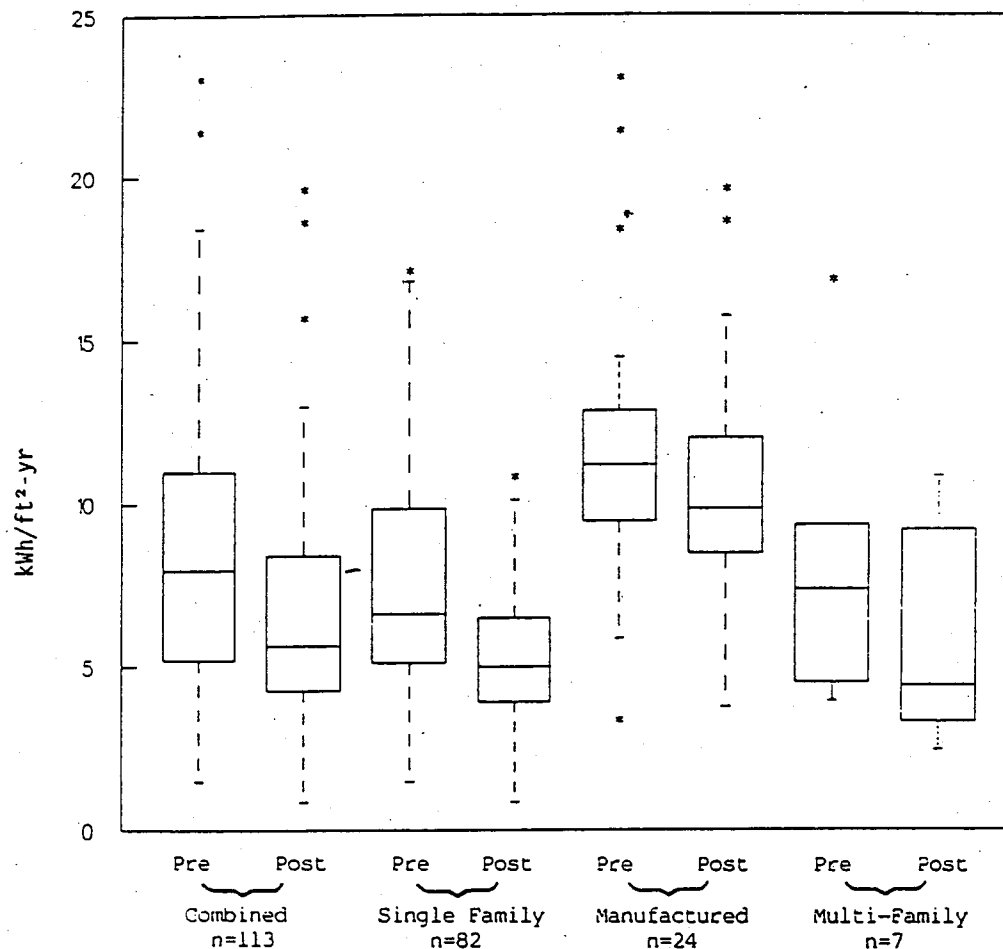


FIGURE 6.1. Annual Electric Space Heat Consumption for 113 Hood River Homes - Before and After Retrofitting

family, manufactured, and multifamily samples represent decreases of 28%, 10%, and 30% in the pre-retrofit consumption level, respectively. Note that the small difference on the savings fractions when based on total space heat as opposed to floor area normalized space heat results from the slightly uneven distribution of savings with floor area.

The slope of the robust linear fit is the as-operated heat loss coefficient for the residential envelope when converted to units of Btu/hr and multiplied by floor area. Since this coefficient can be interpreted as a measure of the resistance of the envelope to heat transport, changes in the

TABLE 6.1. Summary of Performance Statistics for 113 Hood River Homes

Measures	Combined			Single-Family			Manufactured			MultiFamily		
	Pre-	Post-	%	Pre-	Post-	%	Pre-	Post-	%	Pre-	Post-	%
AEC/ft (kWh/yr-ft)	8.46	6.41	-2.05 -24	7.56	5.32	-2.24 -30	11.66	10.38	-1.28 -11	8.12	5.64	-2.48 -30
AEC (kWh/yr)	10111	7679	-2432 -24	10315	7415	-2899 -28	10482	9491	-991 -10	6450	4550	-1900 -30
Slopes From Linear Model (kWh/day- F-ft)	2.19	1.75	-0.44 -20	1.95	1.48	-0.46 -24	3.03	2.69	-0.33 -11	2.11	1.64	-0.48 -23
UA, As-Operated (Btu/hr- F)	377	301	-76 -20	385	296	-89 -23	389	350	-39 -10	246	192	-54 -22
Balance Delta-T from Linear Model (F)	11.9	12.9	1.0 9	11.7	12.9	1.2 10	11.5	11.6	0.10.8	11.7	12.9	1.2 10
Inside Air Temperature (F)	70.9	71.1	0.3 0.4	70.8	71.1	0.3 0.4	70.5	70.5	00 70.8	71.1	0.3 0.4	
Mean Conditioned Floor Area (ft)	1293			1422			988			839		
Sample Size	113			82			24			7		

as-operated UA (and slopes) are summarized across building types for the pre- and post-retrofit heating seasons in Table 6.1. Increased thermal resistance to heat transport is indicated by a downward shift in the UA. The mean drop in as-operated UA for the manufactured homes represents a 10% change, compared to a change of 23% for single-family homes, and a 22% decrease for multifamily units. The mean combined as-operated UA for the pre- and post-retrofit are 377 and 301, respectively. This represents an average change of 20%.

The upward change in balance temperature difference also indicates improvement in thermal performance in the expected way. An increase in balance temperature difference is evidence of the shell's improved ability to support a greater temperature difference solely with internal heat gains from appliances and solar heat gains. The means for the sample distributions are summarized in Table 6.1. The single-family sample shows a shift upward in the mean of 1.2°F (an 11% change), as do the multifamily units. Corresponding to low changes in as-operated UA, the manufactured homes show a mean shift upward of only 0.1°F (a 1% change) over the mean pre-retrofit balance temperature difference.

6.3.2 Consistency of Changes in the Derived Linear Fit Parameters and AECs

The change in the insulation levels due to the Hood River retrofits provide a unique opportunity to evaluate the consistency of the parameters derived from the ELCAP thermal analysis technique. When effective heating-degree days are defined using a base temperature equal to the home's balance temperature, the space-heating consumption should approximately equal the product of the as-operated UA and the effective heating-degree days if the linear fit parameters are consistent with the AECs. Thus (by the chain rule for differentiation) the change in total energy consumption should be approximately the change in the UA multiplied by the effective heating-degree days, plus the UA multiplied by the change in effective heating-degree days caused by the change in balance temperature. This dual effect is characteristic of retrofits, because the increased insulation directly affects the UA, while the balance temperature is a function of the combined effects of the UA and the levels of internal and solar gains.

Using the sample averages in Table 6.1 as a test, Figure 6.2 shows the changes in AEC, UA, and effective heating-degree days compared across the various housing types. When the change in AEC represented by the left bar of each pair is compared to the adjacent bars that represent the sum of the changes from the lower as-operated UAs and lower effective heating degree-days, very close agreement is observed. The percentage changes for as-operated UA and balance outdoor temperatures sum to within 1 or 2% points of the percentage change in total AEC for each of the building groups displayed. Moreover, for all home samples, excluding the manufactured homes, the reduction in total kWh for space heating is about 80% from the reductions in as-operated UA and 20% from the change in the effective heating-degree days that the home experiences. For the manufactured homes approximately 91% of the reduction in space-heating requirements shows up in the as-operated UA.

This agreement indicates that the linear fit parameters and the AECs based on nonlinear fits produce results that are self-consistent. This lends

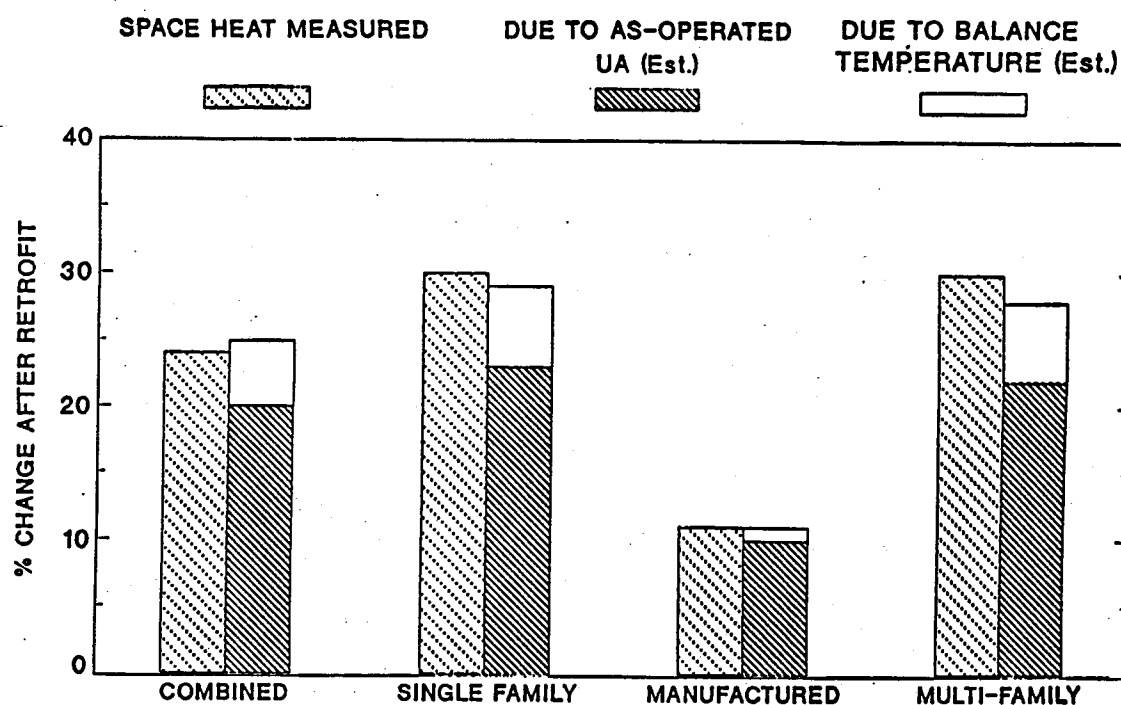


FIGURE 6.2. Space Heating Conservation Due to Changes in UA and Balance Temperature

confidence to the thermal analysis methodology used in ELCAP, and also indicates that the levels of internal and solar gain were reasonably constant across the two Hood River heating seasons analyzed.

6.3.3 Takeback Effects for Indoor Air Temperature

After a major home weatherization program, the residents of Hood River might be expected to raise their thermostat set points and take some of their expected energy savings in increased comfort in what is commonly termed a "takeback" effect. This effect is widely hypothesized to be a primary reason for widespread overestimation of savings from residential retrofits.

Inspection of indoor temperature data does not reveal conclusive evidence for temperature increases in the main living area for these homes. Figure 6.3 shows the distribution of the mean heating season temperature for

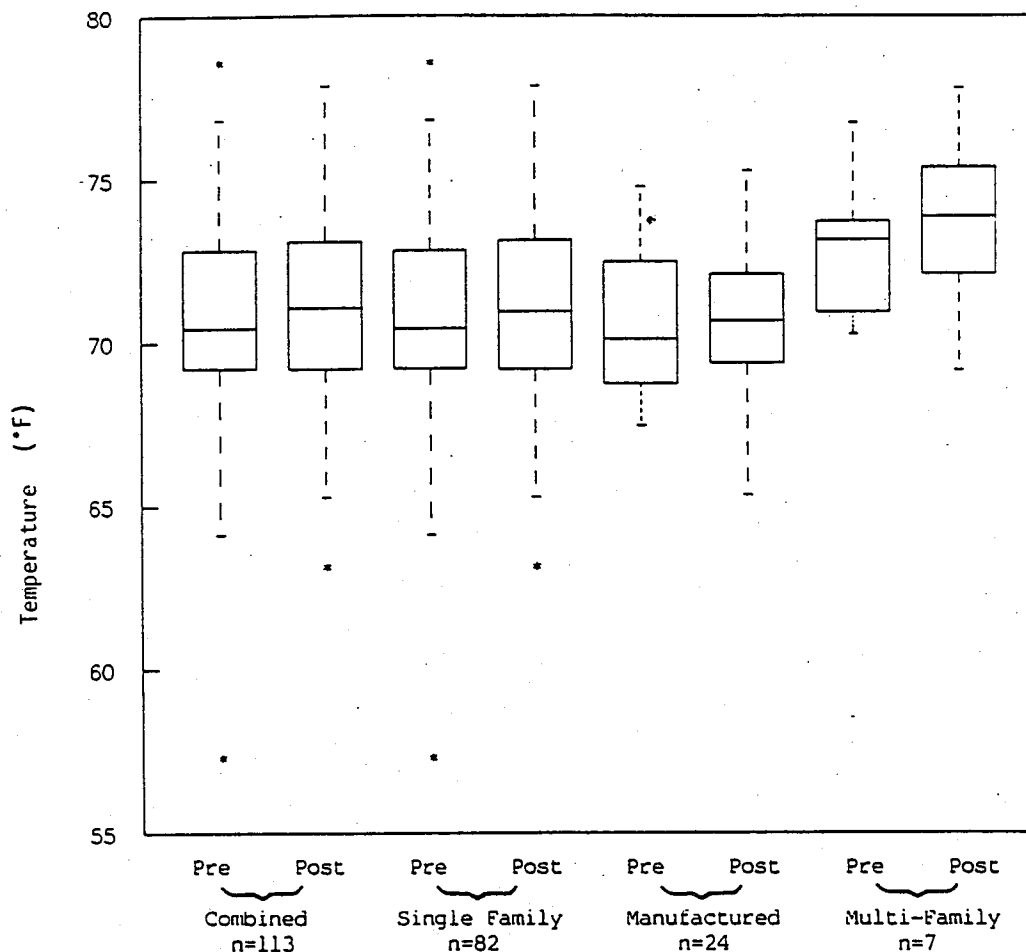


FIGURE 6.3. Mean Indoor Temperatures for 113 Hood River Homes - Before and After Retrofitting

each sample both before and after retrofit. Although there is a slight trend upward in the median, the mean change for the combined home sample is only 0.3°F. To better understand what magnitude of change in inside air temperature would be indicative of an increase in thermostat set point, several hourly thermal performance simulations have been performed.

A home is initially simulated with a UA of 385 Btu/hr-°F and then with a UA of 307 Btu/hr-°F, roughly equivalent to the observed averages in Hood River for single-family dwellings. The change in indoor air temperature was compared for three distinct thermostat control strategies, a constant 70.5°F, a single evening setback to 60°F from 70.5°F, and a double setback (morning and evening) to 60°F from 70.5°F. The resulting changes in inside air temperature vary from 0.4°F to almost 1°F, purely from higher temperatures during periods when the air temperature "floats" above the set point. The number and length of these periods increase as a result of lower UAs. The mean changes observed in the indoor air temperatures for the Hood River homes are within these limits, and so do not indicate "takeback" in the traditional sense.

6.3.4 Takeback Effects for Wood Stove Usage

About 60% of the end-use metered homes are not included in the thermal analysis results cited in Section 6.3.1. Since the analysis technique used excludes days of wood burning, there are not enough days free from the effects of wood burning available to characterize the heating requirements for these sites. (Only 14% of the homes with wood-stove sensors are included in the results stated previously. As described earlier, days with wood-stove usage for these homes are excluded before thermal characterization.)

The magnitude of the Hood River wood-stove signal is designed to be proportional to the heat output. Wood usage was analyzed for a total of 43 single-family homes with a reliable wood-stove sensor and having data for at least 90% of the November to March heating seasons of both 1984/1985 and 1985/1986. These months are selected to eliminate weatherization installation activities, to pick up the period of heaviest potential wood use, and to minimize missing data for the greatest number of sites. Additionally, little difference between the two years is noted in mean outdoor air temperature for the 5 month period.

A mean daily wood-stove signal is created by averaging each of the 15-minute records for the day. The total number of days that the wood stove is in use during the 5 month period is counted for each site. Those numbers are then averaged across sites for each heating season. The total number of days that the electric space-heating system is used is also counted for each site. These numbers are then averaged across sites (Table 6.2).

The means in Table 6.2 indicate very little change in the number of days in which the wood stove was used before and after weatherization measures were installed. There is a slight decrease (6%) in the mean total number of days that the wood stove was used. The mean number of space-heat usage days are the same. The mean wood-stove signal, however, drops by 27% in the post-retrofit period, indicating a reduction in the number of hours and/or intensity of wood use. In contrast, the mean electric space-heat load drops by only 17%. For this group of homes, it appears that a greater share of the savings was taken in reduced wood-stove usage, although a significant reduction in space heating was also observed. This can be interpreted as evidence of a "takeback" effect for wood use, with consumers willing to spend less time with the inconvenience involved in burning wood.

The analysis of indoor air temperatures, however, suggests the possibility that a similar effect involving the interaction of lower UAs with wood burning may be involved. Wood-use patterns observed in ELCAP (and reported in Section 8.0) are heavily concentrated during the morning and evening hours when most people are home and active, and are lowest at night.

Table 6.2. Wood Stove Usage Summary for 43 Single-Family Homes
(November - March, No Weather Normalization)

	<u>Wood Stove Mean Days In Use</u>	<u>Space Heat Mean Days In Use</u>	<u>Wood Stove Mean Signal</u>	<u>Mean Space Heat Load (kWh/day)</u>
Pre-retrofit	127	51	1640	25.8
Post-retrofit	120	51	1202	21.4
Change (%)	- 6	0	- 27	- 17

The lower UA from the retrofit produces an increased number of hours in the year in which no heating is required, and these also tend to occur more frequently at these times because of the higher daytime and evening outdoor air temperatures. Thus the retrofit would be expected to reduce wood consumption more than the electric space heating. If the electric heating in these homes is to be used primarily as a backup for cold nights when the fire dies down in the wood stove, then this effect is increased. In conclusion, a takeback effect for wood use is evident in the Hood River metered data. However, this may not be intentional on the part of the occupant, but rather a function of wood-use patterns. This issue will be further analyzed.6.4

6.4 APPLICATIONS

The results of this analysis of end-use metered data confirm the findings based on billing data reported by Hirst (1987), in that less than 50% of the predicted annual savings were achieved in the Hood River experiment. The magnitude and cost-effectiveness of the conservation resource in existing buildings is indicated to be much less than predicted by the engineering models as used for the prediction.

There are several basic conclusions and/or hypotheses put forward by Hirst (1987) regarding why the expected savings were not achieved. These can be summarized as:

- post-retrofit increases in thermostat setting
- disproportional, larger post-retrofit decreases in use of wood
- "typical" discrepancies between predicted and achieved savings
- reduced pre-retrofit baseline energy consumption.

Both the first and second points are commonly termed "takeback" effects. The analysis reported here suggests that there is no intentional behavior on the part of the occupants to use some of the savings for increased comfort and convenience by increasing room temperatures, the traditional definition of "takeback". The point regarding the effect of wood use, on the other hand, is supported by the analysis here. However, it is possible that at least part of the disproportionate reduction in wood burning is also unintentional on the part of the occupant. Thus the existence of "takeback" effects are either

unsupported (in indoor temperatures) or not conclusive (in the case of wood heat) by the Hood River data.

The conclusion that there are typically unrealized savings from retrofit programs is undoubtedly true. However, this observation is central to the research questions that Hood River is designed to answer, and demands further examination. This leads to a focus on the final point, that the Hood River homes had very low pre-retrofit consumption, with the implication that energy savings from retrofits can be expected to be reduced proportionately. The methodology used for the analysis end-use metered data reported here controls for wood use, and so displacement by wood use is not a candidate for the explanation. Room closures (zoning) becomes a primary candidate as an explanation of both reduced pre-retrofit consumption and lower-than-expected benefits. This is supported by the fact that average as-operated heat loss coefficients in ELCAP Base homes were found to be less than theoretical nameplate values, as summarized in Section 5.0 and reported by Miller et al. (1990).

7.0 INTERNAL TEMPERATURES

7.1 INTRODUCTION

This section summarizes a portion of the results of an analysis of internal temperature control strategy and its impact on space heating requirements (Conner and Lucas 1990). In particular, the distribution of observed internal temperatures, frequency of setback behavior, and frequency of internal zoning is discussed, based on data collected from the Residential Standards Demonstration Program (RSDP) residences metered as part of the End-Use Load and Consumer Assessment Program (ELCAP). Estimates of the impact that these factors have on annual space-heating requirements are based on simple model calculations.

In load forecasting, conservation planning, and other utility planning work, it is necessary to make assumptions regarding the strategy by which occupants operate their houses. By necessity, these assumptions tend to be simple; the empirical data needed to describe the distribution of internal temperatures across the population simply have not previously existed. The results summarized here represent a first step in assembling the data necessary to take temperature control strategy into account in utility planning.

7.2 METHODOLOGY

Residences instrumented under ELCAP usually have from one to three internal temperature sensors. Sites with three sensors were those participating in RSDP. An RSDP site has one of the temperature sensors typically located in the main living space, while a second is preferentially placed in the main bedroom. The location of the third sensor varies from site to site, but is usually in a basement or another bedroom. Most of the temperature data are collected at hourly resolutions, although for each site some initial data was collected at 5 minute resolutions. The data used in the analysis were collected within the period of August 1984 through June 1988.

7.2.1 Distribution of Internal Temperatures

The ELCAP Base Sample was chosen to represent a cross-section of single-family, detached, electrically heated residences in the Pacific Northwest. For this reason, the analysis used only the ELCAP Base Sample with one exception; the analysis of variations in temperatures within the house by room or zone. The RSDP sample was used because it had multiple temperature measurements for each home.

Depending on a number of factors, each ELCAP site has a different amount of data including when the metering was started. The required amount of data for inclusion in this study varied depending on the aggregation level in question, such as the monthly, yearly, or hourly profile. Typically, a minimum of 90% of the period is required to meet metering qualifications for the analysis. For example, the annual temperature averages for each site required a minimum of 90% of a year. Each of the graphics in this section contains the number of sites used in the caption below the figure.

There is a significant use of wood stoves for space heating in the Pacific Northwest. Sites with monitored wood stoves (LeBaron 1988) that are known to have had significant wood-stove use were left out of the analysis. The primary reason for eliminating sites using wood stoves is that the internal wood-stove temperature is not easily controlled when the wood stove is in use and, therefore, may not reflect the desires of the occupants. As wood stoves are not governed by a thermostat, they may overheat the room in which they are located. Furthermore, wood stoves rely on natural convection to distribute heat, which is not as effective as the distribution of most heating, ventilating, and air conditioning (HVAC) systems, and therefore may not be effective in heating many rooms in the house. Because of the difficulties and uniqueness of sites with wood stove use, all monitored wood stove sites that averaged more than 20 hours of usage a month on a year-round basis were removed. This decreased the sample size from 289 to 206, or a total of about 400 site-years worth of data.

7.2.2 Average Interior Temperatures and 24-Hour Profiles

Average interior temperatures are shown in Table 7.1 for annual, winter, and summer periods. Winter, or the heating season, is defined as November through March. Winter is presumed to be the range of months when most of the ELCAP-monitored homes are usually in the heating mode. Summer is defined as June through August. These averaged temperatures show a clear difference of about 3.2°C (5.8°F) between summer and winter periods.

TABLE 7.1. Average Interior Temperatures

<u>Season</u>	<u>Average</u>	<u>Standard Deviation</u>
Annual	21.4 (70.5)	1.8 (3.2)
Winter	20.2 (68.4)	2.4 (4.3)
Summer	23.4 (74.2)	1.9 (3.4)

7.2.3 Temperature Variation by Room

The temperatures from room to room in a house may vary, either by occupants choice, from internal or solar gains, or as a result of the HVAC distribution system. The occupant may intentionally maintain a temperature difference by closing ducts and doors, or by turning off baseboard heat (referred to as zoning). Internal gains caused by factors such as stoves, lighting, and people may heat rooms above the temperatures of other rooms. The same is true for solar gains through windows. Finally, the ducting system may not evenly distribute heat to all rooms, causing temperature differences.

7.2.4 Setback Detection

Through use of an automated pattern recognition and classification algorithm it is possible to detect pattern characteristics of setbacks in hourly internal temperature data. During the initial step, all hours, where temperatures were either rising or falling were identified, based on a temperature change above or below the threshold value. If the change over the period examined around each hour was greater than the threshold, then the hour was classified as changing either up or down. Temperature changes for several periods, up to eight hours around every hour, were checked. The longer

periods were needed to identify the slower, more gradual changes. The threshold values for significant temperature changes were chosen by visual inspection of results and were intended to catch meaningful temperature fluctuations. Results for all data indicate that 99% of the periods that were classified as changing had temperature changes greater than 1.7°C (3°F) and 87% had changes greater than 2.2°C (4°F).

Daily patterns at each site were classified as combinations of up, down, and/or even periods; this clearly allows for a large number of potential daily patterns. To summarize the results in a logical and simple method, each day has been split into three periods: 7 p.m. to 3 a.m. (night), 4 a.m. to 11 a.m. (morning), and 12 a.m. to 6 p.m. (afternoon). The beginning and end of the day has been defined at 7 p.m. The boundaries for the parts of the day were chosen as times of day when the least setback or setup activity occurred. In other words, the day was divided to place times with high thermostat activity (e.g., evening setbacks) squarely within one of the three defined periods.

7.3 RESULTS

7.3.1 Internal Temperature Distributions

Figure 7.1 displays the monthly temperature distributions for ELCAP Base sites. The middle line of each box represents the median, and the top and bottom of each box represents the upper and lower quartiles. The median temperatures start at 20.3°C (68.5°F) in January, increase steadily to a peak in August, and drop off sharply in September and October. Ranges for the monthly temperatures from the upper to lower quartile, or the middle 50% of sites, are about 2°C to 3°C (3.6°F to 5.4°F). The range of the extreme high and low average temperatures by site vary significantly, about 10°C to 20°C (18°F to 36°F). This figure demonstrates the variation present in real data; in this case, a wide range of actual temperatures across sites. Note that in a sample of 148 residences, as displayed in Figure 7.1, there is a high likelihood that some of the outlying points may be caused by vacancies (with no or little heating or cooling) during the months.

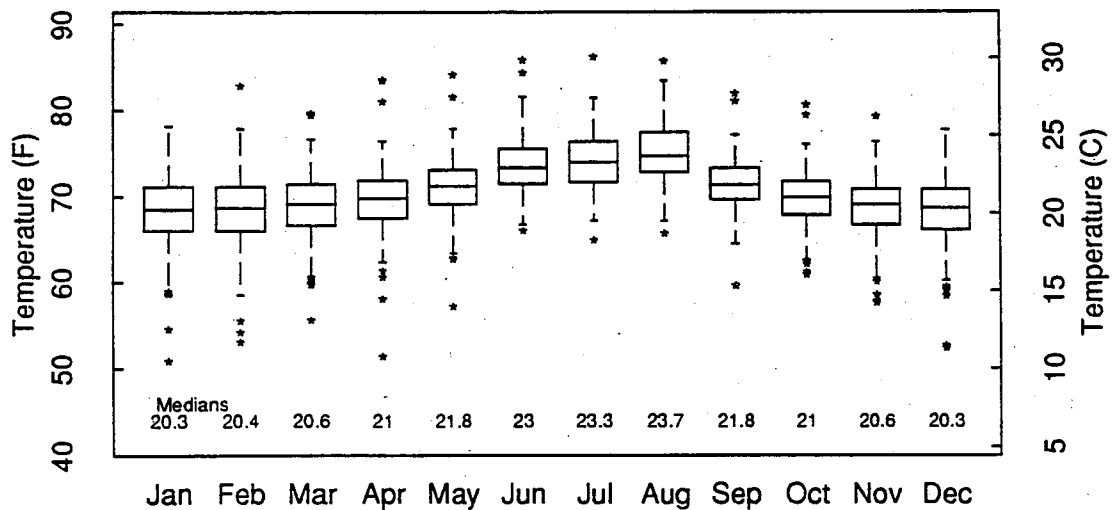


FIGURE 7.1 Monthly Temperature Distributions of 148 ELCAP Sites

Histograms of average winter and summer temperatures by site are displayed in Figures 7.2 and 7.3. The height of each bar represents the number of sites having average temperatures in the range specified on the horizontal line. In Figure 7.2 most winter average temperatures fall in the range of 18°C to 23°C (64.4°F to 73.4°F). As seen in Figure 7.3, summer temperatures are typically in the range of 21°C to 26°C (70°F to 78.8°F). These figures indicate that for both heating and cooling, the common range of

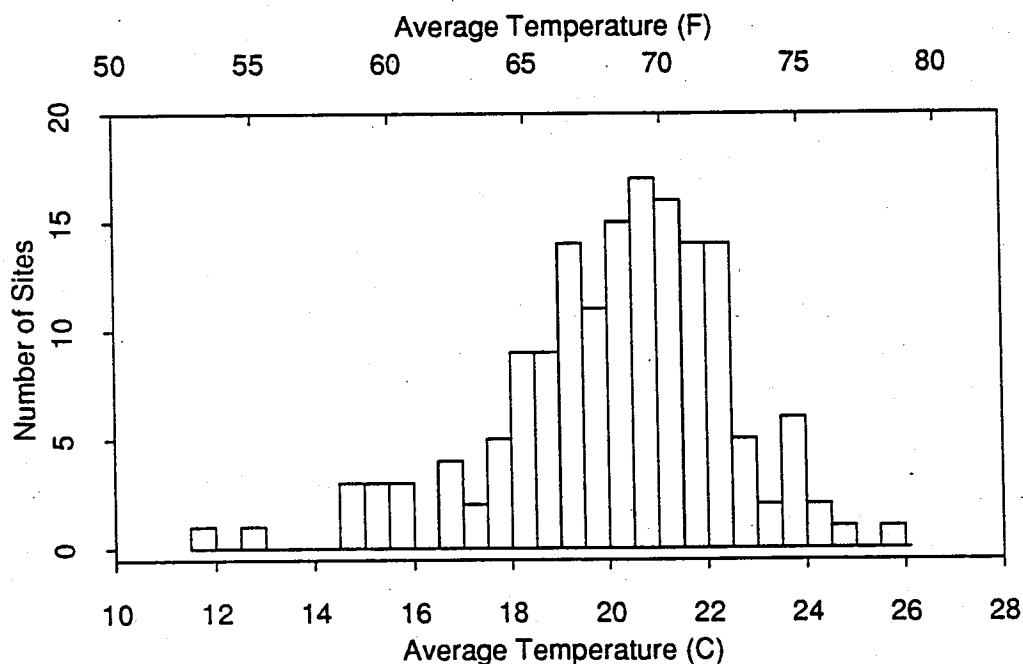


FIGURE 7.2. Average Winter Temperatures (November through March)

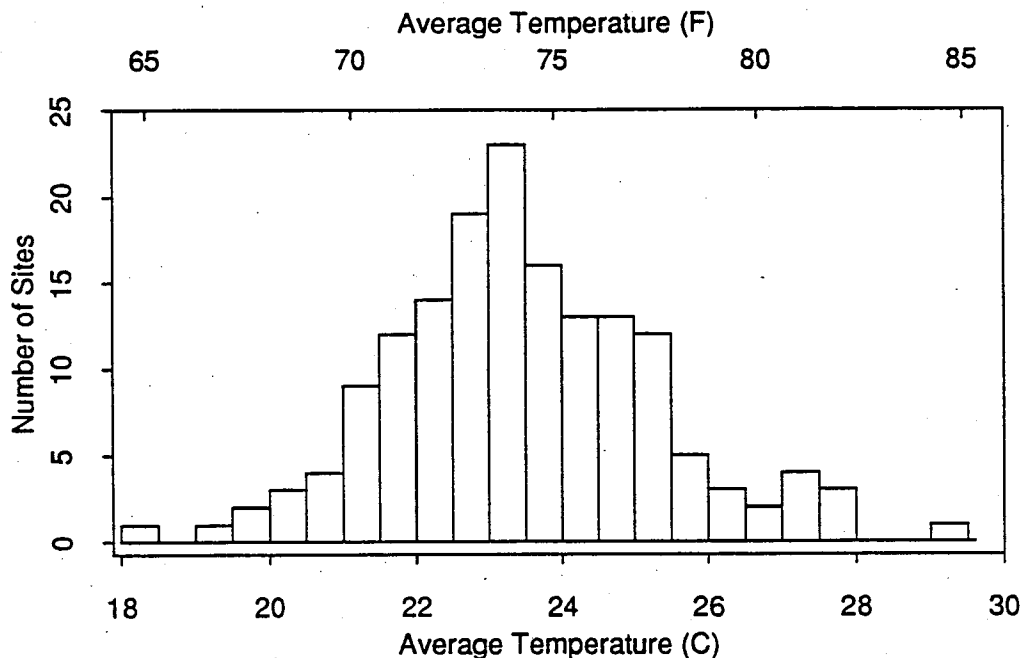


FIGURE 7.3. Average Summer Temperatures (June through August)

average temperatures across sites appears to be about 5°C (9°F), though some sites fall beyond this range.

Figure 7.4 displays the average daily profiles for four months of the year along with the yearly average profile. January, April, July, and October, represent the four seasons. Temperatures for other months will fall between the extremes seen here. January is coldest with the two swing months,

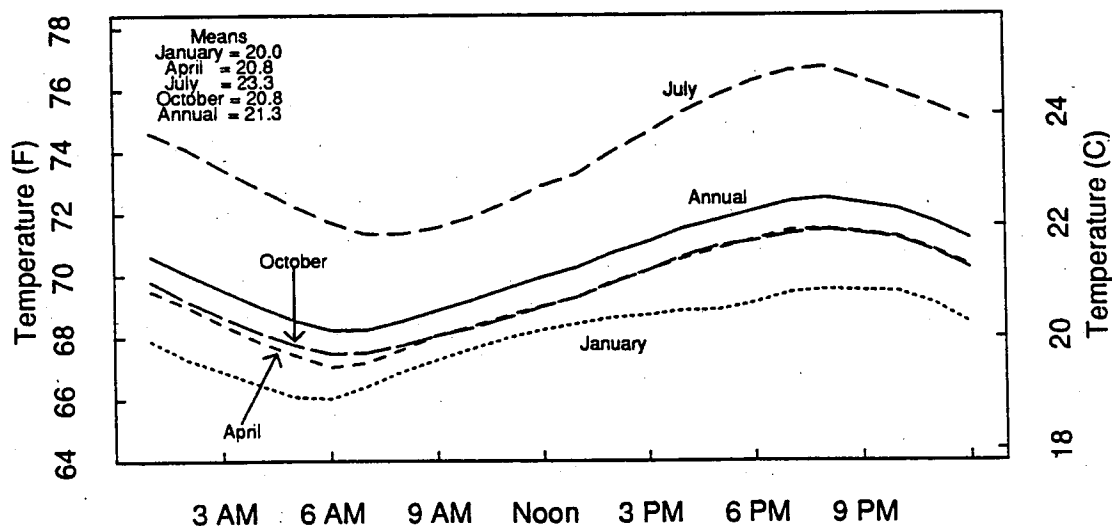


FIGURE 7.4. Selected Monthly Temperature Profiles (n = 142)

April and October very similar in temperature, and July far warmer than the other months. The maximum daily temperature occurs at 8 p.m. for all months.

The minimum daily temperature is at 6 a.m. for all months except July, which has a low at 7 a.m. To allow the calculation of temperatures for any daily time period, the temperature data in Figure 7.4 for the annual, January, and July periods are reproduced in Table 7.2.

TABLE 7.2. Seasonal Temperature Profiles

Hour of Day	Average Temperature in °C (°F)		
	Annual	January	July
1 a.m.	21.5 (70.6)	19.9 (67.9)	23.7 (74.6)
2 a.m.	21.1 (70.1)	19.6 (67.3)	23.4 (74.1)
3 a.m.	20.8 (69.5)	19.4 (66.9)	23.0 (73.5)
4 a.m.	20.6 (69.0)	19.2 (66.5)	22.7 (72.9)
5 a.m.	20.3 (68.6)	18.9 (66.1)	22.4 (72.3)
6 a.m.	20.1 (68.2)	18.9 (66.0)	22.1 (71.7)
7 a.m.	20.1 (68.2)	19.1 (66.4)	21.9 (71.3)
8 a.m.	20.3 (68.5)	19.4 (66.9)	21.9 (71.4)
9 a.m.	20.5 (68.9)	19.6 (67.3)	22.0 (71.6)
10 a.m.	20.7 (69.2)	19.8 (67.6)	22.2 (71.9)
11 a.m.	20.9 (69.6)	20.0 (68.0)	22.4 (72.4)
Noon	21.1 (70.0)	20.1 (68.2)	22.7 (72.9)
1 p.m.	21.3 (70.3)	20.2 (68.4)	22.9 (73.3)
2 p.m.	21.5 (70.7)	20.4 (68.6)	23.3 (74.0)
3 p.m.	21.7 (71.1)	20.4 (68.7)	23.7 (74.6)
4 p.m.	22.0 (71.5)	20.5 (68.9)	24.0 (75.3)
5 p.m.	22.1 (71.8)	20.5 (68.9)	24.3 (75.8)
6 p.m.	22.3 (72.1)	20.6 (69.1)	24.6 (76.3)
7 p.m.	22.4 (72.4)	20.8 (69.4)	24.8 (76.6)
8 p.m.	22.5 (72.5)	20.9 (69.6)	24.9 (76.7)
9 p.m.	22.4 (72.3)	20.8 (69.5)	24.6 (76.3)
10 p.m.	22.3 (72.1)	20.8 (69.5)	24.4 (75.9)
11 p.m.	22.1 (71.7)	20.6 (69.1)	24.2 (75.5)
Midnight	21.8 (71.2)	20.2 (68.4)	23.9 (75.0)

7.3.2 Zoning

Data for this zoning analysis were taken from the RSDP study, which include control homes built to current practice, and Model Conservation Standard (MCS) homes built to high conservation levels. Only the RSDP homes were monitored with multiple temperature sensors, which allows the study of zoning. A box plot containing the distribution of winter temperatures for living spaces^(a), bedrooms, and basements is illustrated in Figure 7.5. There is a statistically significant difference in temperatures between each of the three room types. Comparison of individual rooms in the living spaces did not produce statistically significant differences. Each site used on this plot has a monitored temperature for the living spaces and bedroom zones. About one-half of the sites have baseboard heat, one-quarter use central forced air and one-eighth have heat pumps. The RSDP data indicates the possible use of zoning, with bedrooms and basements being maintained at lower temperatures. Inspection of nighttime data shows the temperature difference between bedrooms

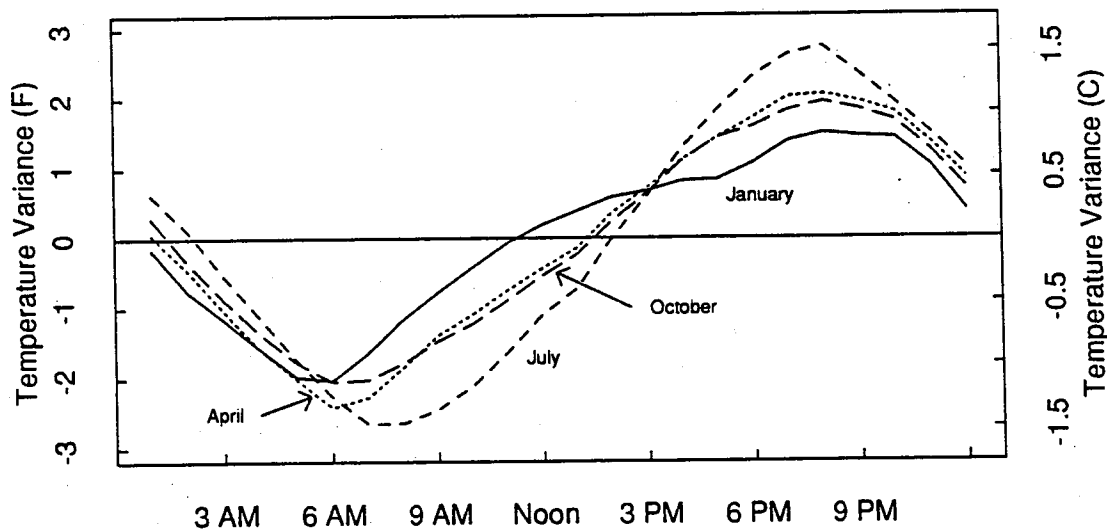


FIGURE 7.5. Selected Monthly Temperature Profiles (n = 144)

- (a) Living spaces is defined as the combination of living rooms, dining rooms, hallways, family rooms, and general living areas.

and main living space decreases (i.e., the temperature reduction from day to night is less for bedrooms than it is for the living space.) This indicates that temperature control varies both by zone and by time-of-day within zones.

7.3.3 Setback Detection

To classify behavior, the timing of thermostat changes must be inferred from the temperature data. The time at which temperature changes start are of particular interest as these indicate thermostat setting changes. The setup start is defined as the beginning of a temperature rise period. The setback start is defined in a likewise manner. In reality, these temperature-change starts may not become apparent until sufficient time has passed since the occupant has changed the thermostat temperature. This is particularly true for temperature setbacks.

The start of both setbacks and setups were identified by time-of-day across all sites. Figure 7.6 displays the frequency with which setbacks have started during each hour of the day for all sites combined. Each bar represents

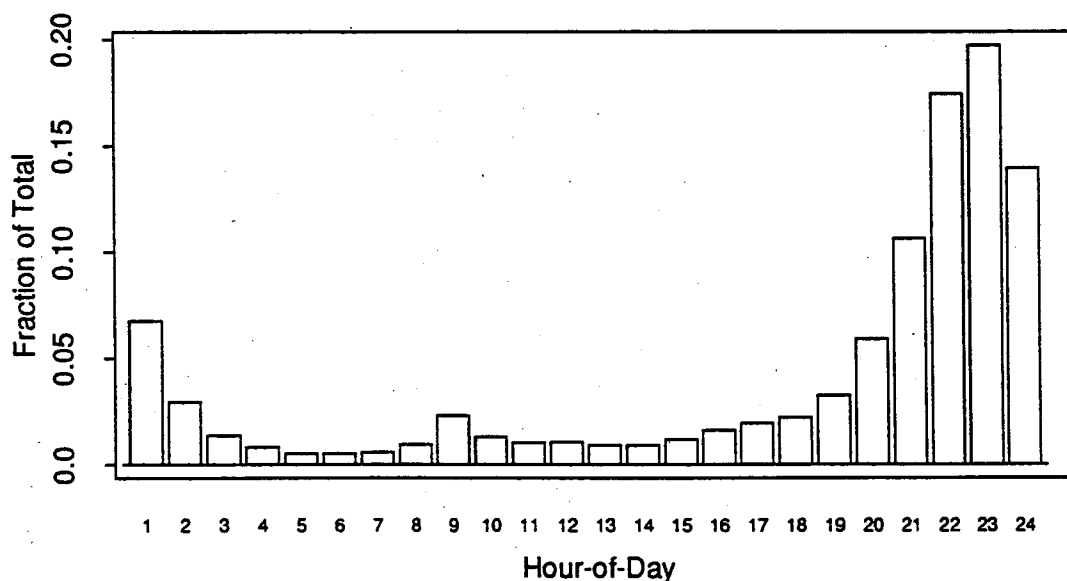


FIGURE 7.6. Setback Starts (n = 145)

the fraction of setbacks that start during that hour relative to all hours combined. Note that the temperature for each hour is the average of the preceding 60 minutes; for example, 1 a.m. is the average temperature from midnight to 1 a.m. Setbacks may not become evident immediately after the thermostat is lowered; the hour identified as the setback start could actually be the hour after the thermostat changes. The large majority of the setback starts are between 7 p.m. and 1 a.m., peaking in the 10 p.m. to 11 p.m. hour. The actual time when thermostat setbacks peak is estimated to be 10 p.m., this accounts for the delay between the time when the setback is made and when the temperature change becomes apparent. This is also likely to be the time when occupants are going to bed. There is a small peak in setbacks between 8 a.m. and 9 a.m. in the mornings. This is probably because of setbacks occurring as occupants leave for work at around 8 a.m.

Figure 7.7 displays the starting hour for setups across all sites. Each bar represents the fraction of setups that begin during that hour relative to all hours combined. The starts of the setups are much more bimodal than the

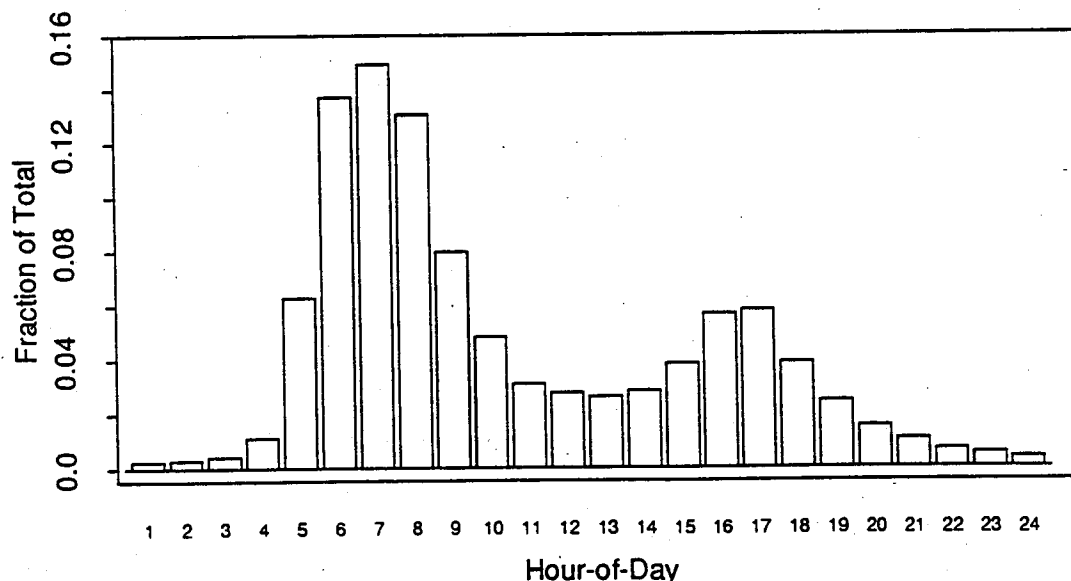


FIGURE 7.7. Setup Starts (n = 145)

starts of the setbacks. The greatest number of setup starts occur in the morning, peaking between 6 a.m. and 7 a.m.. These can primarily be attributed to setups in response to nighttime setbacks. A second group of setups occur in the late afternoon, peaking between 4 p.m. and 5 p.m., or the time many occupants will be returning from work. Many of these afternoon setups can be coupled directly to nighttime setbacks with the occupants forgoing raising the thermostat in the morning.

Figure 7.8 displays the fraction of all combined setbacks and setups that start during each hour. The combined totals give justification to the choices of using 3 a.m., 12 a.m., and 7 p.m. for dividing the day into three parts (night, morning, and afternoon). These are clearly the periods of lowest thermostat activity.

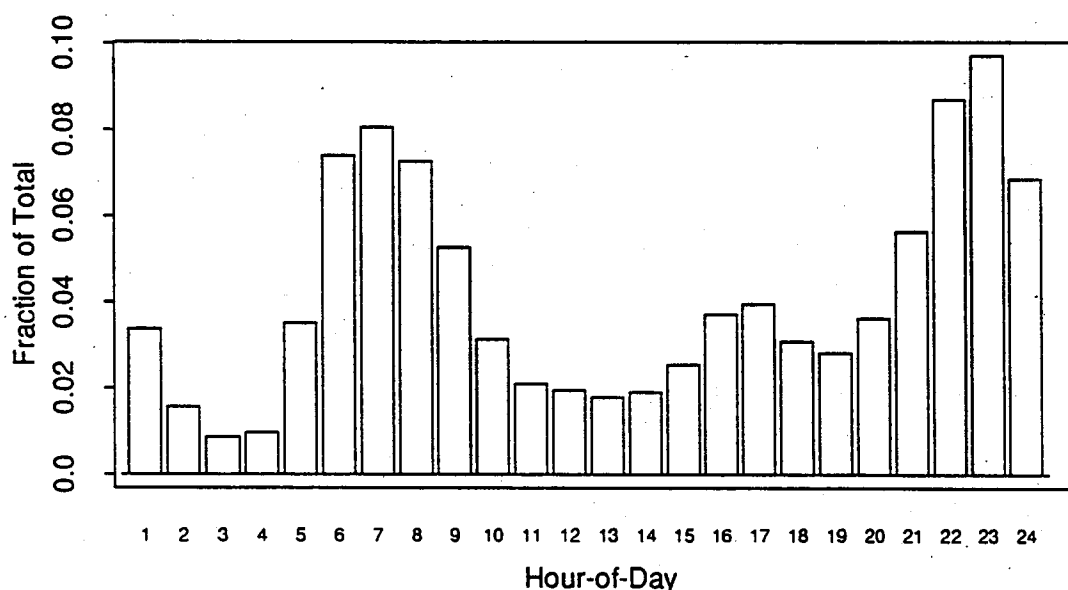


FIGURE 7.8. Combined Setback and Setup Starts (n = 145)

The ELCAP temperature data also can be used to understand the strategy of the participants in setting their thermostat. For example, no change in the setting or various combinations of setback and setup according to time of day. Detailed information on the frequency of occurrence by combination, magnitude of the temperature change, and thermostat control by daytype and thermostat type can be found in the more detailed analysis report by Lucas and Conner (1990).

7.4 APPLICATIONS

In load forecasting, conservation planning, and other utility planning work, it is necessary to make assumptions regarding the strategy by which occupants operate their houses. The average indoor temperature for ELCAP sites in the winter is 69.4°F. This is significantly higher than the assumptions in the Northwest Power Plan (Northwest Power Planning Council 1986), typically 65°F. Simulation analysis shows that the estimated impact of this differential on annual space heating loads ranges from an increase of around 35% in Seattle to 20% in Great Falls, if the entire floor space of the homes was kept at this temperature.

However, this study clearly shows that differences between the living areas of homes and the bedrooms are about 4°F in the median. This indicates extensive zoning behavior that reduces space heating loads considerably. The impact of zoning can range from estimated reductions of as much as 45% of annual heating load in Seattle to 28% in colder climates such as Great Falls, more than offsetting the effects of higher-than-expected living area temperatures.

The prevalence of this zoning behavior in the RSDP Sample suggests that similar behavior exists in the Base Sample. The effect of zoning is magnified in the less well insulated homes of the Base Sample, because the effect of the interior partition wall in reducing heat loss from the zoned areas is proportionally greater in homes that are less well insulated. Thus zoning is confirmed as a widespread effect of sufficient magnitude to account for the observed differential in the performance of ELCAP metered homes above theoretical expectations discussed in Miller and Pratt (1990).

These observations, although based on a preliminary study with a limited sample, strongly indicate that key indoor temperature assumptions that are central to forecasting and conservation programs may need adjustment. The data suggest that the lower room temperature assumptions used in utility planning are attempting to compensate for two competing effects: higher thermostat settings in main living areas and reduced temperatures elsewhere because of zoning. Together, these effects can produce a response to outdoor temperature that is nonlinear with insulation levels and internal gain levels, possibly producing part of the observed discrepancy between theory and practice in savings estimated for Hood River. Models of space heating used by forecasting and conservation programs could potentially be developed to take these effects into account, and hence improve their accuracy. The results summarized here represent a first step in assembling the data necessary to take temperature control strategy into account in simulation exercises used as part of the utility planning process.

8.0 WOOD STOVE USAGE PATTERNS

8.1 INTRODUCTION

This section summarizes the analysis of wood-stove use for 2 years of data collected as part of ELCAP as reported in LeBaron (1988). The particular goals of this study were to assess the frequency of wood burning in homes equipped with wood stoves by defining daily, seasonal, and yearly patterns. Residential wood energy use in the United States has increased significantly since the mid-1970s, following the surge in conventional heating costs (Applied Management Sciences 1982). It has been estimated that approximately 20 million households burn wood, and of these, about 30% use wood as their primary heating source (Skog and Watterson 1983).

The Pacific Northwest is no exception to this trend. Regional surveys report that as high as 62% of homes have wood-burning equipment (Del Green Associates 1982; Lane Regional Air Pollution Authority 1984). Most of these homes apparently make use of this heating source. For example, the Oregon Department of Energy's Residential Energy Conservation Survey (Oregon Department of Environmental Quality 1985) estimated that 58% of Oregon's households burned some wood. However, the number of homes which burn wood as a primary heating source is only about 21% (Tonn and White 1986; ECO Northwest 1984).

For the ELCAP Residential Base Sample, 21% of the residences reported they heated primarily with wood (Figure 8.1). Forty-three percent had wood stoves or fireplaces with inserts, and an additional 28% had standard fireplaces. These percentages were obtained from the ELCAP residential onsite inspections.

While it may be unclear whether wood heating is continuing to enjoy popularity in light of recent energy price declines, one thing is certain; the hardware for wood heating remains widespread throughout the Northwest population. This capability for wood heating is reflected in findings that residential space heating in the Northwest is rapidly becoming an electric/wood market (Tonn and White 1986), and alludes to the potential for large swings in the residential demand for electricity because of fuel switching.

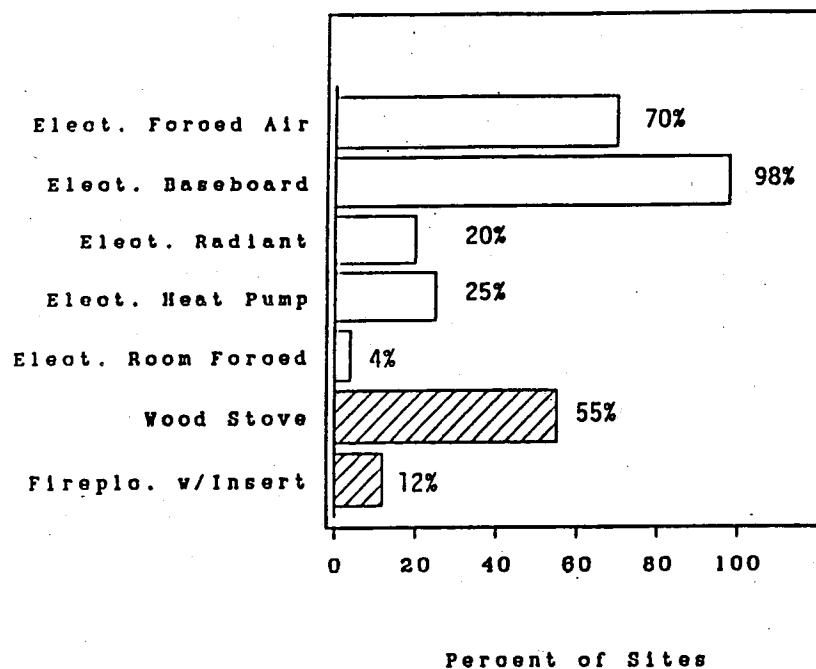


FIGURE 8.1. Distribution of Primary Heating Devices in ELCAP Residential Base Study Sites

Thus, an understanding of the current usage patterns of wood heating is essential for predicting the effects of fuel switching.

In the ELCAP study, end-use monitoring by a microprocessor-controlled data logger (Tomich and Schuster 1985) allows precise knowledge of the electrical consumption over short intervals of time. The same equipment is also used to track the duration and frequency of use for wood-burning devices. Analysis of the data set for a large number of houses having wood heating equipment provided new insights into the role wood heating plays in residential building energy. First, a short description of the sample and measurement technique will be given, and then the significant results will be discussed.

8.2 METHODOLOGY

The analysis encompasses a database of 109 sites taken from the 197 ELCAP Residential Base sites having wood-burning capabilities. These sites were carefully selected from 145 equipped with wood-burning sensors to be those providing reliable data for a reasonable fraction of the study period.

Table 8.1 indicates the distribution of the sites among the climate zones defined by the Northwest Power Planning Council.

Each site has one sensor monitoring a wood-burning device. It was assumed that at sites having more than one wood heating device (i.e., a wood stove and a fireplace) the sensor monitors the major wood heat source. For the sample, 90 sites had the capability for major wood heating (wood stoves, fireplaces with inserts or heat exchangers, and wood furnaces) and five sites were capable of minor wood heating (fireplaces). The type of wood-burning device is not known for the remaining 14 sites; however, the relative distribution is expected to be the same. In this report, references to wood stove usage include the few monitored fireplaces in the sample.

Frequency of wood stove use was examined for the period August 1, 1985, through May 31, 1987. Not all sites have data for the entire period. Statistics on the usage across the time period are based on data from the 109 sites having at least 60% of the possible data (Figure 8.2). This restriction reduces the chance of biasing the results to a particular portion of the year.

The sensor used to monitor the wood stove is intended to be an indicator of wood combustion and consists of a thermocouple with a floating temperature reference junction. One junction of the thermocouple was positioned inside the chimney approximately 3 ft from the top, and the other junction was formed outside the chimney where the thermocouple was attached to the logger leads. Therefore, the output of the sensor is directly related to the outside air temperature and the temperature in the chimney.

TABLE 8.1. The Number of Wood Stove Study Sites Located in Each Climate Zone

<u>Climate Zone</u>	<u>Study Sample</u>
1	55
2	40
3	<u>14</u>
Total	109

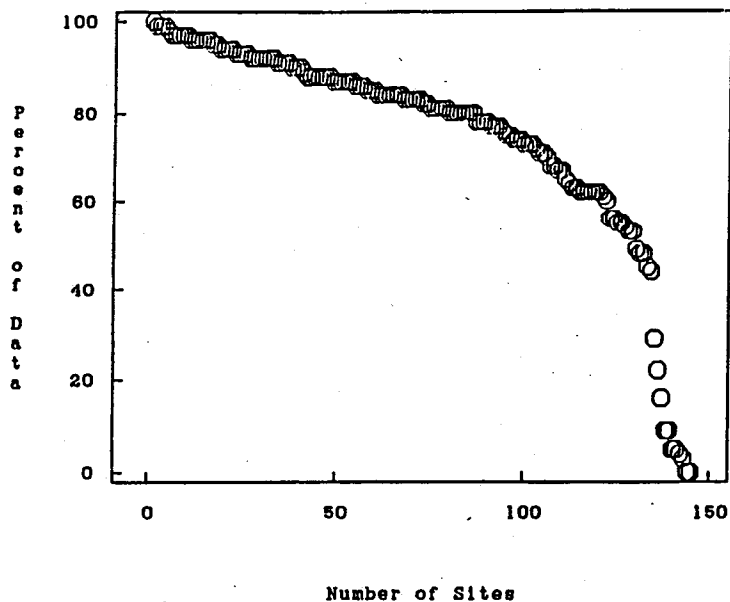


FIGURE 8.2. Percentage of Possible Hourly Data Available for All Wood Sensor Sites

This floating junction results in a small background variation in the sensor signal because of diurnal and seasonal outdoor temperature changes. By carefully choosing a threshold value above the background variation, it is possible to distinguish between hours when the wood stove is in use and hours when it is not in use. For each site examined, a threshold was chosen and the hours partitioned into wood use and nonwood use hours. A value of one was assigned to each wood use hour and a value of zero was assigned to each nonwood use hour. For additional information on the sensor and threshold determination see LeBaron (1988).

8.3 RESULTS

8.3.1 Daily Usage Patterns

This section deals with the characterization of daily usage patterns for the sample of ELCAP wood stove homes, disaggregated by weekday, weekend, and month. Percent-on-time profiles by hour calculated for each of the individual sites, with each day for which data is available weighted equally, serve

as the basic data. A stove is considered to be "on" for the full hour it appears to be supplying significant heat to the residence, even though it may be cooling.

Figure 8.3 shows the average weekday and weekend profiles for the sample. Diurnal patterns are evident in both profiles, with maximums at 8:00 to 10:00 A.M. and at 9:00 to 11:00 P.M. Roughly speaking, the data are reminiscent of typical load shapes for electric space heating, except that the relative magnitude of the morning and evening peaks is reversed. That is, wood usage appears to be more intense in the evening than in the morning. Comparison of the weekday and weekend profiles suggests that, just as is regularly observed in electrical space heating profiles, the weekend schedule is shifted towards later hours with less morning use and more afternoon use.

Mean hourly profiles disaggregated by month are shown in Figure 8.4. In general, all profiles exhibit a diurnal pattern similar to that noted previously. The strongest variation in the diurnal pattern is seen in the spring and fall months, reflecting the tendency of the home owners to burn intermittently during these seasons. Notice also, that the mean percentage of wood use for all hours of the day appears to be directly correlated to the severity of the month.

In Figure 8.5 the mean number of hours of wood-burning per day are plotted against the daily outdoor temperature for each day for the period April 1, 1986 through March 31, 1987. It can be seen that the average behavior of the sample is characterized by a relatively predictable number of hours of wood-burning as a function of outdoor temperature. The wood use versus temperature curve for the regional sample is "S" shaped, with a cutoff temperature of about 60°F above which little or no wood-burning is indicated. It also exhibits a "rolloff" that begins at outdoor temperatures of about 30°F, below which usage increases more slowly to a maximum average of 14 hours per day. Between these limits, the average wood use for the sample increases by about 2 hours for every 10°F drop in outdoor temperature.

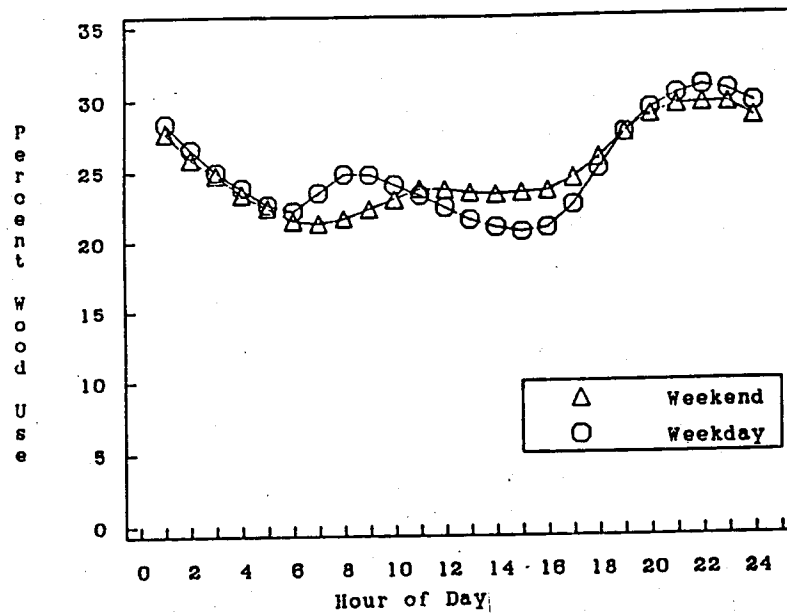


FIGURE 8.3. Weekday and Weekend Diurnal Patterns in Frequency of Wood Stove Use

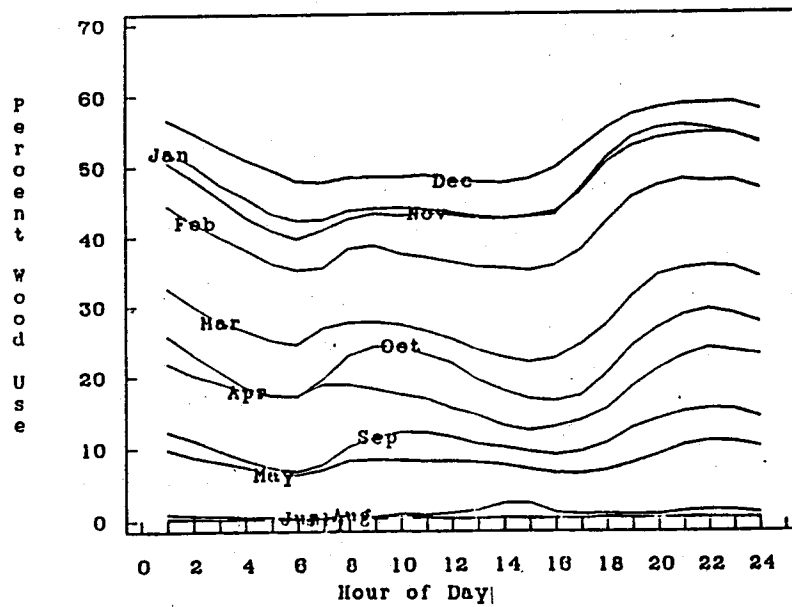


FIGURE 8.4. Monthly Variation in the Mean Diurnal Pattern of Wood Use

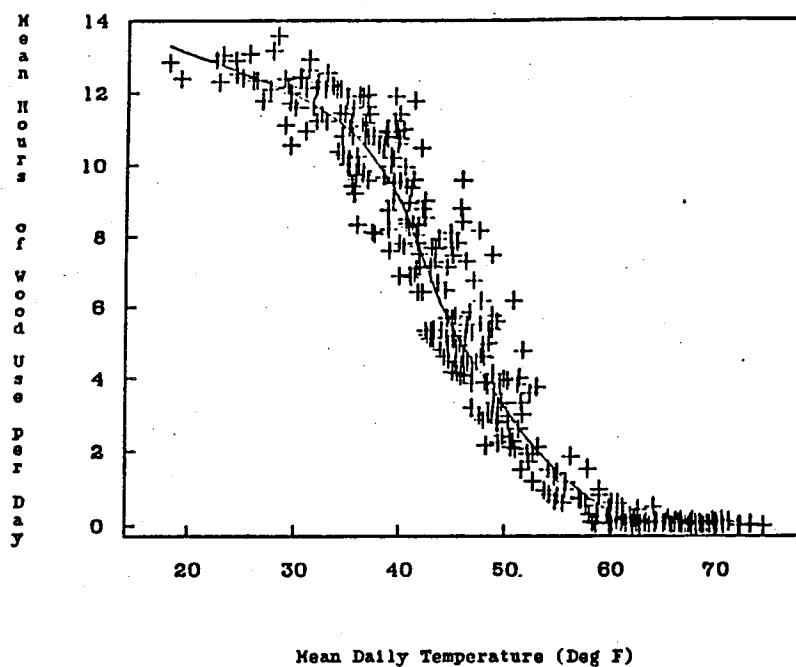


FIGURE 8.5. Daily Mean Hours of Wood Use Versus Mean Outdoor Air Temperature

8.3.2 Monthly Usage Patterns

This section addresses the variation of frequency of wood-stove use with season. To develop the results reported here, the number of hours of wood use are calculated by site for each month between August 1, 1985, and March 31, 1987. The hours of use are divided by the number of hours of available data to determine percent frequency of use. The resulting ratios are averaged for common months to form twelve monthly values. This classification permits examination of seasonal usage patterns, but does not retain information about quantity of use.

Figure 8.6 summarizes these results for the entire 12 months in the form of a histogram that can be used to characterize the frequency of wood use for the sample in general. The sample includes sites at which the wood-burning equipment was used almost 80% of the time and sites at which it was

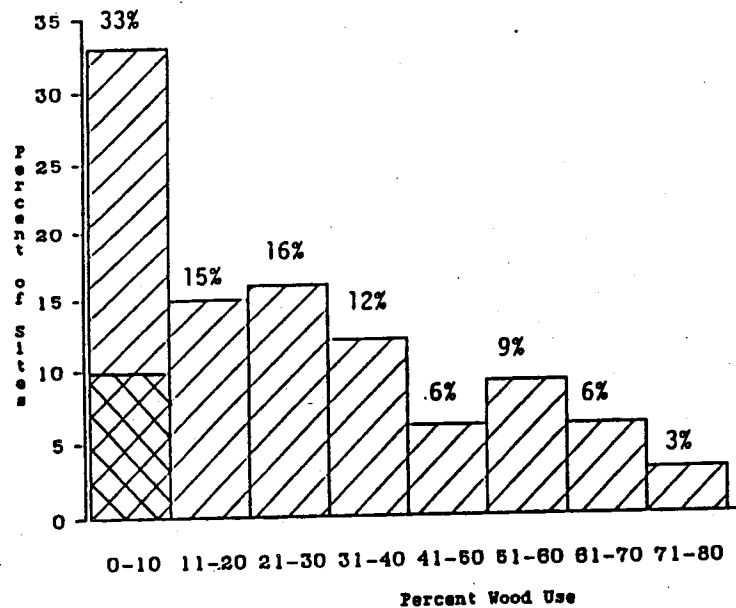


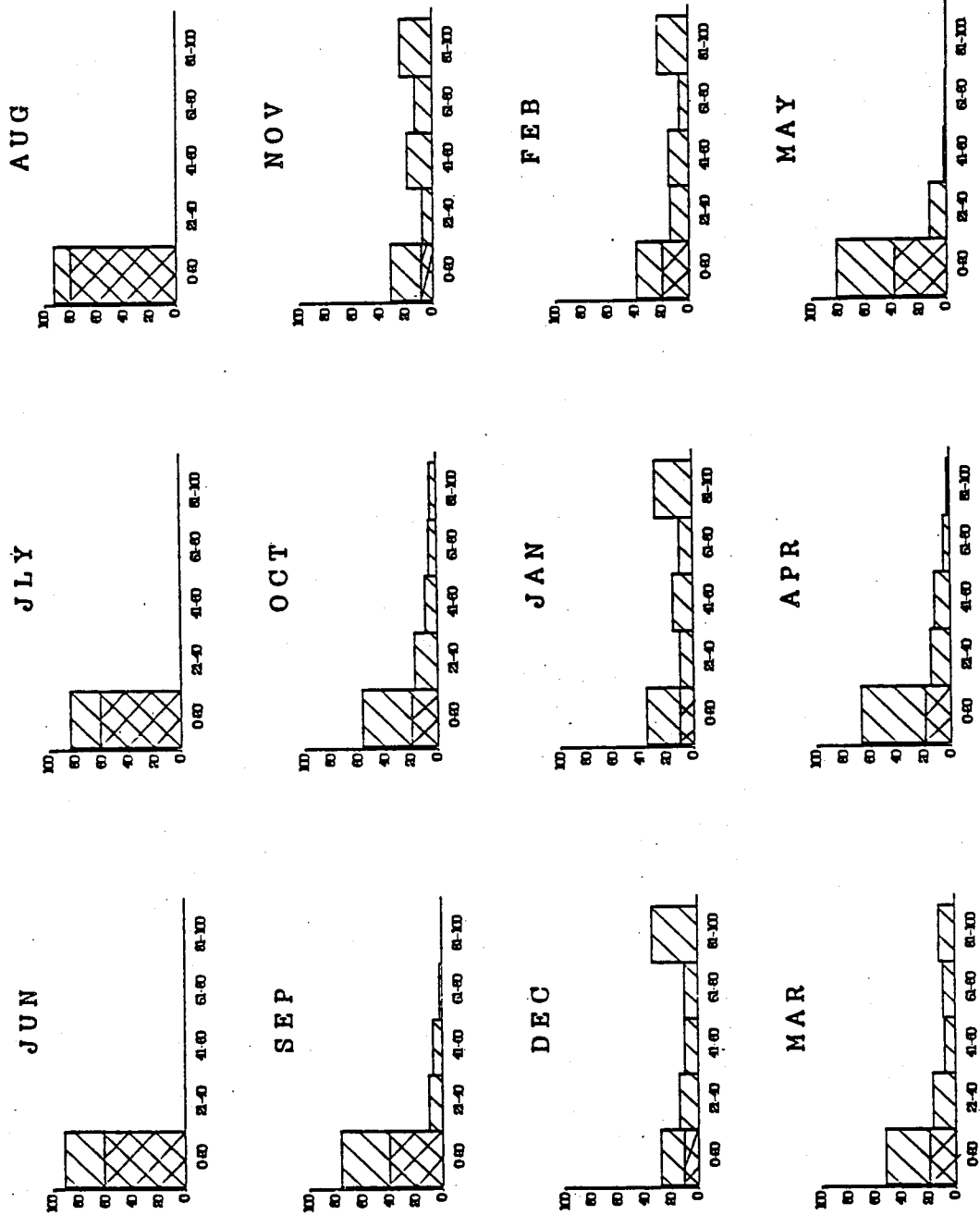
FIGURE 8.6. Distribution of Frequency of Wood Use for 109 Wood Burning Sites

not used at all. As judged by frequency of use, the bulk of the sites appear to burn wood regularly, with 57 out of 109 burning wood at least 20% of the year. However, 11 sites (denoted by cross hatching) never burned wood.

The variation of frequency of use with season can be seen in Figure 8.7, in which the distribution of sites as a function of percent of daily wood use is shown for each month. The data show very low use in the summer months, a steady increase from infrequent to frequent use during the fall, and a decrease back from intensive to rare use during the spring months. It is interesting to note that during the winter months, 30% of the sites burned wood more than 80% of the time; however a small number of sites (the 10% denoted by cross hatching) never burn wood.

The monthly distribution of wood use in the coldest months (November through February) in Figure 8.7 indicates that there is a bimodal distribution of wood-burning behavior in the region, with a majority of the homes burning wood either less than 20% or more than 80% of the days. These can be termed "recreational" and "serious" wood burners, respectively. This bimodal behavior is indicative of the potential for large and sudden shifts in wood

FIGURE 8.7 Monthly Distributions of Wood Use Frequency



usage, should the motivating factors for either of these two groups change. It is interesting to note that nearly 10% of the homes did not burn wood at all during these winter months.

A different view of these data is provided in Figure 8.8, where the mean percent of wood usage days is plotted by month. The pattern shows a steady decrease in wood usage from January through August, followed by an increase. The rate of change in frequency of wood use is large at the beginning and end of the heating season, but was slow during the coldest months. It is possible that the relatively high use in November was associated with the early arrival of cold weather in much of the region during 1985.

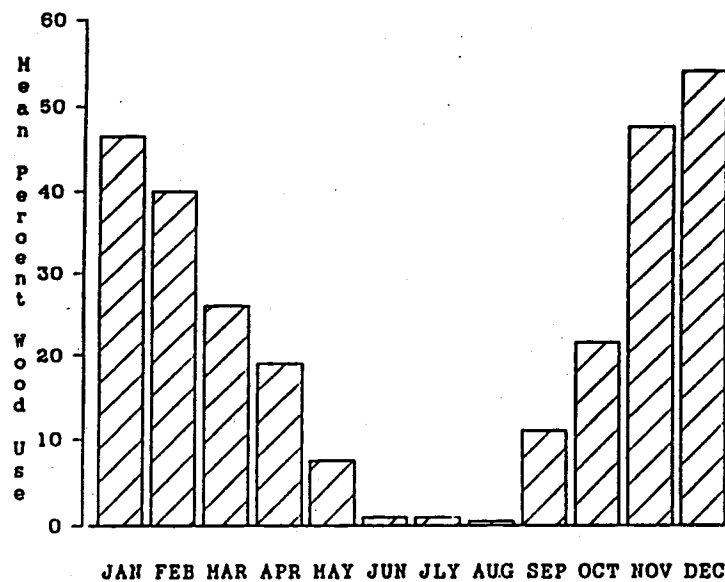


FIGURE 8.8. Mean Percent Wood Use by Month

8.3.3 Trends

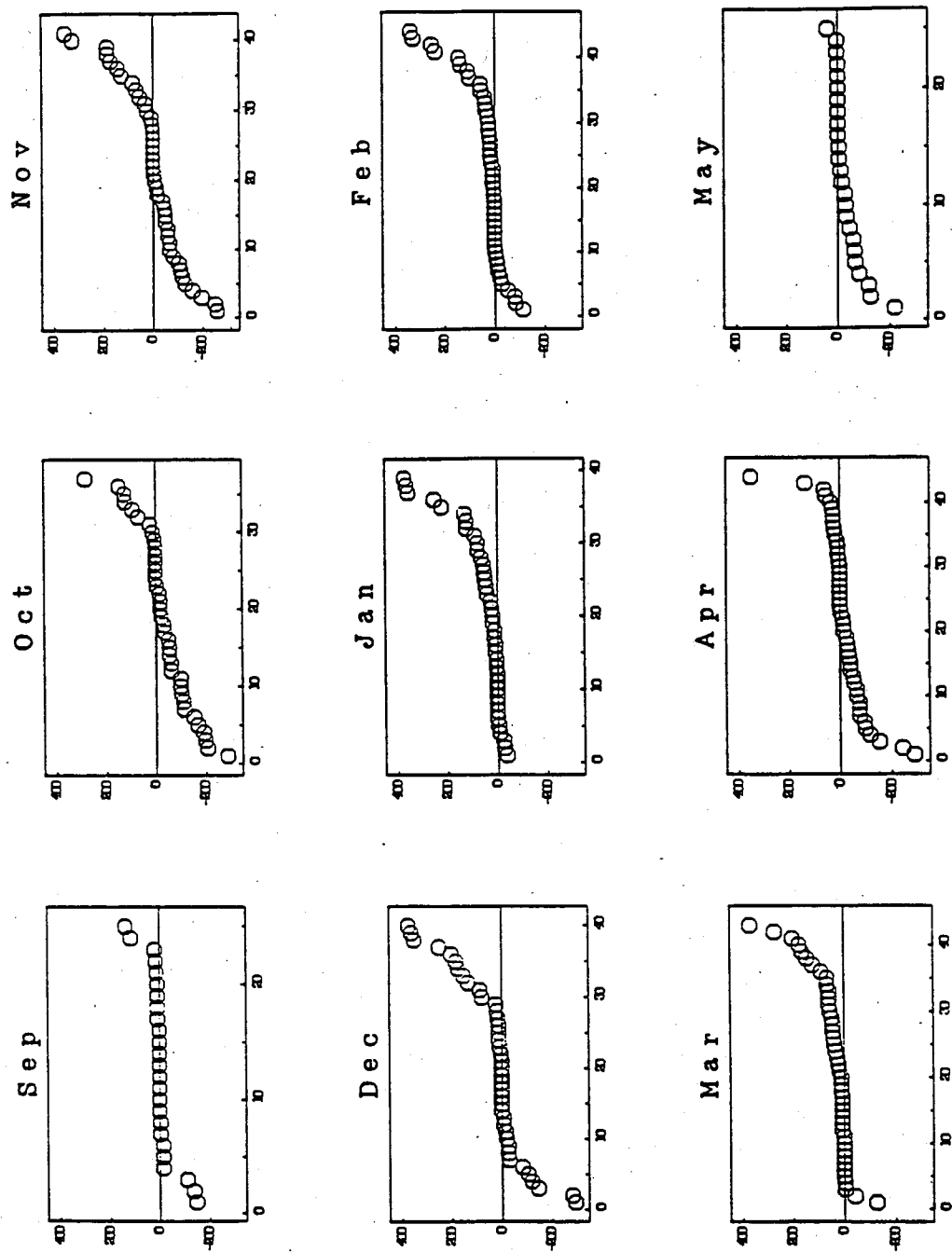
This section examines the stability of the monthly usage patterns from year to year. Only the months September through May are compared since very little space heating occurs in the rest of the year. In this examination it was necessary to further restrict the sample to the 46 sites that had more than 60% of the hourly data available, and the same occupants for the comparison periods. In addition, the few sites having only minor wood-burning capabilities are excluded.

Figure 8.9 shows the intra site variation in wood stove use for individual heating months. The variation for a particular site is plotted as the monthly deviation of the wood use for the 1986/1987 heating season from that in the 1985/1986 heating season. Each point represents the deviation for one site for that particular month. The results show significant variation from year to year for individual households, even with the same occupants. The plots also imply that there was more wood use in December through January of 1986/1987 than there was for the corresponding months in 1985/1986.

A comparison of wood usage across the 46 sites for the two heating seasons is provided in Figure 8.10, and here the difference between the two years is more obvious. In December through January of 1986/1987, wood use was higher than for the same months in the prior heating season. This is in spite of the fact that the monthly average outdoor temperatures were similar, if not warmer, for the same period (Figure 8.11). Although these comparisons are based on only 2 years of data the trend suggests increased wood use.

This study of wood usage patterns is concluded by noting that there appears to be a dependence in the frequency of wood use on climate zone. Figure 8.12 shows the frequency of use distributions for the sample partitions of the Northwest Power Planning Council's climate zones. Climate Zone 1 is the mildest, and includes the bulk of single-family homes in the region, while Climate Zone 3 is the most severe. The median frequency of wood use increases in colder climates. This figure suggests a dependence of wood use based on

FIGURE 8.9. Monthly Deviation by Site of Percent Wood Use Between the 1985/1986 Heating Season and the 1986/1987 Heating Season



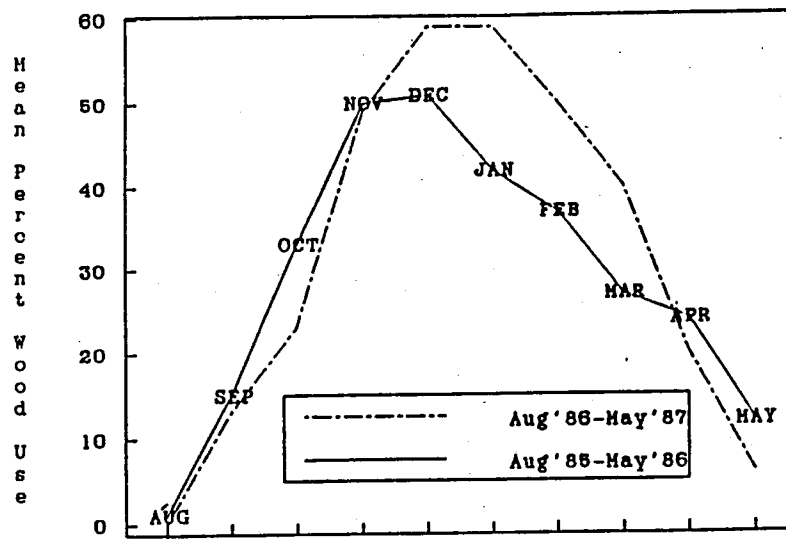


FIGURE 8.10. Mean Monthly Wood Use for the 1985/1986 and 1986/1987 Heating Seasons

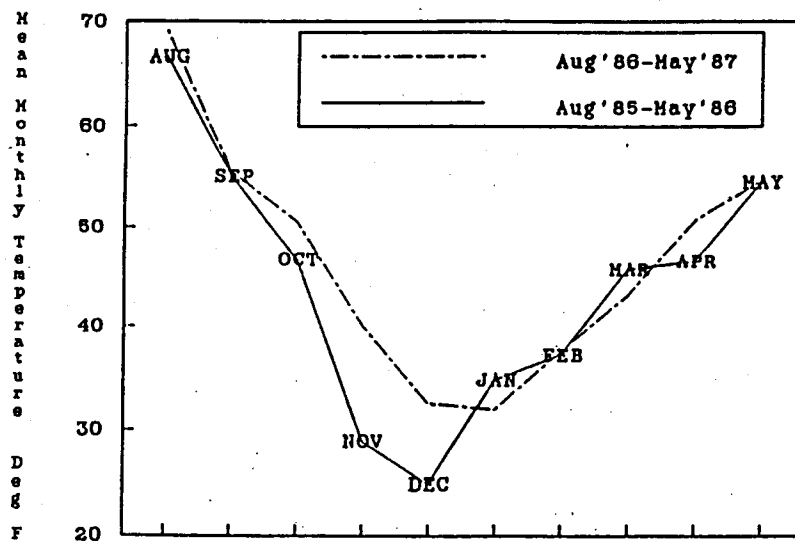


FIGURE 8.11. Mean Monthly Outdoor Temperature for the 1985/1986 and 1986/1987 Heating Seasons

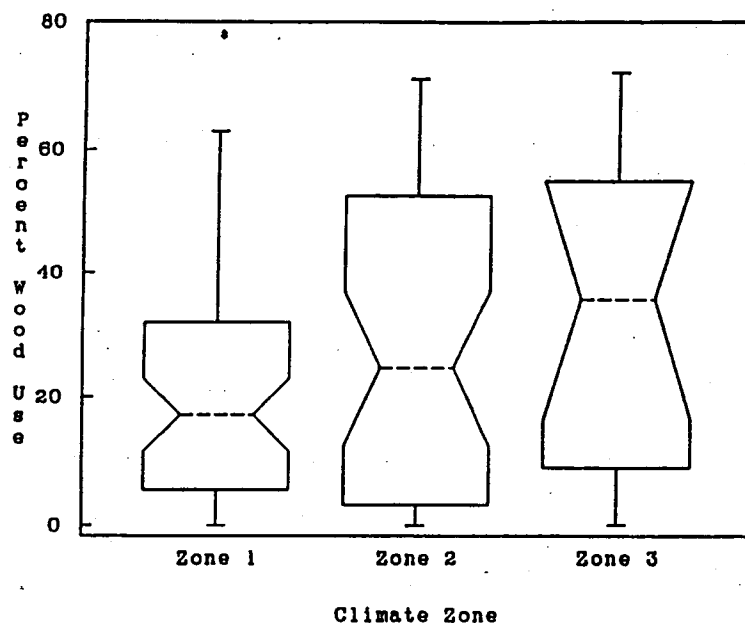


FIGURE 8.12. Distributions of Frequency of Wood Use for Sites Climate Zone

geographic location, however the actual factors responsible for this dependence are unclear. For example, the availability of wood or local burning restrictions may be as important in determining the frequency of wood use as the climatic conditions.

8.4 APPLICATIONS

The results of the investigation permit several observations about the usage of wood stoves in the ELCAP Residential Base Sample. Frequency of wood use increases dramatically in the colder months and on the colder days within given months. Thus, electrical displacement by wood heating increases as the demand for space heating increases, and is greatest on days which tend to have the highest system loads. This has important implications for peak load forecasts, in that wood-burning behavior is heavily concentrated during times of day and year when peak loads occur. It also tends to increase the load factor (ratio of peak to average load) for wood-burning sites above that which would be anticipated if wood-burning occurred uniformly in the heating season. Heating load factors are a little higher for the sites on wood-

burning days than on non wood burning days, however, indicating that there is still a net reduction in monthly load factors compared to non wood heated buildings.

The average behavior of the sample as a whole is characterized by a relatively predictable number of hours of wood use as a function of outdoor temperature. For the years examined, the correlation exhibits an "S"-shaped relationship with an increase of about 2 hours per day for every 10°F drop in the outdoor temperature (between the inflection points). This predictable behavior suggests the possibility of incorporating such behavior into hourly demand forecasts, and in the analysis of billing data when comparing actual loads to regional load forecasts.

On an annual basis, the population of wood users is strongly bimodal, with large groups either burning wood almost every day or quite rarely. Wood can be informally classified as either "recreational" or "serious," with the bulk of the electrical displacement by wood heating resulting from the latter. This bimodal behavior is indicative of the potential for large and sudden shifts in wood usage should the motivating factors for either of these two groups change.

Analysis of the data from the two heating seasons suggests, in fact, that wood use is increasing in the region, despite the fact that outdoor temperatures were the same or warmer in the second season. This suggests a pattern of increasing wood use even in a period of relatively low electrical rates. Future ELCAP data will be used to monitor this trend.

9.0 AIR-TO-AIR HEAT EXCHANGER PERFORMANCE

9.1 INTRODUCTION

As weatherization programs and new construction standards tighten homes, proper ventilation becomes a concern to ensure good indoor air quality. In very tight homes, mechanical ventilation is often used to introduce fresh air to the living space to maintain air exchange rates at levels believed to occur in standard construction. An air-to-air heat exchanger (AAHX) is typically used in combination with mechanical ventilation to recover some of the heat which would otherwise be lost with the exhausting air. Air-to-air heat exchangers are designed to conserve energy in mechanically ventilated homes by transferring the heat from warm stale exhaust air to the incoming cool fresh air. This minimizes the energy required to heat the incoming air used to maintain indoor air quality at an acceptable level. A number of companies have been manufacturing these devices for several years.

This section describes an evaluation of performance data taken from 38 AAHX installations which were part of Bonneville Power Administration's Residential Standards Demonstration Program (RSDP). When the RSDP was implemented during 1983 through 1986, approximately 500 new homes were built to thermal performance standards as dictated by the Model Conservation Standards (MCS). To meet these standards and maintain air quality, many of the homes included AAHXs. Seventy-one RSDP homes were monitored as part of the End-Use Load and Consumer Assessment Program (Parker and Foley 1985). Of these, 38 included AAHXs that were monitored to allow for analysis of both use patterns and thermal performance. These homes provided the largest sample of installed AAHXs ever tested. The primary goal of this analysis is to characterize AAHX operation, to determine the thermal performance of AAHX installations, and to estimate the energy savings attributable to an AAHX. The entire analysis is reported in Drost (1990).

It is important to recognize that AAHXs are not themselves energy-conserving devices; rather they allow very airtight construction practices to be applied that resist natural infiltration and the associated heat loss. The AAHX actually consumes energy to operate its fans, and the space heating load increases during operation because the AAHX does not recover 100% of the

load increases during operation because the AAHX does not recover 100% of the heat potential of the outgoing air. Energy savings associated with the use of AAHXs are a direct result of reducing infiltration through the building envelope to extremely low levels, and providing controlled amounts of pre-heated fresh air to maintain air quality. The energy savings from the heat recovery in the AAHX are in comparison to heat losses from natural or mechanical ventilation that provide an equal quantity of fresh air.

9.2 METHODOLOGY

Air-to-air heat exchangers, typically designed to operate continuously, are often turned off by the homeowner because of undesirable drafts and noise problems. Utilization or "on time" was determined for each of the homes by taking the ratio of actual AAHX energy consumption to the maximum AAHX energy consumption (assuming continuous operation).

Thermal performance was determined by selecting time periods with high utilization (implying nearly continuous AAHX operation). For these time periods, both thermal efficiency and displaced space heating energy were calculated. The thermal efficiency used in this study is occasionally referred to as a "First Law Efficiency" because it only includes the effects of heat transfer between air streams and does not include the air stream temperature rise caused by viscous dissipation of fan work. It is the most meaningful figure of merit for the device.

The calculation of the displaced space heating energy consumption depends on knowing air flow rates through the AAHX. The air flow rates used in this study are based on one-time measurements of air flow. To the extent that these values do not represent actual air flow, errors will be introduced to the calculation of displaced space heating energy.

When condensation occurs in the exhaust of an AAHX, additional heat transfer occurs which improves the performance of the device. These latent heat effects were estimated by determining when the saturation pressure exceeded the vapor pressure and then calculating the energy transferred to the incoming air by conducting an energy balance on the AAHX.

9.3 RESULTS

The best overall characterization of AAHX operation is mean annual utilization over an entire heating season. Table 9.1 presents the mean utilization by climate zone. Figure 9.1A shows these data for each of the 38 homes where the mean annual utilization is plotted in order from lowest to highest. It is obvious that there is wide variation in mean AAHX utilization from a low of zero to a high of 23. Typical daily utilization also varied widely as shown in Figure 9.2 for one home. No seasonal patterns in utilization were observed. Hourly utilization data showed no dominant use patterns.

The mean thermal efficiency for all sites was 52% with a large variation in the results. Figure 9.1B shows the efficiency for each home corresponding to the utilization in Figure 9.1A. A review of hourly thermal efficiency arranged sequentially did not show a widespread impact of filter cleaning on thermal efficiency. Very few of the AAHXs had significant periods of condensation. In general, latent heat effects did not influence AAHX performance.

Low utilization of the AAHX resulted in corresponding low annual estimates for displaced space heating energy consumption compared to mechanical ventilation operated in a similar fashion. Figure 9.1C shows the calculated displaced space heat for each home. The overall mean is 743 kWh/yr while the annual energy consumption of the AAHX was 220 kWh/yr, for a net savings of 523 kWh/yr.

TABLE 9.1. Mean Utilization of Air-To-Air Heat Exchangers

	Mean Utilization (hours of operation per day)		
	<u>Climate Zone 1</u>	<u>Climate Zone 2</u>	<u>Climate Zone 3</u>
Mean	5.4	8.4	9.1
Median	3.1	5.4	7.8
Standard deviation	6.5	7.9	3.9
Number in sample	20	12	6

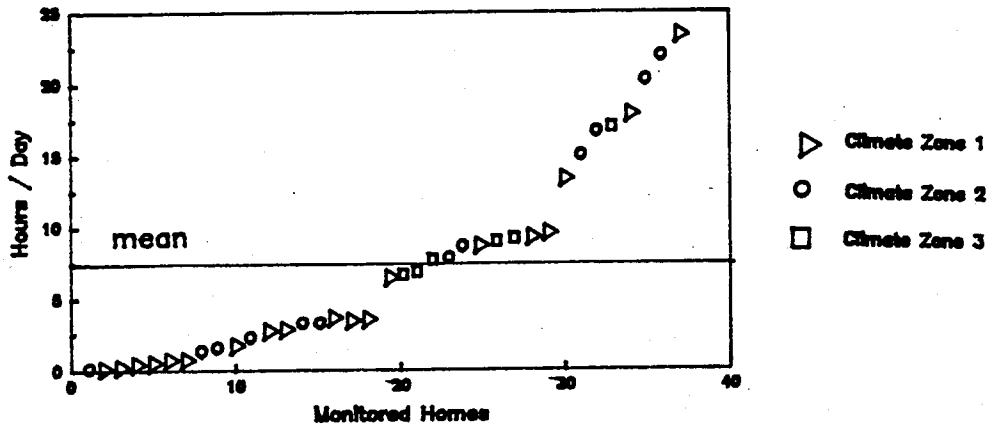


FIGURE 9.1A. Mean Utilization

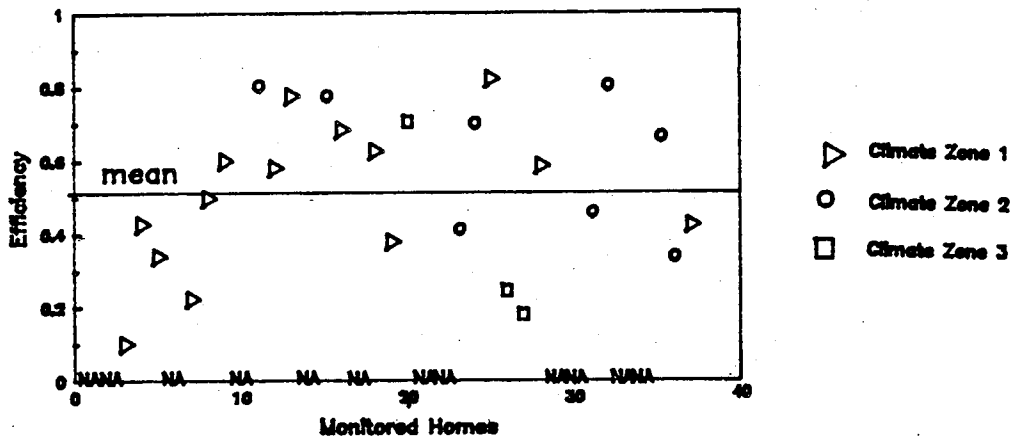


FIGURE 9.1B. Mean First Law Efficiency

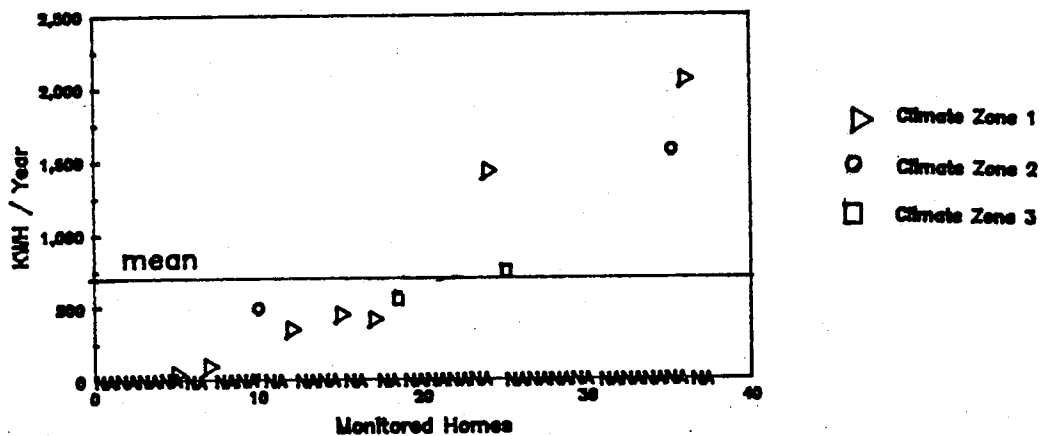


FIGURE 9.1C. Annual Space Heating Energy Savings

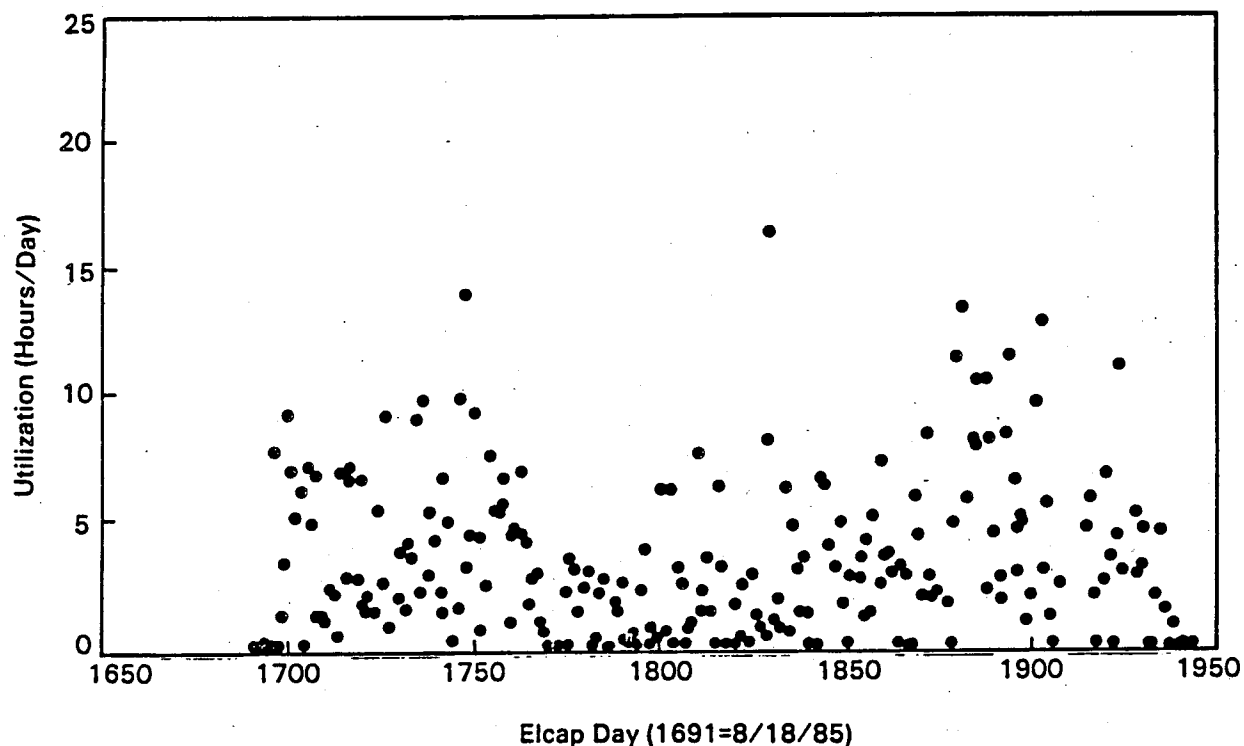


FIGURE 9.2. Daily Air-To-Air Heat Exchanger Utilization During the Heating Season for a Typical Site

9.4 APPLICATIONS

The results of this study will assist conservation planners in determining both the cost-effectiveness of AAHXs and their impact on energy use in homes. The low mean annual utilization for the 38 homes monitored indicates that AAHXs as typically installed and used provide neither the energy savings compared to mechanical ventilation or the maintenance of acceptable air quality for which they were designed.

10.0 SETBACKS AND PEAK LOADS IN COMMERCIAL BUILDINGS

10.1 INTRODUCTION

It is commonly suggested that some strategies employed to reduce energy consumption can also have adverse impacts on peak demand. Thermostat setback during night hours in buildings is an energy conservation strategy which has both consumption and demand impacts. One of the most striking observations from early examination of the End-Use Load and Consumer Assessment Program (ELCAP) commercial building data is the clear difference in load shape between buildings with and without setbacks. Among the office and retail building samples, these preliminary observations indicate that roughly half the buildings use a setback strategy.

While the Pacific Northwest region as a whole is limited by its energy resources rather than its capacity to meet peak loads, certain power generating utilities that are Bonneville Power Administration customers are capacity constrained. Additionally, power distribution facilities may be similarly constrained in certain areas and circumstances. As a result, an exploratory analysis was conducted to develop and test a simple methodology to estimate the impacts of setback strategies on both peak loads and energy consumption in the heating season.

The analysis indicates that while setback strategies result in an average January heating energy savings of about 27%, the hourly peak loads for the buildings increase on the average by about 35% for the same period. While the testing results are based on metered end-use data from only 12 ELCAP commercial buildings, the remarkable consistency of the two classes of heating, ventilation, and air conditioning (HVAC) load shapes during the heating season suggests that the results provide at least a qualitative comparison of the two thermostat strategies. The methodology and results of this analysis are reported in the following sections.

There is an important distinction between instantaneous peak loads, 15-minute peak loads commonly used for demand billing charges, and hourly peak

loads. Hourly peak loads are a relevant unit of analysis for a utility, since the temporal coincidence of morning warmup loads across a regional building population is on the order of an hour or more. On the other hand, the instantaneous peak loads are probably not normally impacted by setback strategies, since these are driven by the capacity of the HVAC equipment. The capacity may be oversized for steady-state loads if setbacks were planned at the time the building was designed; however, oversizing is common design practice to provide for a margin of error. For the same reason, 15-minute peak loads may be similar for both setback and non-setback strategies if the equipment run-cycle is roughly of that duration. By nature of the hourly integration period for the vast majority of the ELCAP data, the resulting peak load impacts estimated here are also on an hourly basis.

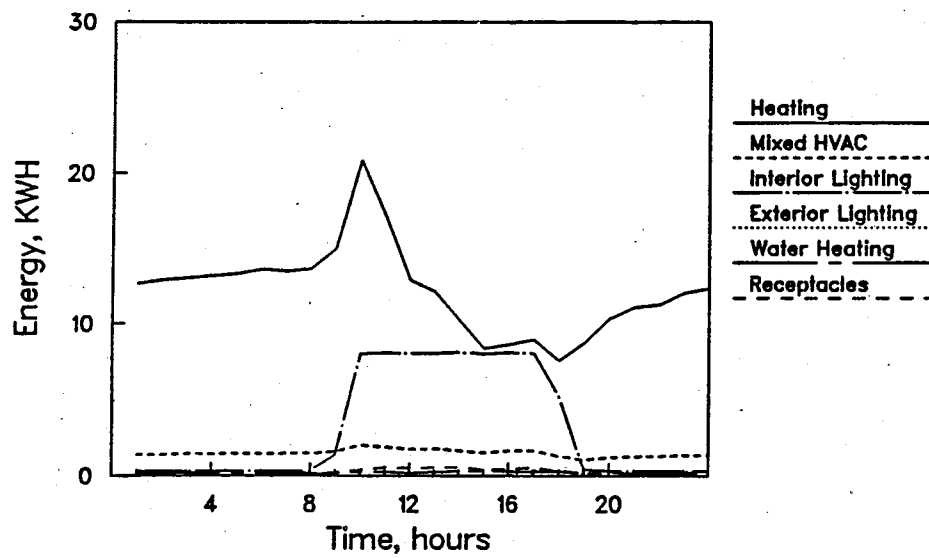
10.2 METHODOLOGY

Buildings in the ELCAP sample are operated normally, and are generally unavailable for manipulation or one-time tests. This presents a fundamental dilemma when attempting to quantify the impacts of specific features of the buildings. A controlled test, with and without a setback strategy in this case, is not available for the buildings. Historically, such impact evaluations have been conducted using simulation models of buildings. While such models can be calibrated to the available data, the cost of doing so is prohibitive for a large sample of buildings such as are in ELCAP. This suggests use of a cross-sectional analysis of buildings with and without setbacks to estimate impacts.

Metered total and end-use loads during the winter for a typical commercial building with a setback thermostat strategy are shown in Figure 10.1. The total load curve shows a marked peak in the morning corresponding to the warmup load for the building in conjunction with the start of the daytime lighting and equipment operation. This is followed by a period after the peak warmup load that exhibits a lesser, but still increased, heating requirement caused by the continuing absorption of heat by the building mass. The end of this period is termed post peak in this discussion.

SITE 287 1/ 1/87 to 1/31/87

Average Daily Electricity End-Use Profile



SITE 287 1/ 1/87 to 1/31/87

Average Daily Total Electricity Use

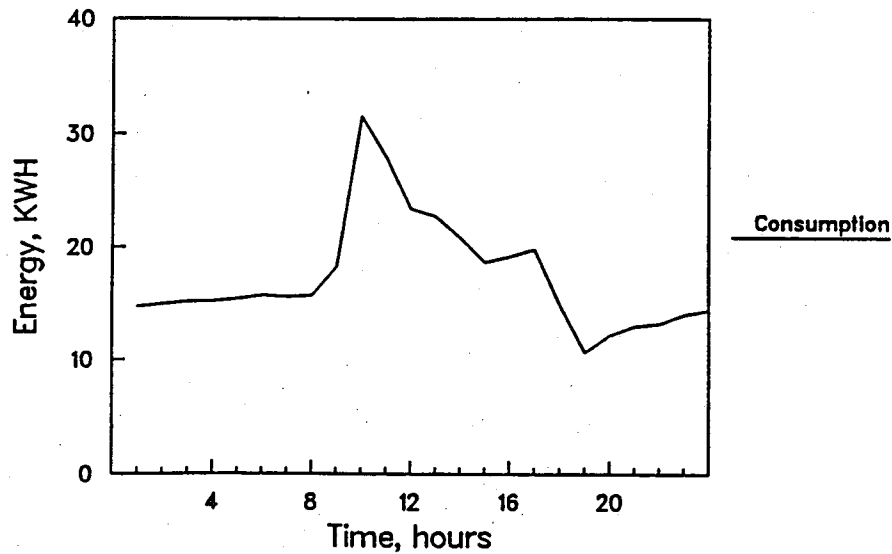


FIGURE 10.1. Typical End-Use and Total Load Profiles for a Setback Building

By mid-afternoon, the total load begins to level off until the setback time is reached, when a rapid drop to the minimum load occurs because of the thermostat setback and turning off lights and other equipment. Subsequently, the load increases fairly rapidly to its evening value as the heat stored in the building mass is discharged, followed by a period of slow increase in load prior to the morning peak as the outdoor temperature continues to drop. The heating and mixed HVAC end-use load profiles exhibit similar shapes. (Note that in the two buildings used here as examples, both have packaged heating/cooling rooftop units that are metered as mixed HVAC end-uses, as well as separate resistance heaters metered as pure heating end-uses.)

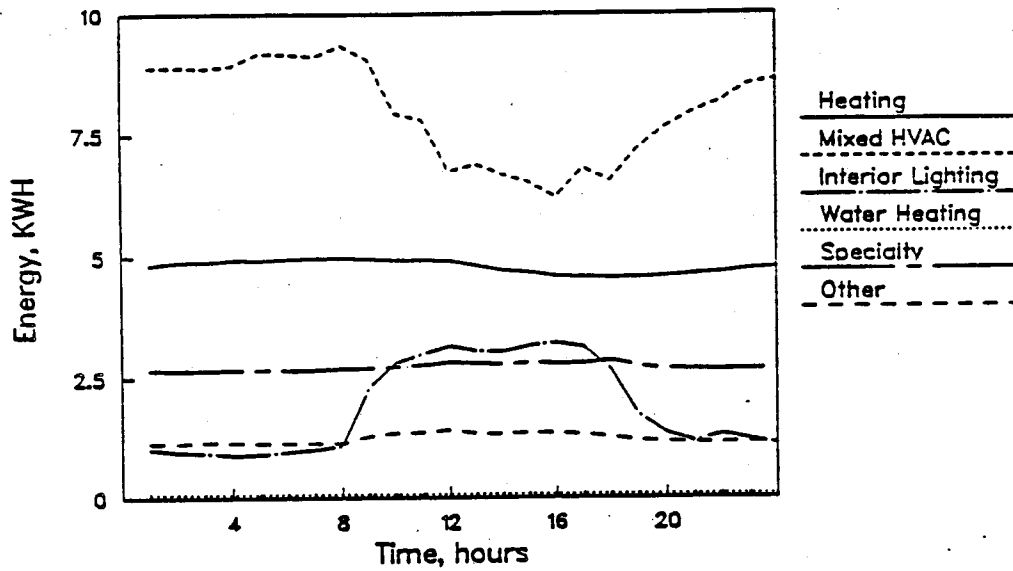
In contrast, total and end-use loads during the winter for a typical non-setback building are shown in Figure 10.2. Note the almost complete absence of any marked peak load. This can be explained by observing that while the lighting and equipment loads increase during working hours, the heat given off by these devices displaces an essentially equal amount of space-heating energy (again the combination of the mixed HVAC and heating end-uses). The result is a total building load that reflects primarily the changing outdoor temperature. Ventilation air flow controls and heat pump systems affect the degree of flatness in the total load, but the basic trend toward smooth loads is generally evident.

In this analysis a simple analytical technique, here termed load normalization, is developed that can be applied to facilitate the comparison across buildings that vary in size, insulation level, and heating system efficiency. The fundamental assumption is that by late afternoon the building HVAC load has stabilized after a morning warmup load, and at that time is essentially equal to the load the building would exhibit if it had no setback. By normalizing the building HVAC and total loads to the late afternoon reference load, the hourly loads of different buildings can be brought to a common basis.

The assumption of an afternoon reference load implies that the time required for the mass temperature to come into equilibrium with the room air temperature must be less than the length of the daily operating schedule for the building. This is related to the time constant of the building internal

Site 286 1/ 1/86 to 1/31/86

III. Average Daily Electricity End-Use Profile



IV. Average Daily Total Electricity Use

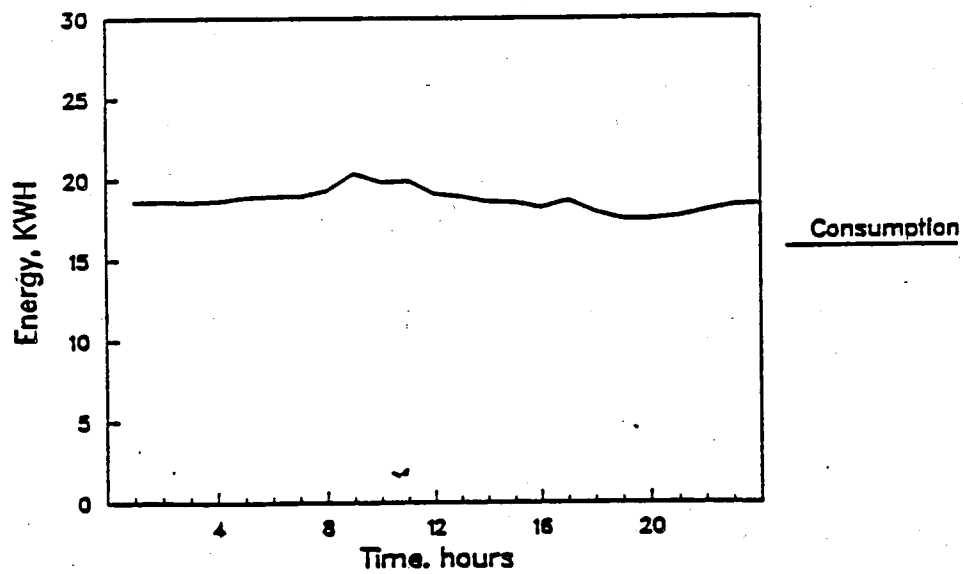


FIGURE 10.2. Typical End-Use and Total Load Profiles for a Non-setback Building

thermal mass. Note that this building internal thermal mass time constant is distinct from the commonly used overall building time constant, in that it includes only the conductance to the room air rather than also including the (possibly much lower) conductance to the outdoor air.

Schedules of operation are typically about 8 hours or more in the commercial sector, corresponding to the length of the business day. Observations of the ELCAP data show that the thermal mass in most buildings appears to reach equilibrium with the interior air temperature in the range of two to six hours, and so may appropriately be analyzed with the reference load methodology. Very massive buildings are exceptions to this generalization (e.g., buildings with large areas of exposed massive construction in their internal partitions). Fortunately, this type of construction is relatively uncommon in commercial buildings.

The motive for implementing a setback strategy is energy conservation, and the peak load effects must be placed in perspective with the energy conservation potential of setbacks. Six times of day (termed dawn, peak, post-peak, afternoon, minimum, and night) were chosen to best characterize each building's HVAC load shape, creating a piece-wise linear approximation of the rather complex HVAC load shape of the setback buildings. Schedule differences caused the peak, post-peak, and minimum times to vary somewhat across buildings. The average time across the buildings of these load transition points is used for all the buildings, approximately adjusting for the differences in their schedules of operation.

The normalized profiles from a number of buildings are then classified as setback or non-setback shapes, and the mean profile for the two classes developed. The normalizing method does not adjust for differences between buildings in the depth of setback or the levels of internal gains. The estimated impact of setback on the peak HVAC load then is the difference between the average ratio of the measured peak load to the reference afternoon load for buildings with and without setbacks. Similarly, the estimated energy impact can then be determined by integrating the normalized load profiles over the day to form a daily average cumulative dimensionless energy consumption.

10.3 RESULTS

Twelve ELCAP commercial buildings with readily available January average end-use profiles were analyzed for this prototype methodological development, six with setbacks and six without setbacks. All the buildings chosen were small in floor area, ranging from 2,000 to 50,000 ft². (with one exception of about 100,000 ft²). Large buildings were excluded from the analysis because they tend to exhibit cooling loads in the late afternoons, even in January, and so they tend to have a somewhat different characteristic shape associated with setbacks.

The results of normalizing the HVAC load shapes to the afternoon reference load using the methodology described in the previous section are shown in Table 10.1 and illustrated in Figures 10.3 and 10.4. The setback buildings' HVAC load shapes in Figure 10.3 are clearly distinct from the non-setback shapes in Figure 10.4. The load shapes in Figure 10.3 all have the large warmup spike that characterizes the setback buildings, while in Figure 10.4 the non-setback profiles are uniformly U shaped.

Investigation of the cause of the variance among the setback profiles in Figure 10.3 indicates that the buildings with higher relative peaks also had a longer post-peak period. These post-peak periods ranged from 6 hours for Site 13 to 2 hours for Site 445. The length of the post-peak period is roughly equivalent to the time required for the mass to come into equilibrium with the air, which in turn is proportional to the thermal mass. Thus the assumption appears to be valid, that the interior thermal mass time lag in typical commercial buildings is less than the length of hours of operation. For the buildings with high time constants, and hence presumably high thermal mass, it also takes more energy to bring the mass up to temperature during the morning warmup. This is reflected in the association of higher relative peak loads for buildings with higher time constants. It should be noted that, in theory, the magnitude of the peak load is also proportional to the depth of the thermostat setback, which has not been analyzed here.

In Figure 10.4 the HVAC profiles for the buildings without setbacks also show some variance. This is associated with the relative magnitude of the daytime and nighttime levels of internal heat gain from lights and equipment

TABLE 10.1. Normalized Commercial Building HVAC January Load Shapes

SETBACK BUILDINGS

<u>ID#</u>	<u>Building Type</u>	<u>Ratio of Loads to Afternoon Load</u>					
		<u>Dawn</u>	<u>Peak</u>	<u>Post-Peak</u>	<u>After-noon</u>	<u>Minimum</u>	<u>Night</u>
13	Other	0.9	3.7	1.5	1.0	0.6	0.4
458	Office	1.2	3.0	1.6	1.0	0.6	1.2
287	Retail	1.4	3.0	1.5	1.0	0.6	1.1
273	Office	0.5	2.4	1.3	1.0	0.3	0.3
445	Restaurant	0.6	2.3	1.2	1.0	0.7	0.8
456	Office	0.6	2.2	1.4	1.0	0.3	0.3
	Average	1.0	3.0	1.5	1.0	0.5	0.7
	Hour	7	8	11	16	19	24
	Energy	6.0	8.1	14.8	21.0	23.3	26.5

(cumulative, dimensionless)

NON-SETBACK BUILDINGS

<u>ID#</u>	<u>Building Type</u>	<u>Ratio of Loads to Afternoon Load</u>					
		<u>Dawn</u>	<u>Peak</u>	<u>Post-Peak</u>	<u>After-noon</u>	<u>Minimum</u>	<u>Night</u>
449	Retail	2.5	2.7	1.5	1.0	1.6	2.4
453	Office	2.1	2.1	1.4	1.0	1.3	1.9
451	Office	1.8	2.0	1.5	1.0	1.4	1.7
286	Office	1.7	1.8	1.5	1.0	1.1	1.2
714	Office	1.7	1.8	1.2	1.0	1.3	1.6
697	Office	1.8	1.8	1.2	1.0	1.4	1.6
	Average	2.0	2.1	1.5	1.0	1.3	1.8
	Hour	7	8	11	16	19	24
	Energy,	13.4	15.5	21.0	27.2	30.7	38.5

(cumulative, dimensionless)

Estimated average savings (sample average profile) = 31%

Estimated HVAC peak increase (sample average profile) = 42%

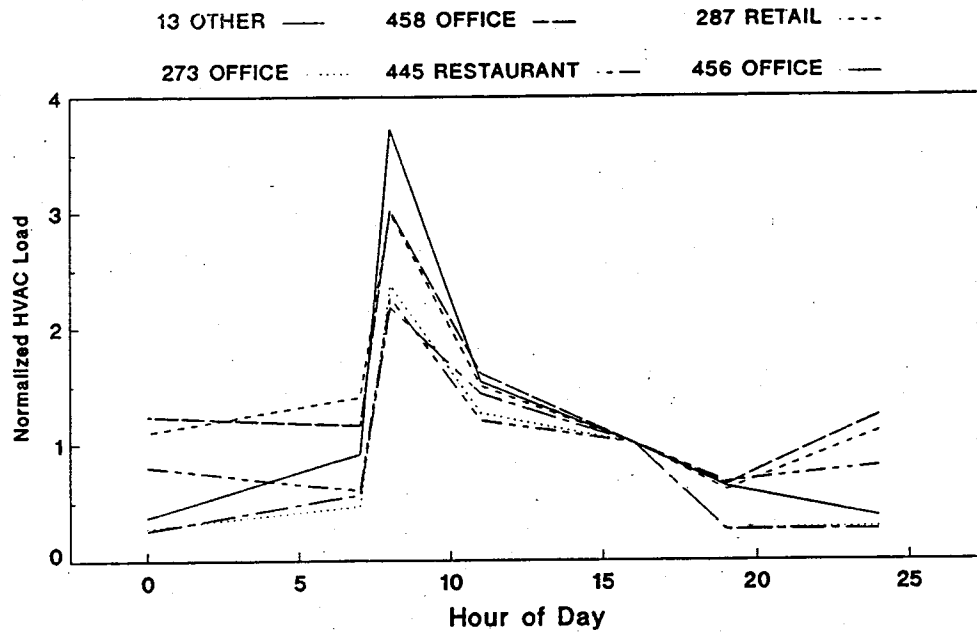


FIGURE 10.3. HVAC Load Shapes - Setbacks (Average January)

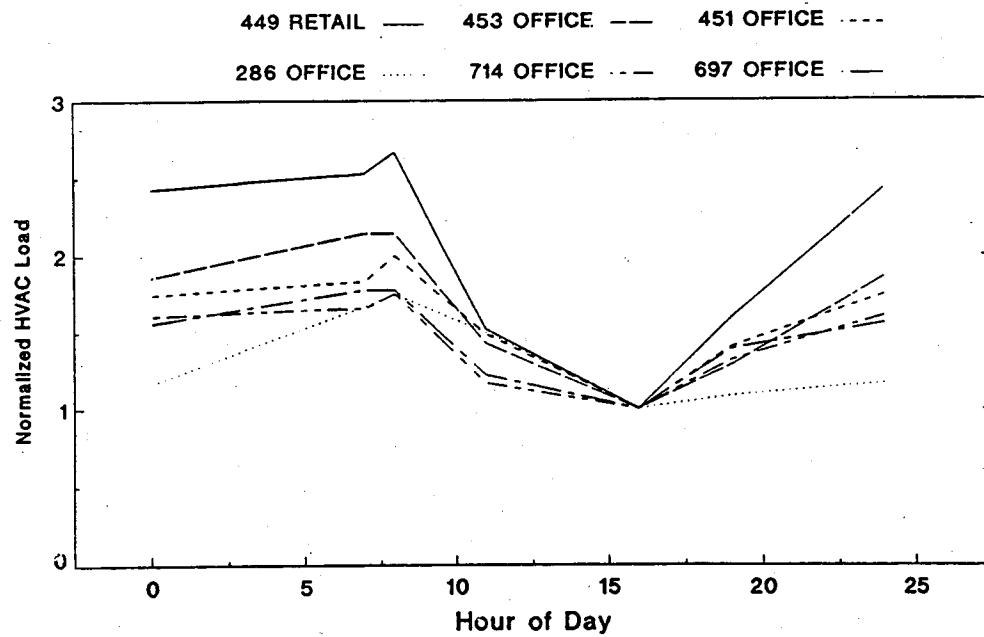


FIGURE 10.4. HVAC Load Shapes - No Setbacks (Average January)

in the buildings. Generally, the higher the relative shift in the level of internal gains from night to day, the higher the nighttime loads are relative to the daytime loads. This is true for nearly all the buildings analyzed, with the notable exception being the only very large building (more than 100,000 ft²). By analogy, buildings with a large response to solar radiation would be expected to exhibit a similar effect. The effects of the relative day/night internal gain levels as well as the effect of the thermal mass and setback depth are indicated by these observations to be prime variables to control in further refinements of this methodology.

The average normalized HVAC load shapes for each of the groups of buildings are shown in Figure 10.5. The mean peak HVAC load in the setback buildings is 42% higher than for the group of non-setback buildings. The impact on total building peak load is less than that on HVAC load, because of the contribution of the other end-uses that are not affected by the setback. The normalized building total peak loads for the buildings analyzed are shown in Table 10.2. The average effect of the setbacks is to increase the peak total loads by an average factor of about 15%. Thus the impact of setback strategies in commercial buildings on winter peak loads are shown to be considerable.

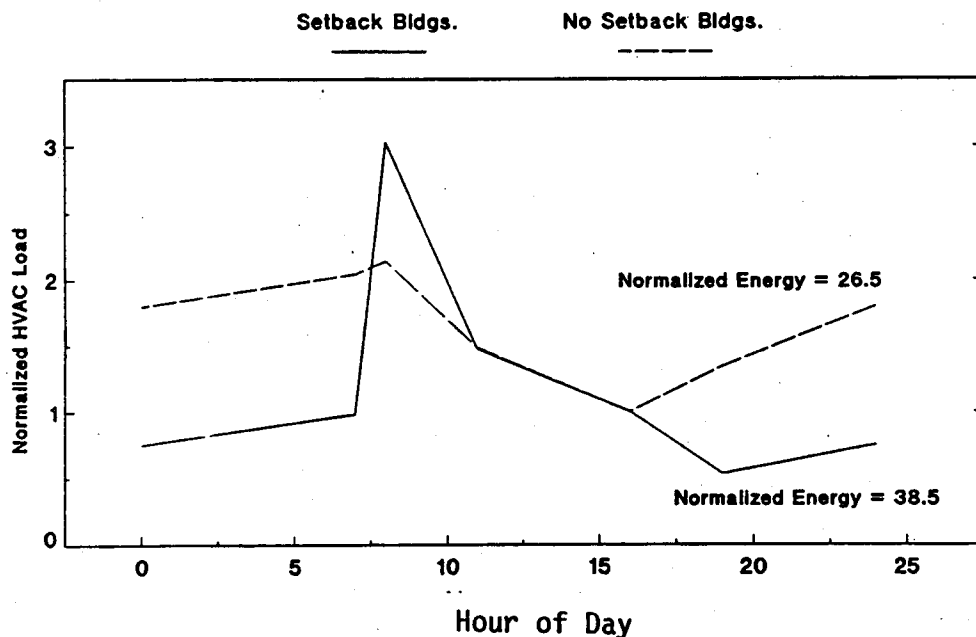


FIGURE 10.5. Mean HVAC Load Shapes (Average January)

TABLE 10.2. Normalized Commercial Building Heating Season Peak Loads

<u>Setback Buildings</u>			<u>Non-setback Buildings</u>		
<u>ID#</u>	<u>Building Type</u>	<u>Peak Load/ Afternoon Load Ratio</u>	<u>ID#</u>	<u>Building Type</u>	<u>Peak Load/ Afternoon Load Ratio</u>
13	Other	1.40	449	Retail	1.13
458	Office	1.29	453	Office	1.21
287	Retail	1.59	451	Office	1.08
273	Office	1.20	286	Office	1.15
445	Restaurant	1.38	714	Office	1.27
456	Office	1.06	697	Office	1.06
	Average	1.32		Average	1.15

Estimated total peak load impact = 15%

savings estimate can be developed for each individual building by integrating its normalized load profile and comparing the energy consumed by the average for the setback or non-setback samples, as appropriate. The resulting savings estimate for each building is shown in Table 10.3. The mean and median savings from the setbacks are 35% and 37%, respectively, with the savings estimates ranging from 16% to 53%. Thus the energy savings potential from setback strategies is also seen to be considerable.

10.4 APPLICATIONS

The consequences of thermostat setback strategies can be estimated from ELCAP data using a rather simple analytical technique. Application of this technique to a small sample of the ELCAP buildings clearly indicates there is a tradeoff between energy conservation and peak demand associated with setback thermostat strategies. Designers of conservation programs and building operators can implement thermostat setback strategies in electrically heated buildings to avoid peaking problems. For utilities where peak load is a concern, clock driven setback thermostats might be set to begin the warmup load a few hours earlier, avoiding coincidence with the winter residential peak loads that also occur in the morning. This tactic could prevent an adverse effect on peak load, while achieving much of the potential energy

TABLE 10.3. Individual Building Energy Savings Estimates

Setback Buildings				Non-setback Buildings			
Potential							
<u>ID#</u>	<u>Building Type</u>	<u>Normal-ized Energy</u>	<u>Setback Savings Estimate</u>	<u>ID#</u>	<u>Building Type</u>	<u>Normal-ized Energy</u>	<u>Setback Savings Estimate</u>
13	Other	26.0	33%	449	Retail	46.5	43%
458	Office	31.1	19%	453	Office	38.9	32%
287	Retail	18.3	53%	451	Office	37.4	29%
273	Office	18.3	53%	286	Office	31.5	16%
445	Restaurant	18.9	51%	714	Office	33.7	21%
456	Office	18.9	51%	697	Office	34.5	23%

Estimated average savings (individual buildings) = 35%

Estimated median savings (individual buildings) = 37%

savings. This would also have the effect of reducing coincidence of increased post-peak loads in setback buildings with the typically sudden morning start up of the lighting and equipment loads in commercial buildings.

Commercial buildings increasingly utilize heat pump HVAC systems for the purpose of energy conservation and to meet energy design standards. These units tend to have lowered performance when operating in a poorly controlled setback mode because of the resulting backup resistance heater operation. This is further exacerbated by the lower outdoor temperature and resulting lower heat pump performance in the early morning hours. Again, the energy savings potential of this technology is significant. Careful design and operation of heat pump systems can help avoid peak load problems.

The ELCAP metered end-uses and the accompanying commercial buildings survey data sets provide the opportunity to determine the region wide impacts of setback strategies in commercial buildings and make decisions to promote or discourage their adoption. The results of this prototype analysis suggest that the technique be refined and applied to the entire ELCAP sample to support such policy analysis.

11.0 AUDIT PREDICTIONS OF COMMERCIAL LIGHTING AND PLUG LOADS

11.1 INTRODUCTION

The Commercial Audit Program (CAP) buildings instrumented to collect end-use metered data as part of the End-Use Load and Consumer Assessment Program (ELCAP) illustrate the uncertainty and range of error that can result from the energy audit process in commercial buildings. In theory, lighting loads should be easy to predict, based on the site inspection of installed lighting and the business operating hours reported by the building owner/manager. However, comparison of annual metered lighting loads to audit predictions for the first 12 metered CAP sites indicate that significant uncertainty in the predicted consumption exists, with an average error of $\pm 39\%$. The consumption estimates per square foot of floor area are high by an average of 16%. Comparisons of actual and predicted plug loads show that these loads were under-predicted by an average of 57%. The implications of these results go far beyond these end-use loads themselves. This becomes clearer when it is recognized that the audit process involves subtraction of the estimated lighting and plug loads from monthly billing data, followed by efforts to match the predicted heating, ventilation and air-conditioning (HVAC) loads predicted to the remainder.

The objective of the CAP metering is to provide data to the Bonneville Power Administration for assessing the quality and predictive power of commercial building energy audits conducted under CAP. Detailed monitoring of energy consumption in 31 commercial buildings is being conducted, with metering plans specifically designed to test the accuracy of thermal analysis methods used as major tools for the energy audit process. The data are being used to evaluate the accuracy of the audit predictions of total and end-use energy consumption in the buildings, and the effectiveness of conservation measures that are being installed in more than half the buildings.

11.2 METHODOLOGY

The results reported here are based on a brief exploratory analysis designed to make a simple comparison of actual metered interior lighting and

equipment (plug) end-use loads with audit predictions. These comparisons are made on an annual basis, since the original estimates were provided by the auditors to Bonneville on that level of aggregation. Unlike the evaluation report that focuses on individual buildings as case studies, this analysis takes a cross-sectional view of two end-uses across a number of buildings.

The only manipulation of basic ELCAP end-use data involved in the analysis is for four sites (the large office B, restaurant A, the first restaurant B, and retail A) in which a mixed general (lights and plugs) end-use load was present. This occurs because of the ELCAP protocol of metering loads at the circuit level, where some circuits have a dual end-use. The mixed loads for these sites were approximately disaggregated by making the simple assumption that the ratio of the mixed general load to the pure lighting load is the portion of the mixed general load that is purely plugs. Only in the two restaurants was this uncertainty larger than 35% of the pure lighting load.

To place the results in some perspective, a brief discussion outlining the audit process follows. Audits are used to establish baseline consumption estimates at the end-use level. These end-use load estimates then form the basis for estimating energy and peak load savings that ensue from installation of energy conservation or demand-side management technologies. It is crucial to understand that energy audit analysis tools do not predict end-use loads, but in fact predict heating, ventilation, and air conditioning (HVAC) loads as a function of assumed lighting and equipment loads, weather, thermostat strategy, and building thermal characteristics. The attempt to match the total load predictions to monthly billing data typically is the only process in which the assumptions about the lighting and equipment load levels and schedules are (indirectly) tested. Because as much as 60% to 70% of the total load may result in lights and equipment in commercial buildings, the predictive accuracy of audits can vary widely depending upon the skill level of the modeler, the accuracy of the building characteristics data used, and the HVAC load simulation model itself.

There are typically four types of information available to the auditor.

- A physical description of the building's envelope, HVAC system, and lighting and other connected equipment loads.
- Data from interviews with the owner/manager and occupants regarding schedules of occupancy, thermostat settings, and ventilation.
- Utility billing data indicating monthly total consumption and possible peak load.
- Temperature data for the recent year and the long-term average weather for the nearest National Weather Service station.

Additionally, the auditor may make some one time measurements of air and/or water flow rates and temperatures, and may also contact the HVAC equipment manufacturer for performance specifications of the HVAC equipment.

The basic tool the auditor uses in this process is an energy analysis of the HVAC system loads. This analysis typically takes the form of computerized hourly simulations of the heat flows in the building, or may use simpler bin methods that group hours with similar outdoor temperatures and time of day. The simulations typically account for hourly weather; transient conductive heat flows through the various building envelope surfaces; transmission of solar energy through the windows and other opaque surfaces; assumed schedules of internal heat gains from lights, equipment, and occupants; assumed schedules and rates of ventilation and infiltration; and the capacity and conversion efficiency characteristics of the HVAC equipment. While bin methods do not account for these processes with the same high level of detail or on a time-series basis, bin method modeling accounts for most of these effects.

There are inherent difficulties in using billing data for calibrating building simulations for energy audits. The input data describing the building systems and their use are adjusted until a reasonable fit to the monthly totals and peak demands is achieved. A typical situation is shown in Figure 11.1. Indicated is a base load consisting of lights and equipment, that the auditor estimates based on the available survey data. These loads are the product of the number of hours of operation of each lighting circuit

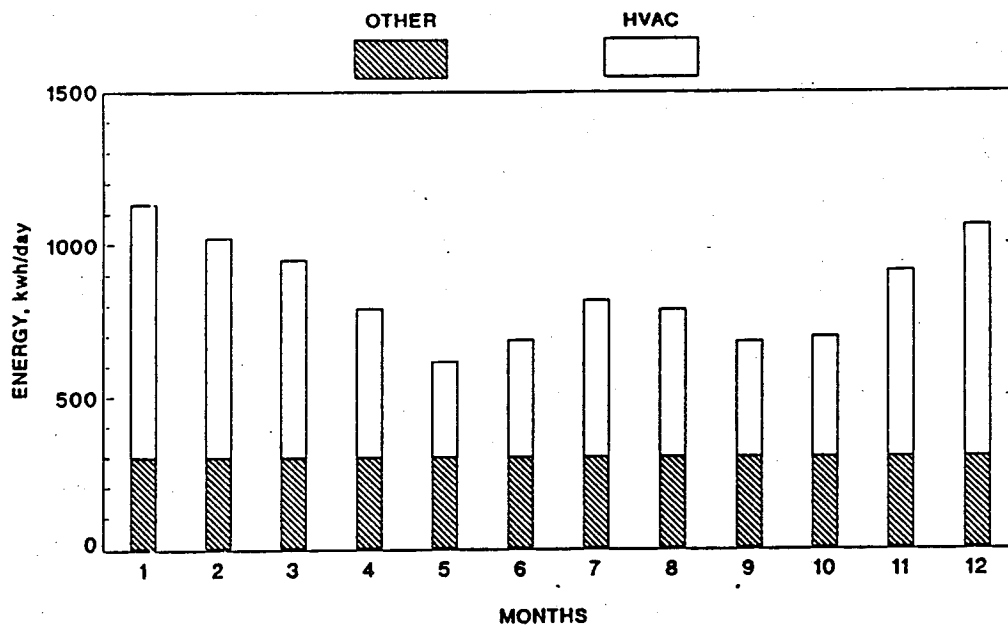


FIGURE 11.1. Winter Peaking Building Monthly Loads

or piece of equipment, times the actual power consumption of the device when operating (which may differ significantly from its nameplate rating). These loads may vary by time of year, but are typically assumed to be steady. The auditor then develops a monthly engineering estimate of the HVAC loads for the building, by entering a detailed description of the thermal characteristics of the envelope and HVAC system into a simulation model. The model accepts a weather data file (usually a typical weather year, as the actual weather for the period analyzed is not readily available in a form suitable for most engineering tools) and a thermostat schedule developed on the basis of discussions with the building operator. The heat given off by the lights and equipment displaces heating loads or increases cooling loads, and so these are also critical data entered into the simulation.

The monthly HVAC load predicted by the model is then added to the assumed lighting and equipment loads to produce a monthly building total energy estimate, which is then compared with the billing data. It is particularly useful to make these comparisons across months, as the monthly pattern of HVAC loads provides clues as to the actual thermal response of the building. In Figure 11.1, the monthly pattern indicates that the building is

dominated by its heating requirements, as noted by its higher winter loads and its minimum loads in May and September. Figure 11.2 shows a cooling dominated building, where the increased summer loads and minimum consumption in March and November are indicative of a lower balance temperature (the temperature at which heating and cooling are zero or minimized) than the building in Figure 11.1.

The auditor examines the predicted pattern of total building consumption, and then iteratively adjusts parameters of the building description or the assumed schedules until a reasonable fit is obtained. Agreement within 10% is generally considered an outstanding fit to monthly billing data. If the pattern of predicted loads indicates that the balance temperature of the building is wrong, adjustments are made (hopefully within reasonable bounds) to the levels of internal gains or the thermal integrity of the building envelope. If the loads are generally too high or low, this suggests that the internal gains assumptions may in error. Changes in the absolute and relative heating and cooling system efficiency curves can also

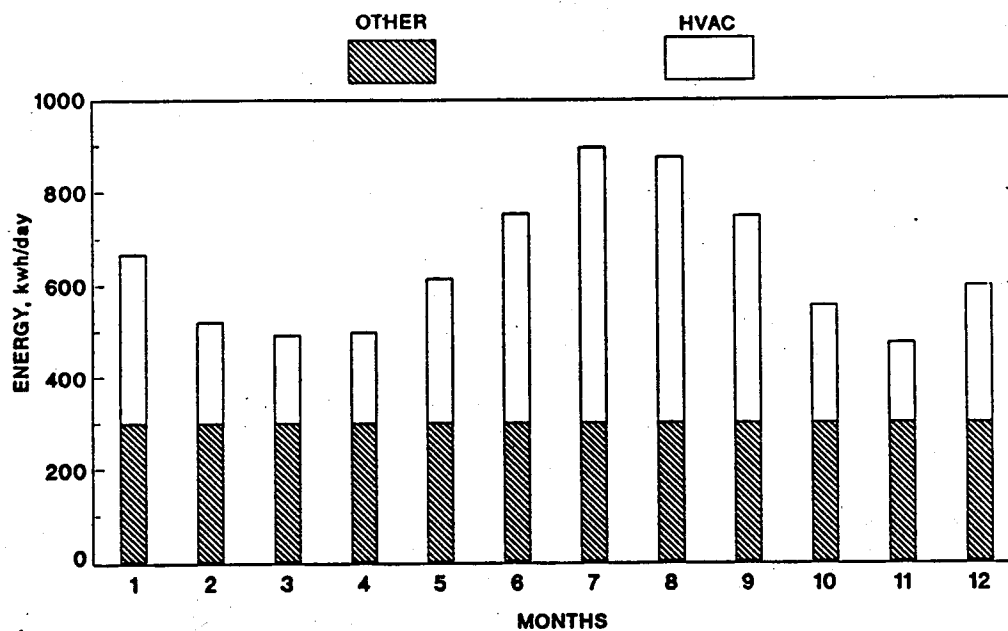


FIGURE 11.2. Summer Peaking Building Monthly Loads

produce similar effects. This is a trial-and-error process in which there is insufficient information in the billing data to make a precise determination of which input parameters that should be adjusted to achieve a proper fit.

The key point is that the energy analysis does not have a unique "solution", but is complete once reasonable agreement is obtained. In this audit calibration process, heat gains from lights and equipment are indistinguishable from one another, and the division of the other (non-HVAC) end-use into lighting and plug loads is usually derived by subtracting the assumed lighting loads from the total of the non-HVAC end uses. Energy savings predictions are then made by changing the engineering model to reflect the characteristics of the conservation measure and simulating the resulting energy consumption.

It is entirely possible for this "solution" to provide a reasonably accurate description of the total consumption for the wrong reasons. Where these reasons result in incorrectly attributing consumption to one end-use at the expense of another, predictions of savings from conservation measures involving those end-uses are usually proportional to the error in the estimated baseline consumption. An example is the savings from a lighting retrofit in which 15% more efficient fixtures are installed. If an average of 80% of the lights are on during the day whereas the model assumption was 90%, then the predicted savings will be high by 11%. Note that the lighting technology performs as expected, saving 15% of the power when the lights are on, but the usage simply was not as predicted.

11.3 RESULTS

11.3.1 Lighting Loads

The actual metered lighting loads and loads predicted by the audits are compared in Table 11.1 and Figures 11.3 and 11.4 for 12 sites. The audits were conducted by several different audit firms for four different building types and a range of building sizes, as shown. The consumption and savings data are normalized by floor area to facilitate comparison of the lighting loads across buildings of different sizes. The data is not weighted by floor area, since the sites are not a random sample of either the region or the CAP

TABLE 11.1. End-Use Metered Data Versus Audit Estimated Lighting Loads

Audit Firm	Building Type	Floor Area (ft ²)	Consumption (kWh/yr-ft ²)		Audit Error (%)
			Metered	Audit	
A	Grocery	3,538	3.7	8.4	128
B	Grocery	25,500	23.3	17.8	-24
A	Restaurant	8,193	5.3	6.0	13
B	Restaurant	4,859	10.5	9.2	-12
B	Restaurant	2,964	13.8	16.0	16
B	Office	50,500	10.4	5.7	-45
F	Office	6,336	3.4	8.2	142
A	Retail	11,720	9.4	10.8	15
B	Retail	69,283	9.9	11.2	13
F	Retail	5,140	5.0	4.8	-6
J	Retail	15,600	9.1	6.1	-33
N	Retail	115,300	13.0	10.5	-19
Mean Error			16		
Median Error			7		
Standard Deviation			57		
Mean Absolute Error			39		

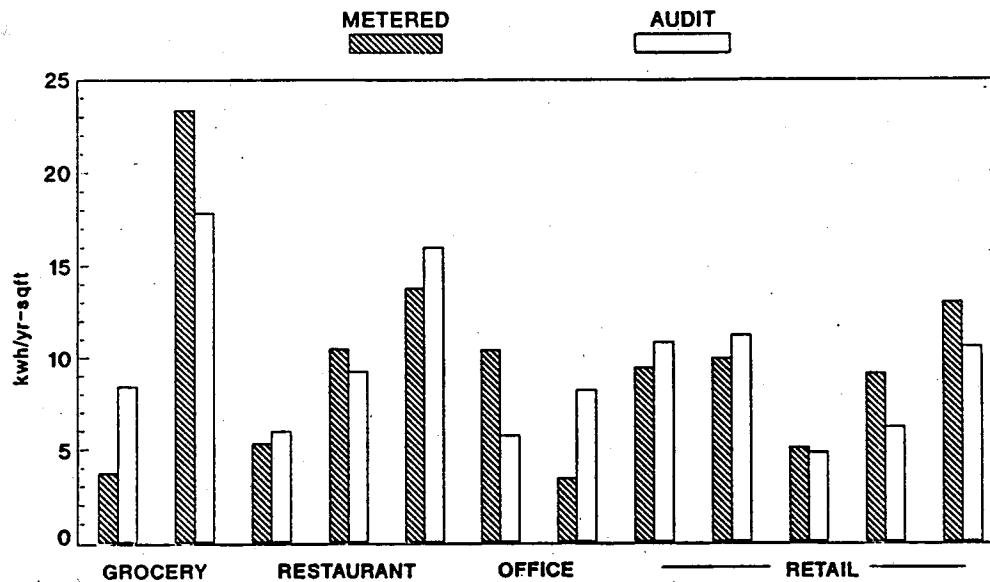


FIGURE 11.3. Metered Versus Audit Estimated Lighting Loads

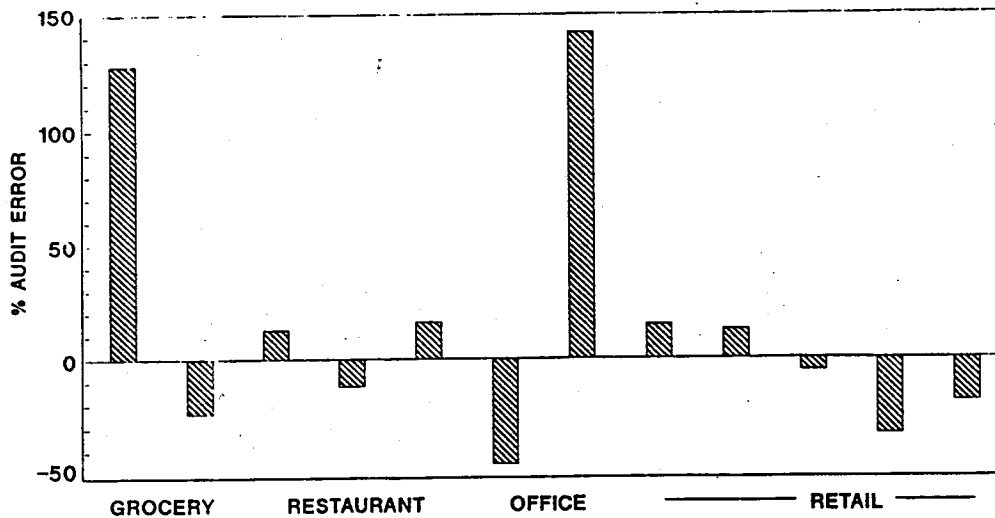


FIGURE 11.4. Percent Audit Lighting Load Error

audit sites, and better represent the diversity due to the audit process. As can be seen in Figure 11.4, the audit predictions are more accurate for the restaurant and retail buildings, compared to the grocery and office buildings.

The audit error is the percentage difference of the audit prediction from the actual measured load. As illustrated by Figure 11.4 for this set of metered CAP sites, the error ranges from 142% over-prediction to 33% under-prediction. The mean and median error indicated in Table 11.1 for the 12 sites are 16% and 7% over-prediction, respectively. In the case of the small office building, this is known to be in part caused by a partial vacancy during the period of metering. If this building is excluded the mean error is reduced to 4% over-prediction, and the mean absolute error is reduced to $\pm 30\%$. In the case of this building an external cause for error in the consumption estimate is present, nevertheless the shifting of commercial occupancy is noted to continually affect the loads in ELCAP buildings and most likely will affect programmatic energy savings in a similar way.

Although this sample of buildings is too small to provide a statistical basis for conclusions, the variance in predicted versus actual loads is clearly large. The standard deviation of the audit errors is 57%, and the mean absolute error is $\pm 39\%$. Thus the data analyzed to date suggests that

there is a range of uncertainty on the benefit side of the cost/benefit calculations for lighting loads that is on the order of $\pm 50\%$ for individual buildings.

11.3.2 Plug Loads

The comparison of audit estimated baseline plug loads with the metered loads for the set of CAP metered buildings is shown in Table 11.2 and Figures 11.5 and 11.6. Plug loads are defined here as receptacle loads exclusive of major process loads such as refrigeration or mainframe computers. Because plug loads are diverse, major energy conservation measures are difficult to implement and as a consequence are infrequently recommended. Nevertheless, it is widely hypothesized that plug loads are underestimated and increasing fairly rapidly because personal computers and other office automation equipment have penetrated into the work place. Also, as pointed

TABLE 11.2. End-Use Metered Data Versus Audit Estimated Plug Loads

Audit Firm	Building Type	Floor Area (ft ²)	Consumption (kWh/yr-ft ²)		Audit Error (%)
			Metered	Audit	
A	Grocery	3,538	17.0	3.9	-77
B	Grocery	25,500	4.0	0.8	-79
A	Restaurant	8,193	10.7	12.8	19
B	Restaurant	4,859	12.0	10.2	-15
B	Restaurant	2,964	7.2	0.8	-89
B	Office	50,500	5.5	1.0	-83
F	Office	6,336	6.5	3.6	-44
A	Retail	11,720	1.7	0.5	-73
B	Retail	69,283	1.3	0.1	-94
F	Retail	5,140	0.6	0.4	-25
J	Retail	15,600	5.8	1.4	-76
N	Retail	115,300	2.6	1.4	-47
Mean Error				-57	
Median Error				-75	
Standard Deviation				33	
Mean Absolute Error				60	

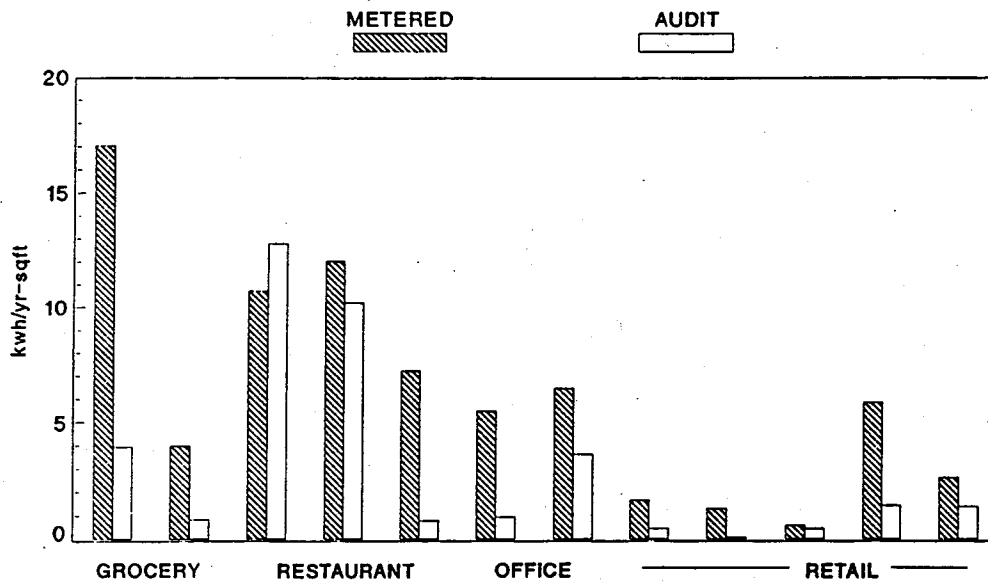


FIGURE 11.5. Metered Versus Audit Estimated Plug Loads

out in the discussion of the audit process, plug loads are typically the unaccounted remainder from the process of resolving the assumed lighting and the predicted HVAC loads with the building total, and so may also be indicative of one form of error in the overall audit process. As shown in Figure 11.5, plug loads are almost universally under-predicted by large amounts for the set of analyzed CAP buildings. The audit error in Figure 11.6

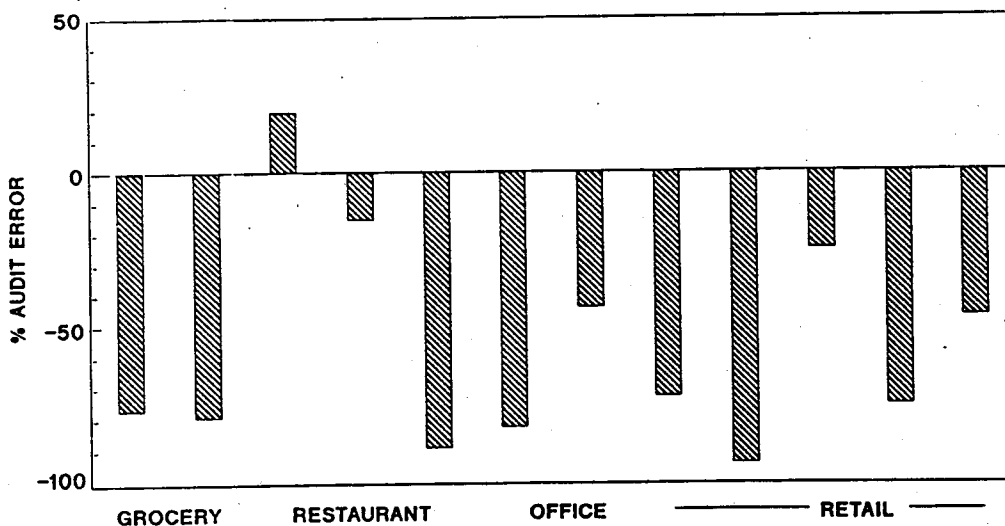


FIGURE 11.6. Percent Audit Plug Load Error

ranged from 94% under-prediction, to 19% retail and grocery buildings as for the office building. The sample is too small to be conclusive, but the results indicate that plug loads may be in error from misestimation of the equipment usage, capacity, and/or the audit process itself, rather than a consequence of underestimating penetrations of automated data processing equipment.

11.3.3 Combined Lighting and Plug Loads

Given the nature of the audit process, the total of the lighting and plug loads might be expected to be more accurately estimated than the individual end-uses. Table 11.3 and Figures 11.7 and 11.8 indicate that this observation may be valid. The average of the audit estimates for the combined end-use are 17% under-predicted compared to the actual loads (the median is also -17%).

TABLE 11.3. End-Use Metered Data Versus Audit Estimated Lighting/Plug Loads

Audit Firm	Building Type	Floor Area (ft ²)	Consumption (kWh/yr-ft ²)		Audit Error (%)
			Metered	Audit	
A	Grocery	3,538	20.7	12.4	-40
B	Grocery	25,500	27.3	18.6	-32
A	Restaurant	8,193	16.0	18.8	17
B	Restaurant	4,859	22.5	19.4	-14
B	Restaurant	2,964	21.0	16.7	-20
B	Office	50,500	15.9	6.7	-58
F	Office	6,336	9.8	11.8	20
A	Retail	11,720	11.1	11.3	2
B	Retail	69,283	11.2	11.2	0
F	Retail	5,140	5.6	5.2	-8
J	Retail	15,600	15.0	7.6	-49
N	Retail	115,300	15.6	11.9	-23
Mean Error			-17		
Median Error			-17		
Standard Deviation			24		
Mean Absolute Error			24		

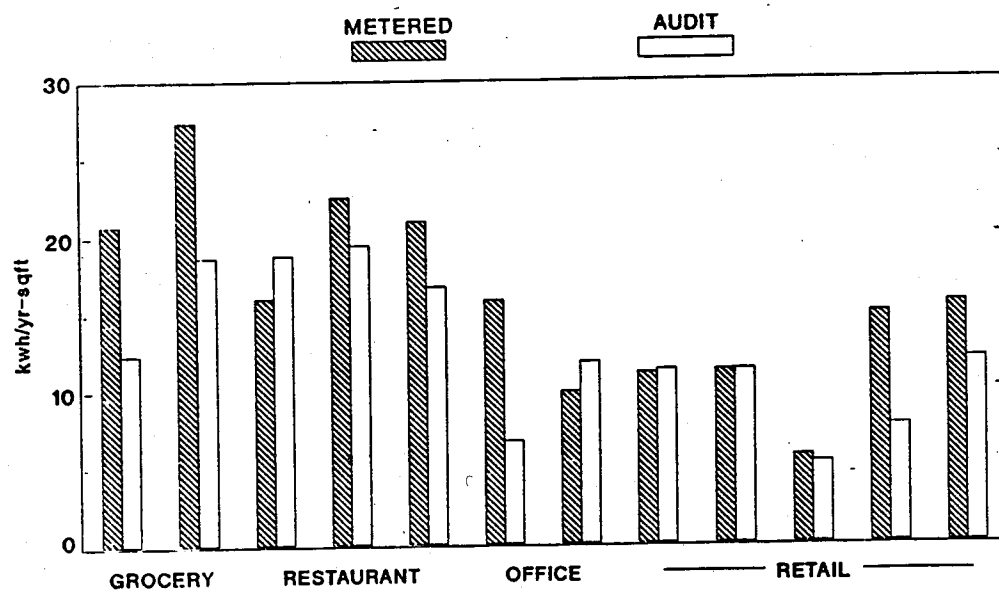


FIGURE 11.7. Metered Versus Audit Estimated Lighting/Plug Loads

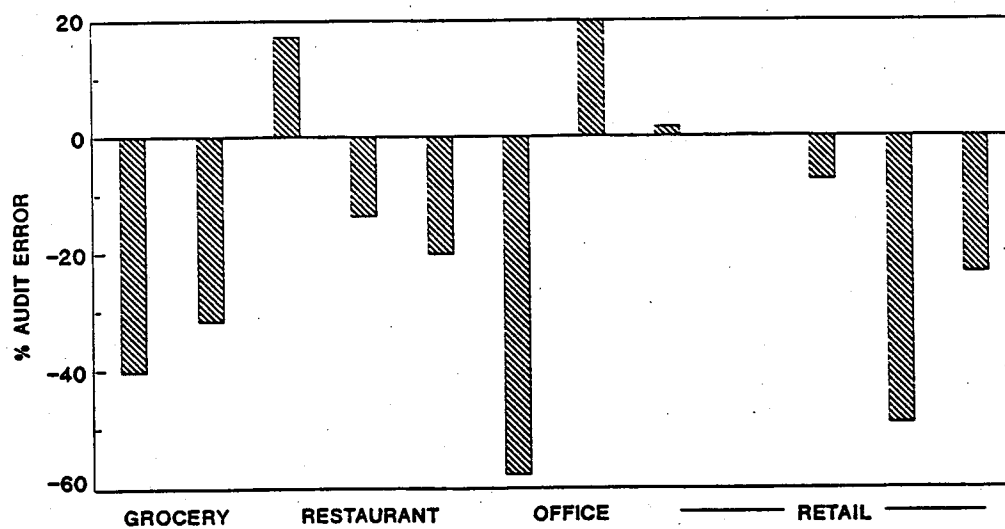


FIGURE 11.8. Percent Audit Lighting/Plug Load Error

This is a reversal in sign, but is similar in magnitude to the observed 16% over-prediction error for the lighting loads. This represents a significant improvement in the mean error for the plug loads.

The variance of the estimates from the actual loads is also reduced, with the standard deviation dropping to 24% and the mean absolute error dropping to 24%. In both cases this is a significant improvement over the individual end-use estimates. The analysis of the combined end-uses did not greatly increase the audit error for any building, and significantly improved it for several sites. Although only a small sample of buildings is analyzed here, the data suggest that some of the errors in prediction of the individual lighting end-use may be offset by compensating errors in the plug load end-use.

Of the four sites in which pure end-use loads had to be approximated from mixed general loads, only retail building A showed significant improvement. This indicates that the arbitrary nature of the disaggregation approximation for these sites did not appreciably alter the results of the analysis.

11.4 APPLICATIONS

The magnitude and range of errors in audit baseline estimates of lighting and plug loads (standard deviations of $\pm 57\%$ and $\pm 33\%$, respectively) indicates that significant uncertainty exists for CAP audit based conservation predictions involving these end-uses for individual buildings. The error in predicting direct benefits might increase further when the interactive effects on heating and cooling loads are included. The risk for investment in conservation from the viewpoint of an individual building owner is thus seen to be significantly greater and in part of a different nature than is normally recognized. For the relatively small sample of buildings as a whole, the mean error in the baseline estimates are +16% for the lighting loads and -57% for the plug loads. This indicates the possibility that systematic over-prediction or under-prediction errors of these magnitudes for audit based conservation potential involving these end-uses are possible. While the analysis needs to be completed for more of the metered CAP sites and extended to the full set of end-use loads to strengthen these conclusions, serious

questions are raised as to the validity of savings estimates based on large commercial audit programs. This has important implications for resource and program planners intending to utilize the conservation resource.

These early results have already resulted in an experimental design involving systematic reaudits of these buildings, using increasing amounts of ELCAP end-use data to evaluate the potential benefits of acquiring various levels of measurements as part of an improved audit protocol. Similarly, the indication that lighting loads may be over-predicted at the expense of plug loads as a consequence of the audit process itself may lead to guidelines improving these estimates.

The data also suggest plug loads may be consistently underestimated across building types, and that the errors are not concentrated solely in office buildings. If supported by analysis of more buildings, this result would indicate that audit plug load errors are not related to the penetration of personal computing equipment in the office environment, but more likely are a consequence of poor estimates of equipment usage patterns generally. Thus the hypothesis that plug loads are growing rapidly in the commercial sector is neither supported nor refuted, but is not indicated as a source of error when the equipment in a building is observed first hand by the energy analyst. This result may have importance for commercial sector load forecasters and modelers involved in the development of conservation supply curves.

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