PNL-6595
UC-350

Thermal Performance of the Hood River End-Use Metered Homes

N. E. Miller
R. G. Pratt

September 1990

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

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Battelle

PNL-6595

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831;
prices available from (615) 576-8401. FTS 626-8401.

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

NTIS Price Codes, Microfiche A01

Printed Copy

Price Code	Page Range	Price Code	Page Range
A02	1- 10	A15	326-350
A03	11- 50	A16	351-375
A04	51- 75	A17	376-400
A05	76-100	A18	401-425
A06	101-125	A19	426-450
A07	126-150	A20	451-475
A08	151-175	A21	476-500
A09	176-200	A22	501-525
A10	201-225	A23	526-550
A11	226-250	A24	551-575
A12	251-275	A25	576-600
A13	276-300	A99	601-Up
A14	301-325		

PNL-6595
UC-350

THERMAL PERFORMANCE OF THE HOOD RIVER END-USE METERED HOMES

N. E. Miller
R. G. Pratt

September 1990

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

Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

The Hood River Conservation Project (HRCP) sponsored by the Bonneville Power Administration (Bonneville) involved the entire community of Hood River, Oregon, in one of the largest weatherization experiments ever conducted. Two goals were set in the experiment: to weatherize all homes to a predetermined cost-effectiveness limit and to gather the necessary data to assess the success of the retrofitting in terms of saved kWh/yr. The results reported here were commissioned by Bonneville as part of the effort to determine the thermal performance characteristics based on high time-resolution data. Results were then compared to results obtained from another methodology that uses billing data.

As part of the HRCP data collection, approximately 300 homes were end-use metered. These homes were predominately single-family homes but did include several multifamily units and about 50 manufactured homes. The end-use data, along with some survey data, form the data set for the thermal characterizations summarized in this report. In the thermal analysis described here, the metered data is used to characterize the heating load as a function of inside-outside temperature difference. An annualized estimated consumption (AEC) for electrical space heat for the home is estimated under a set of standard conditions. This quantity is ideally suited for pre- and post-retrofit comparisons as it is weather-normalized, adjusts for any changes in inside air temperature on a daily basis, and is not affected by intermittent wood use. Additional thermal parameters are derived from a robust linear fit of space heat to inside-outside temperature difference. Changes in inside operating temperatures and wood-stove usage patterns are also investigated.

Previous analyses by others (Hirst 1987; Stovall 1987) indicated a discrepancy between the predicted savings (an average of 6,100 kWh/yr) and the mean savings actually achieved of 2,600 kWh/yr. This work, although using a very different analytic technique and the end-use metered data, shows savings similar in magnitude to those previously found. The biggest difference is that this analysis specifically accounts for items that were used to discount some of the discrepancy between predicted and observed savings in the previous work.

The chief conclusions of this analysis for the sample of end-use metered homes characterized are as follows:

- The estimated total space heating consumption in the post-retrofit period dropped by 24% of the pre-retrofit level for the combined sample of homes. This represents a decrease in consumption of 2,432 kWh/yr or 2.05 kWh/ft^2-yr. The change in single-family consumption was greater at 2,899 kWh/yr (or 2.24 kWh/ft^2-yr), close to a 30% drop compared to pre-retrofit levels. The percentage drop for the few multifamily units was similar to that of the single-family homes. The manufactured homes experienced about one-third the reduction of the single-family and multifamily units.

- Changes in heat loss coefficients (UA) and effective heating-degree-days experienced by these homes, derived from the linear fits of the heating data to inside-outside temperature difference, show a magnitude of total savings similar to that of the AEC estimates. For the combined sample, the mean percentage change in the derived UAs and effective heating-degree-days are 20% and 5%, respectively. Greater changes were noted for the single-family and multifamily units, less for the manufactured homes.

- Although a slight increase is noted in inside air temperatures over the two heating seasons, the rise is not large enough to conclude that the occupants raised their thermostat set points after weatherization. The weatherization of the homes could produce larger increases in inside air temperatures than those seen in the analyzed sample.

- Wood-stove usage dropped after installation of the weatherization measures. Although the total number of days of heater usage and the total number of days of wood-stove usage are fairly comparable across the heating seasons, the mean wood-stove signal, which is proportional to heat displacement, dropped in the post-retrofit period by about 27% for these homes. The mean heater usage, over the same period, dropped by about one-half as much. More of the savings appear to have been taken in reduced wood burning than in reduced use of permanent electrical space heating equipment.

CONTENTS

FIGURES

TABLES

TABLES (Contd)

1.0 INTRODUCTION

The objectives of the Hood River Conservation Project (HRCP), conducted from 1983 through 1987, were to fully weatherize the community of Hood River, Oregon, and to gather the information required to compare actual savings to projected savings from that weatherization effort. This project, commissioned and funded by the Bonneville Power Administration (Bonneville), was successful in weatherizing the majority of homes in Hood River to a full predetermined cost-effectiveness limit. This report evaluates savings from that conservation effort.

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. Data were collected every 15-min. detailing total, space heating, and hot water (usually) 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 the 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, the end-use metered homes had a variety of conservation measures installed. These measures were aimed at improving the thermal performance of the residential envelope and minimizing the heat loss and inefficient 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 and survey data, have been used to characterize the end-use metered homes' pre- and post-retrofit, omitting the period during which the set of measures were installed. Space heating requirements and shell performance characterizations were derived for all the end-use metered homes when possible.

Section 2.0 of this report summarizes previous analyses on Hood River savings. Section 3.0 describes the methodology used to estimate the space heat savings and changes in the thermal integrity of the residential envelope that occurred after installation of the weatherization measures. In Section 4.0, the changes in estimated electrical space heating consumption and other derived measures of thermal integrity are presented. Additionally, observed mean indoor air temperatures are compared; pre-retrofit comparisons are made to post-retrofit; and the average thermal performance of the Hood River Homes, post-retrofit, is compared to that of the End-Use Load and Consumer Assessment Program (ELCAP) monitored homes. Wood-stove usage patterns are examined in Section 5.0 for changes in intensity and frequency of wood-stove use. Section 6.0 provides a comparison savings analysis of the HRCP end-use metered homes and their actual retrofit savings against those projected at the inception of the project. Our conclusions are provided in Section 7.0.

2.0 BACKGROUND

Several other studies of the HRCP have also been completed. Hirst (1987) used monthly billing data from the community of Hood River, collected both before and after installation of the weatherization measures, to evaluate the change in space heating consumption. Using the Princeton Scorekeeping Method (PRISM) (Fels 1984) with the billing data from the pre-retrofit winter 1982 through 1983 and from the post-retrofit winter 1985 through 1986, Hirst found a mean total savings of 2,600 kWh/yr for 2,362 households (or a 35% decrease in the mean pre-retrofit level of consumption). This savings represents a 2.2 kWh/ft² of floor area drop in estimated pre-retrofit space heat consumption. These statistics were also reported according to housing type (single-family, multifamily, and manufactured home). Consumption dropped by 38%, 28%, and 29% for the single-family, multifamily, and manufactured home groups over pre-retrofit levels, respectively. This information is summarized in Table 2.1.

TABLE 2.1. Electricity Use and Savings for Homes Retrofit in the HRCP by Housing Type (Hirst 1987)

		Housing Type		
Electricity Use, kWh/yr	Total	Single-Family	Multifamily	Manufactured Home
Total Use				
1982/83	18,600	20,400	10,700	19,200
1985/86	16,000	17,500	9,200	16,700
Estimated Space Heat				
1982/83	7,500	7,600	5,700	8,500
1985/86	4,800	4,600	3,700	6,300
Decrease in Total Billing Data 1982/83-85/86	2,600	2,900	1,600	2,500
Decrease in Total Compared to 1982/83	35%	38%	28%	29%
Total Savings/ft²	2.2	2.1	2.1	2.5
Number of Households	2,362	1,545	396	421

Because many of these homes relied upon a supplementary fuel source for a significant amount of space heat, Hirst also reports on the levels of estimated space heating savings for those homes that probably used electricity as their primary heating fuel. This designation was based upon occupant survey data. The magnitude of these savings tends to be larger than the savings observed in Table 2.1, although the percent of change over pre-retrofit levels for the total and single family samples is essentially unchanged at 35% and 39%, respectively. The absolute and percent savings rise dramatically for the multifamily sample and drop somewhat for the manufactured home sample. These numbers are summarized in Table 2.2.

The actual savings for the total sample of homes in Table 2.1 averaged 43% of the expected savings. Hirst attributed the discrepancy between actual savings (2,600 kWh) and predicted savings from audits (6,100 kWh) to typical differences between predicted and actual savings, the effect of reduced pre-program electricity use, decreases in wood use, and increased indoor temperature settings after the installation of the weatherization measures.

TABLE 2.2. Electricity Use and Savings as Main Fuel Source by Housing Type (Hirst 1987)

Electricity Use, kWh/yr	Total	Housing Type		
		Single-Family	Multifamily	Manufactured Home
Total Use				
1982/83	21,000	24,400	10,600	20,800
1985/86	17,800	20,400	8,700	18,800
Estimated Space Heat				
1982/83	9,200	10,300	5,000	9,700
1985/86	6,600	7,000	3,200	8,100
Decrease in Total Billing Data 1982/83-85/86	3,200	4,000	1,900	2,000
Percent Decrease Compared to 1982/83	35%	39	38%	21%
Total Savings/ft²	2.5	2.8	2.4	2.0
Number of Households	615	362	115	138

Stovall (1987) also used the end-use metered data from the Hood River homes to study the change in the HRCP peak load, rather than the overall energy savings. She concluded that single-family homes save an average of 24% of their space heating load. The manufactured home sample saved only an average of 8% on their space heating load.

The analysis reported here uses the same load data collected from the end-use metered homes that was available to Stovall (1987). The primary objective of this work is to estimate overall energy savings using a method that provides a weather-normalized estimate between the pre- and post-retrofit years. This estimate automatically accounts for changes in indoor temperature strategies (should they occur), and provides a savings estimate not reduced by the intermittent use of supplementary fuel sources such as wood. Secondary objectives of this work are to study changes over the pre- and post-retrofit heating seasons for mean indoor air temperatures and wood-stove usage patterns.

3.0 METHODOLOGY

For the purpose of this analysis, the heating season is defined as September through May. In some cases this heating season window 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 noted in the data for these sites. 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, described below, include an annual estimate of electrical space heating requirements and a slope and balance temperature difference.

The empirical measure we consider most powerful for comparing structures is the annualized estimated consumption (AEC) for space heating. The AEC is derived separately for each structure. This quantity corrects to the first order for daily changes in inside-outside temperature and thus, is ideally suited for evaluating pre- and post-retrofit performance changes in the Hood River homes. The AEC is derived by fitting a smooth curve to the scatter plot of daily space heating energy consumption versus inside-outside temperature difference. The resulting curve, along with the measured inside temperature (or any desired inside temperature) and outdoor temperatures from a selected reference weather year, can be used to estimate the typical annual space heating requirements for the structure, assuming that the level of internal and solar heat gain is equal to that observed over the data collection interval.

A slope and balance temperature difference is computed from a robust linear fit of the daily space heating data to the inside-outside temperature difference. The slope can be interpreted as the quotient of the conductive heat loss coefficients (UA) and the heating system efficiency and thus, can be viewed as a measure of a building's thermal integrity. The balance temperature difference can be interpreted as the average inside-outside temperature difference that a building can support without use of the space heating equipment, given its average level of internal and solar heat gains.

The sample selected for analysis here contains 113 homes--82 single-family, 7 multifamily homes, and 24 manufactured homes. It is possible to reliably characterize 126 homes in the pre-retrofit heating season and 121 in the post-retrofit heating season. However, because this report makes before and after comparisons, only those homes with characterizations common to both the 1984 through 1985 and 1985 through 1986 heating seasons are selected for final inclusion in results. Close to 60 sites with monitored wood stoves are excluded from the results. After removal of the monitored 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. Few homes are excluded for having inconclusive or missing data. The loss of the balance of the sites is because of dependence on supplementary fuel sources. Moderate-to-heavy wood use appears to be the chief occupant behavior leading to the exclusion of sites from the final analysis summary. These assumptions are based upon a comparison of survey data on occupant's wood use habits with scatter plots of heater load versus inside-outside temperature difference.

All calculations are performed using techniques that are resistant to the effect of outlier points, such as isolated vacation days. For a more detailed discussion of the analytic technique see Drost et al. (1987). The derived measures of thermal performance for the end-use metered Hood River homes are

- not affected by intermittent use of wood heating equipment because these days are removed from the analysis
- corrected for changes between site heating seasons in inside temperature as reflected in the measured data

- corrected for weather variations from one year to the next by using a given reference weather year to derive the annualized electrical space heating estimates for both pre- and post-retrofit periods.

Because all wood use days are removed prior to the parameter derivation, the summary numbers produced in this report are not lessened by the rather extensive use of wood in the Hood River community. Therefore, the AEC savings are comparable to the original savings estimates that ignored the possibility of wood use. Changes in mean inside air temperature for the main living area are directly accounted for in the derived estimates. However, because no multiple sensors are in place for the residences studied, room closures and zoning are not corrected for in this analysis. If the occupants were closing-off rooms before the installation of retrofit measures and then stopped post-retrofit period, the change in structural thermal integrity over the two heating seasons could be underestimated.

4.0 THERMAL PERFORMANCE CHARACTERIZATIONS

The results of the thermal performance characterizations for the various building types of 113 Hood River homes are summarized in this section across the various building types. The differences in the annual estimated electrical space heat consumption for various weather years are examined. Changes in the parameters from the robust linear fit, which tracks changes in the residential shell performance, are also presented. The relation between the AEC and parameters from the linear fit are examined for consistency. The thermal performance statistics for the 113 Hood River sample homes are then compared to those derived for the End-Use Load and Consumer Assessment Program (ELCAP) homes. This program is conducted for Bonneville by the Pacific Northwest Laboratory (PNL),[a].

4.1 CHANGES IN ESTIMATED ELECTRICAL SPACE HEATING CONSUMPTION

Several different weather years and two separate occupant control strategies are used to compute estimates of electrical space heating consumptions for the residences. Estimates are performed using typical meteorological year (TMY) data for Seattle, Washington; Spokane, Washington; Missoula, Montana; and Portland, Oregon. Because no TMY data exists for Hood River, several National Oceanographic and Atmospheric Administration weather years from Hood River are used. The years used (winter only) and associated heating-degree days (HDD) to base 65°F are:

1978 through 1979 ----> 6134 HDD
1976 through 1977 ----> 5502 HDD
1980 through 1981 ----> 5142 HDD

These years are selected for Hood River as they represent the coldest, most typical, and warmest years out of the last 10 years, and in some sense, provide upper and lower bounds on potential savings available from the Hood River retrofit.

(a) The Pacific Northwest Laboratory (PNL) is operated for the Department of Energy (DOE) by Battelle Memorial Institute (BMI) under Contract DE-AC06-76RLO 1830.

Table 4.1 displays the AEC results averaged across the single-family, manufactured home, multifamily, and combined samples. The sample means are displayed before and after the installation of conservation measures using the 7 weather years described above.

The numbers reported are in kWh/ft^2 of conditioned floor area. To produce these estimates, the occupants' mean seasonal inside air temperatures were used. The most typical weather year from Table 4-1 indicates that the combined sample of homes showed a 24% reduction in kWh/ft^2-yr in the post-retrofit heating season. Single-family dwellings demonstrate a reduction in the pre-retrofit level of consumption of 30%. The small sample of multifamily units shows a change of 31%. Manufactured homes show the poorest results with an overall difference of 11%.

Figure 4.1 displays the distributions of floor-area-normalized AECs in the form of box and whisker plots. The median AEC for each class of buildings is represented by the line drawn through the middle of the appropriate box. The lower and upper ends of the box represent the first and third quartiles of the data, respectively. Whiskers are drawn outward to show the outer ranges of the data, while asterisks indicate possible outliers. Significant post-retrofit reductions in estimated heating consumption are evident for all building types.

Figure 4.2 displays these data in a different format. The pre-retrofit AEC of each of the 113 analyzed homes is plotted against its corresponding post-retrofit AEC. Note, that while 90% of the homes lie below the line of equal pre- and post-retrofit consumption (indicating decreased post-retrofit consumption), 10% of the homes showed either an increase or no change in annual space heating estimates.

TABLE 4.1. Summary of Pre- and Post-Retrofit Sample Means: Estimated Electric Space Heating Consumption (kWh/ft^2-yr) (Samples Based on Average Measured Inside Air Temperature)

Weather Year	SAMPLE: Combined				Single-Family				Manufactured				Multi-Family			
	Pre	Post	Δ	Δ%	Pre	Post	Δ	Δ%	Pre	Post	Δ	Δ%	Pre	Post	Δ	Δ%
Hood River 78-79 6134HDD (coldest)	9.57	7.35	-2.22	-23	8.55	6.12	-2.43	-28	13.17	11.78	-1.39	-11	9.25	6.57	-2.69	-29
Hood River 76-77 5502HDD (most typical)	8.46	6.41	-2.05	-24	7.56	5.32	-2.24	-30	11.67	10.38	-1.28	-11	8.12	5.64	-2.47	-30
Hood River 80-81 5142HDD (warmest)	7.62	5.74	-1.88	-25	6.80	4.75	-2.06	-30	10.51	9.34	-1.17	-11	7.28	5.02	-2.25	-31
Seattle TMY	7.77	5.83	-1.94	-25	6.94	4.81	-2.13	-31	10.70	9.51	-1.19	-11	7.45	5.11	-2.34	-31
Spokane TMY	11.16	8.60	-2.57	-23	9.96	7.17	-2.79	-28	15.40	13.76	-1.63	-11	10.71	7.63	-3.08	-29
Missoula TMY	12.91	9.98	-2.93	-23	11.52	8.33	-3.19	-28	17.79	15.93	-1.86	-10	12.44	8.91	-3.52	-28
Portland TMY	6.71	5.02	-1.69	-25	5.99	4.14	-1.85	-31	9.24	8.21	-1.03	-11	6.43	4.39	-2.04	-32
	n=113				n=62				n=24				n=7			

Δ =Post-Pre   Δ% =100• (Post-Pre)/Pre

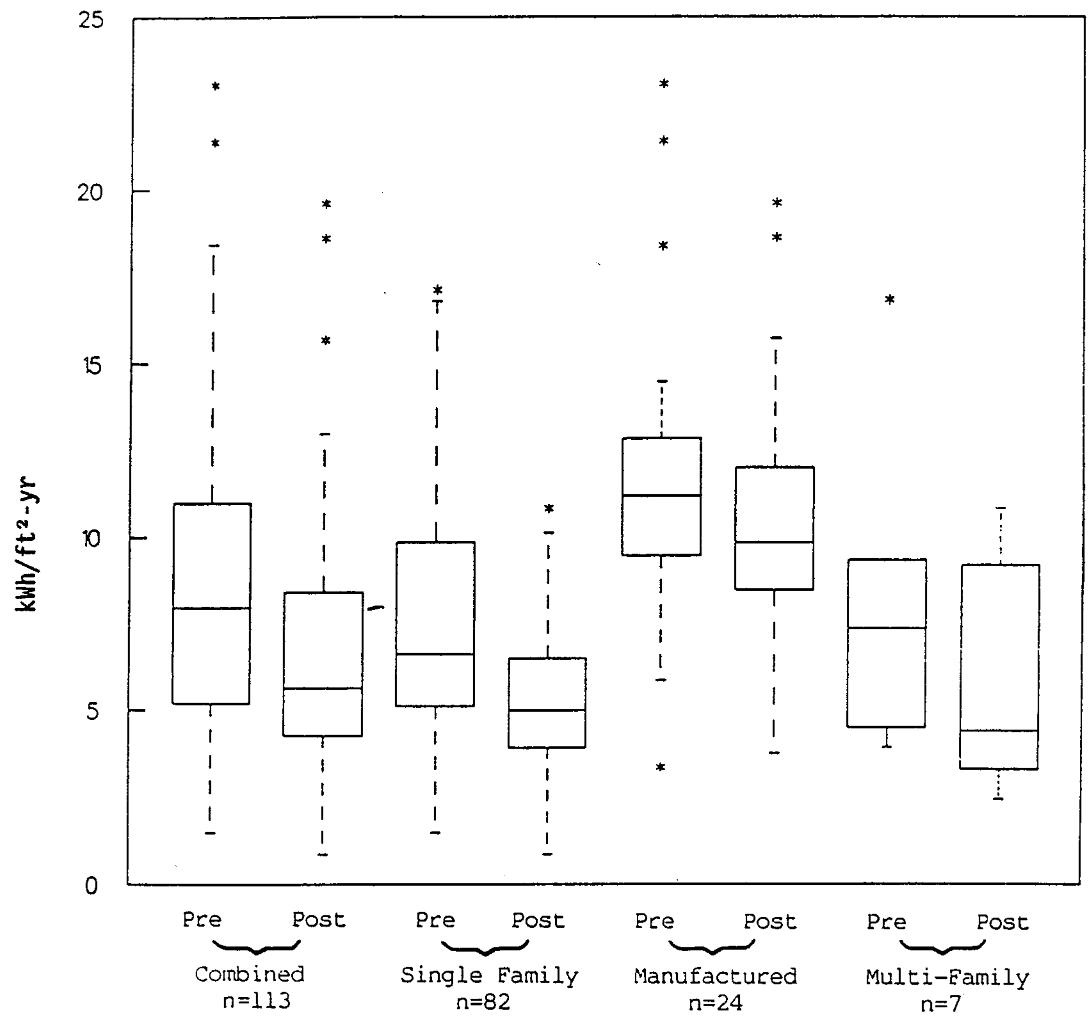

FIGURE 4.1. Annual Electric Space Heat Consumption Estimate for 113 Hood River Homes - Before and After Retrofitting

Table 4.2 displays a performance summary of the various statistics for the 113 Hood River homes. The annual space heating estimates (in the first two rows) are derived by using the occupants measured indoor temperatures and Hood River's most typical weather year. The mean of the total estimated space heating requirements is displayed by housing type in Table 4.2. The pre-retrofit mean AEC value of 10,111 kWh/yr for the combined sample drops to 7679 kWh/yr in the post-retrofit period. This represents a change of 2432 kWh/yr, or a 24% decrease. The change in estimated total space heating consumption

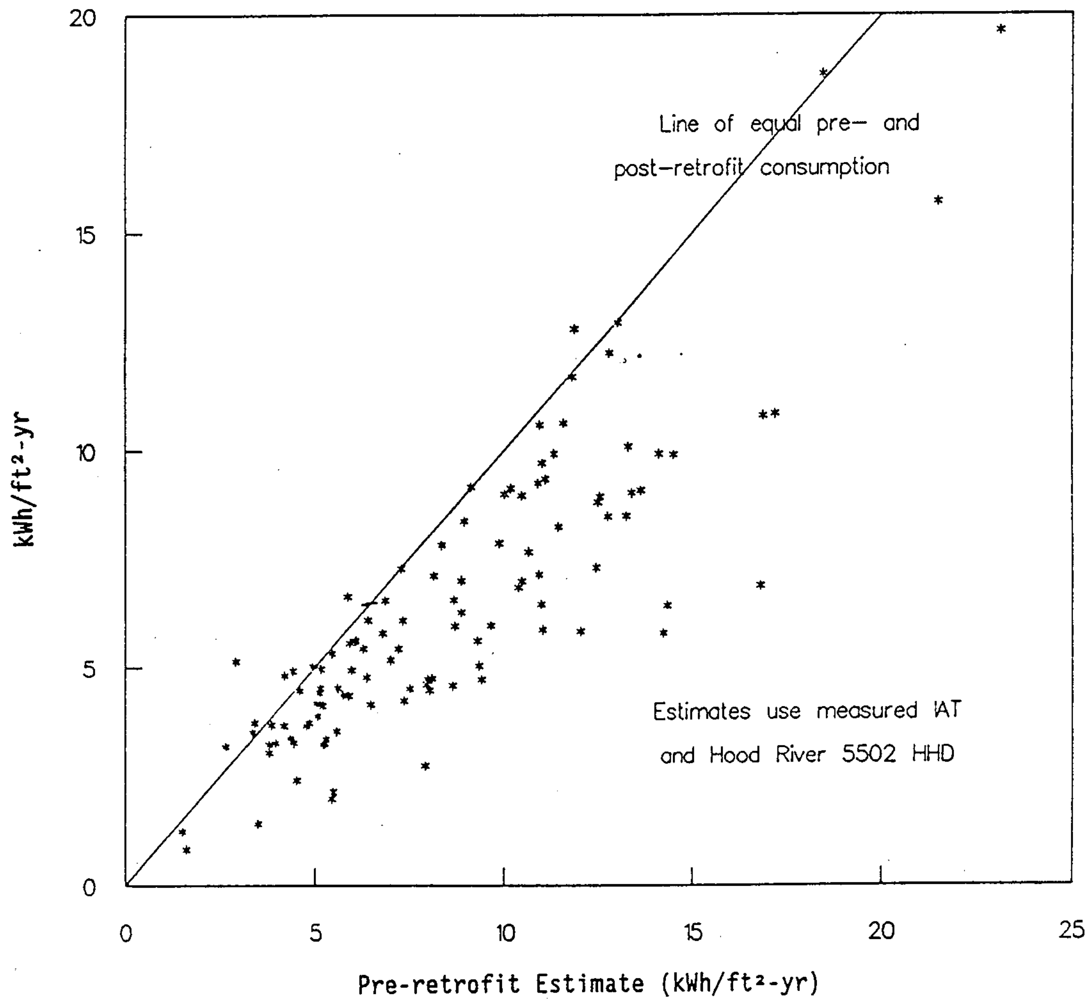

FIGURE 4.2. Pre- and Post-Retrofit Estimated Electrical Space Heat Consumption for Combined Sample: Single-Family, Multifamily, and Manufactured Homes

for the single-family, multifamily, and manufactured home samples represents decreases of 28%, 10%, and 30% respectively, in the pre-retrofit consumption level.

The distribution of floor areas for the various building types is illustrated in Figure 4.3. The average floor area for the few multifamily units is 60% of that for the mean of the single-family homes. The mean manufactured home size tends to be about two-thirds the size of the mean floor area for the single-family dwellings. Although considerable variation exists

TABLE 4.2. Performance Statistics for 113 Hood River Homes

Weather Year	Combined				Single Family				Manufactured				Multi-Family			
Measures	Pre	Post	Δ	Δ%	Pre	Post	Δ	Δ%	Pre	Post	Δ	Δ%	Pre	Post	Δ	Δ%
AEC/sq.ft. (kWh/sq.ft-yr)	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 Derived From Linear Model (kWh/day-sq.ft.-°F)	.00219	.00175	-.00044	-20	.00195	.00148	-.00046	-24	.00303	.00269	-.00033	-11	.00211	.00164	-.00048	-23
As-Operated UA (BTU/hr-°F)	377	301	-76	-20	385	296	-89	-23	389	350	-39	-10	246	192	-54	-22
Balance Delta From Linear Model (°F)	11.9	12.9	1.0	9	11.7	12.9	1.2	10	11.5	11.6	.1	.8	11.7	12.9	1.2	10
Inside Air Temp (°F)	70.9	71.1	.3	.4	70.8	71.1	.3	.4	70.5	70.5	0	0	70.8	71.1	.3	.4
Mean Conditioned Floor Area (sq.ft.)	1293				1422				988				839			
Sample Size	113				82				24				7			

Δ =Post-Pre Δ% =100* (Post-Pre)/Pre

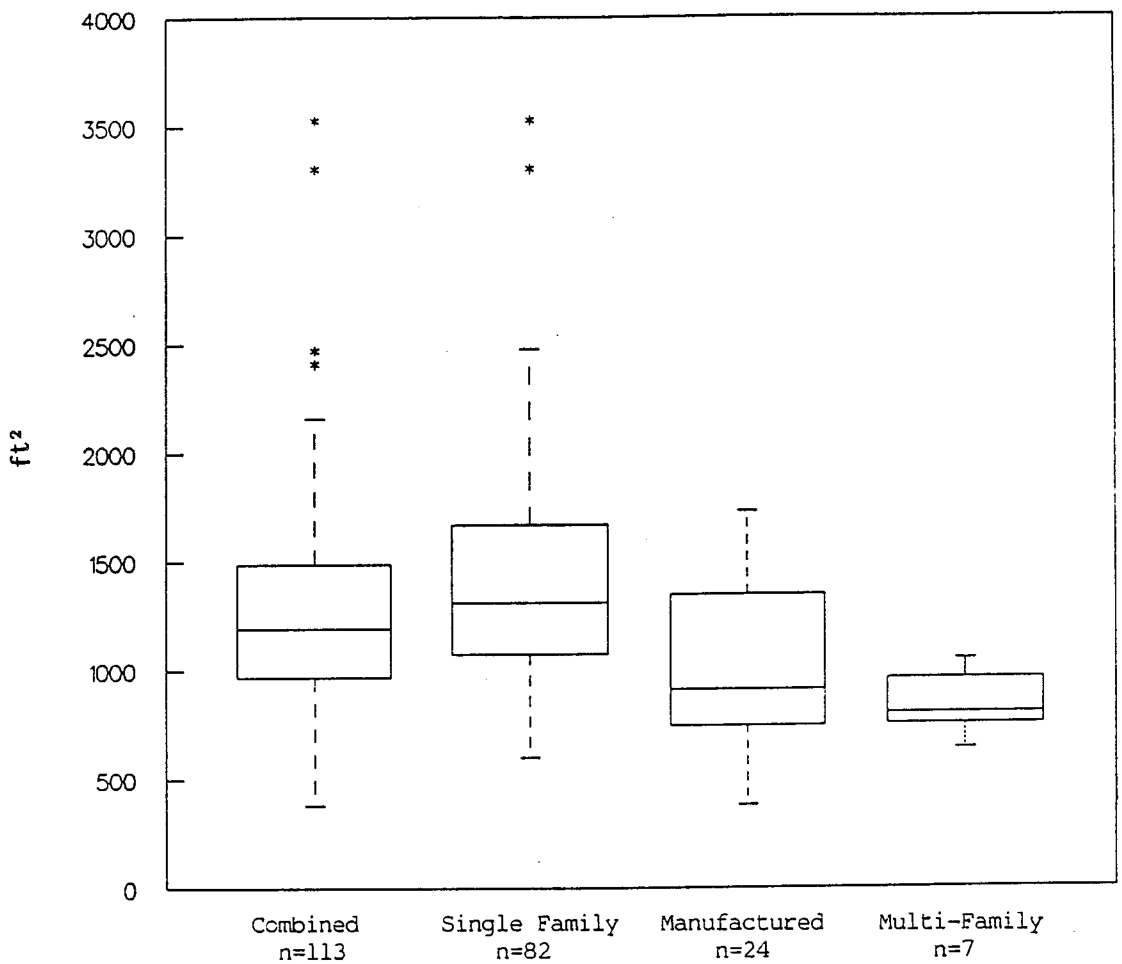

FIGURE 4.3. Conditioned Floor Areas for the Analyzed Set of 113 Hood River Homes

in housing size within both the single-family and manufactured-home groups, comparable changes for total AEC and floor area normalized AEC are observed between the post- and pre-retrofit heating seasons for homes in each of these building classes.

4.2 PARAMETERS FROM THE LINEAR FIT

The slope from a linear fit of daily space heating consumption data to inside-outside temperature difference can be viewed as a measure of a structure's thermal integrity. The distribution of the slopes by building

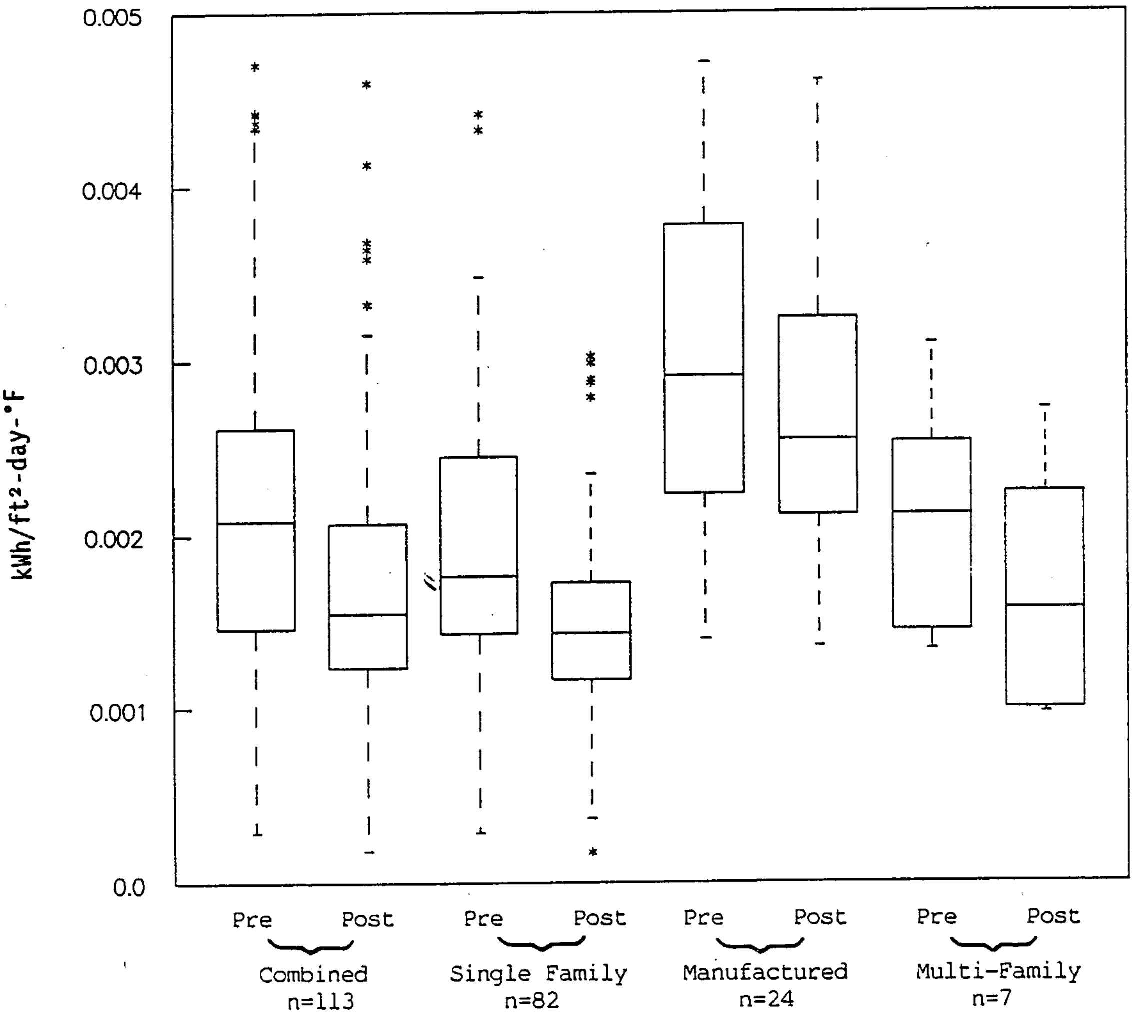

FIGURE 4.4. Slopes from the Robust Linear Fits for 113 Hood River Homes - Before and After Retrofitting

type, before and after retrofit, are displayed in Figure 4.4. The overall change in post-retrofit slopes for the combined sample is approximately 0.00044 kWh/ft²-day°F or 20% of the pre-retrofit level. The single-family and multifamily groups show greater shell improvement than the manufactured homes. This is evidenced by the larger decrease in slope, both in absolute and percentage terms.

In discussing the estimated annual electrical space heating consumption it is useful to consider both kWh/ft²-yr and total kWh/yr. A similar exercise is performed for the slopes. By removing the floor area normalization and applying a change of units, the slope from the robust linear fit is transformed to an "as-operated" heat loss coefficient for the residential envelope. Because this coefficient can be interpreted as a measure of the resistance of the envelope to heat transport, changes in the as-operated UAs are examined across building types for the pre- and post-retrofit heating seasons. Increased thermal resistance is indicated by a downward shift in the UA.

Figure 4.5 compares the before and after as-operated UAs for the analyzed end-use metered homes. In this figure, the single-family homes are

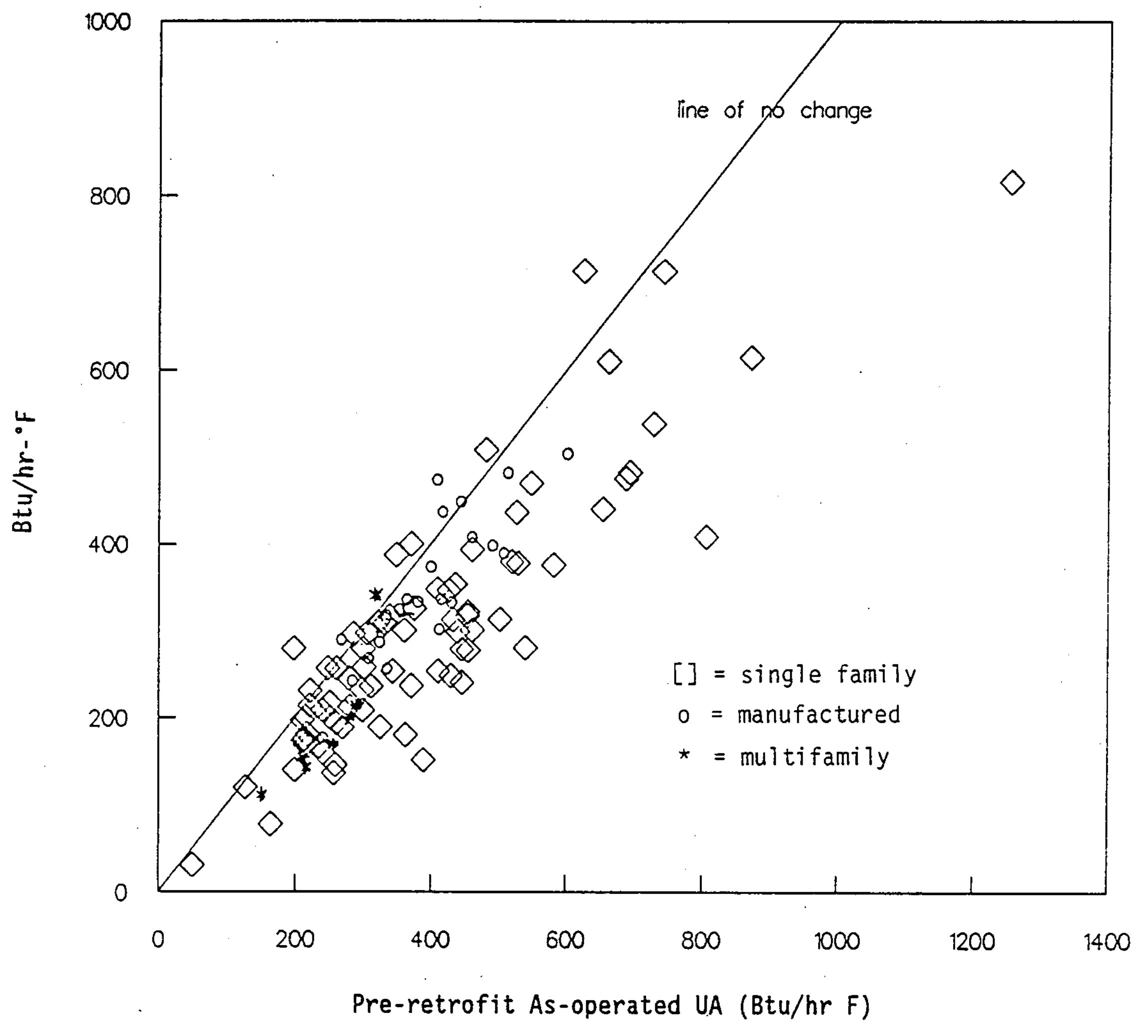

FIGURE 4.5. As-Operated UAs 113 Hood River Homes

noted with diamonds, multifamily homes with squares, and manufactured homes with asterisks. The line of equal pre- and post-retrofit as-operated UAs is drawn to enhance before and after comparisons. The as-operated UA is computed from those slopes illustrated in Figure 4.4 but also includes multiplication by floor area and a conversion factor to change the kWh/ft^2-day°F to Btu/hr-°F. The manufactured homes, as a group, cluster more closely to the identity line than do the single-family units. The change in as-operated UA for the manufactured homes represents a 10% reduction, compared to a change of 23% for single-family homes and 22% for multifamily units. The mean combined UA, pre- and post-retrofit, can be read from row 4 of Table 4.2 at 377 and 301, respectively. This represents an average reduction of 20%.

The upward change in balance temperature difference, illustrated in Figure 4.6 for the various samples, indicates improvement in thermal performance as expected. An increase in balance temperature difference is evidence of the shell's improved ability to support a greater temperature difference without use of the space heating equipment. The means for the sample distributions displayed in Figure 4.6 are summarized in Table 4.2. The single-family sample and multifamily units show a shift upward in the mean of 1.2°F (an 11% change). 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 delta temperature difference.

4.3 FURTHER EXPLORATION OF DERIVED PARAMETERS

Approximating total electrical energy consumption as UA multiplied by heating-degree days, displayed in Equation (1), provides a way to compare the parameters derived from the linear fit with the AEC. The change in total energy consumption can be approximated as the change in the product of UA multiplied by the heating-degree days. This relationship can be expressed as the total differential given in Equation (2). If both sides of this equation are divided by the terms in Equation (1), a new form of the equation is produced that allows comparison of the several percentage changes found in Table 4.2.

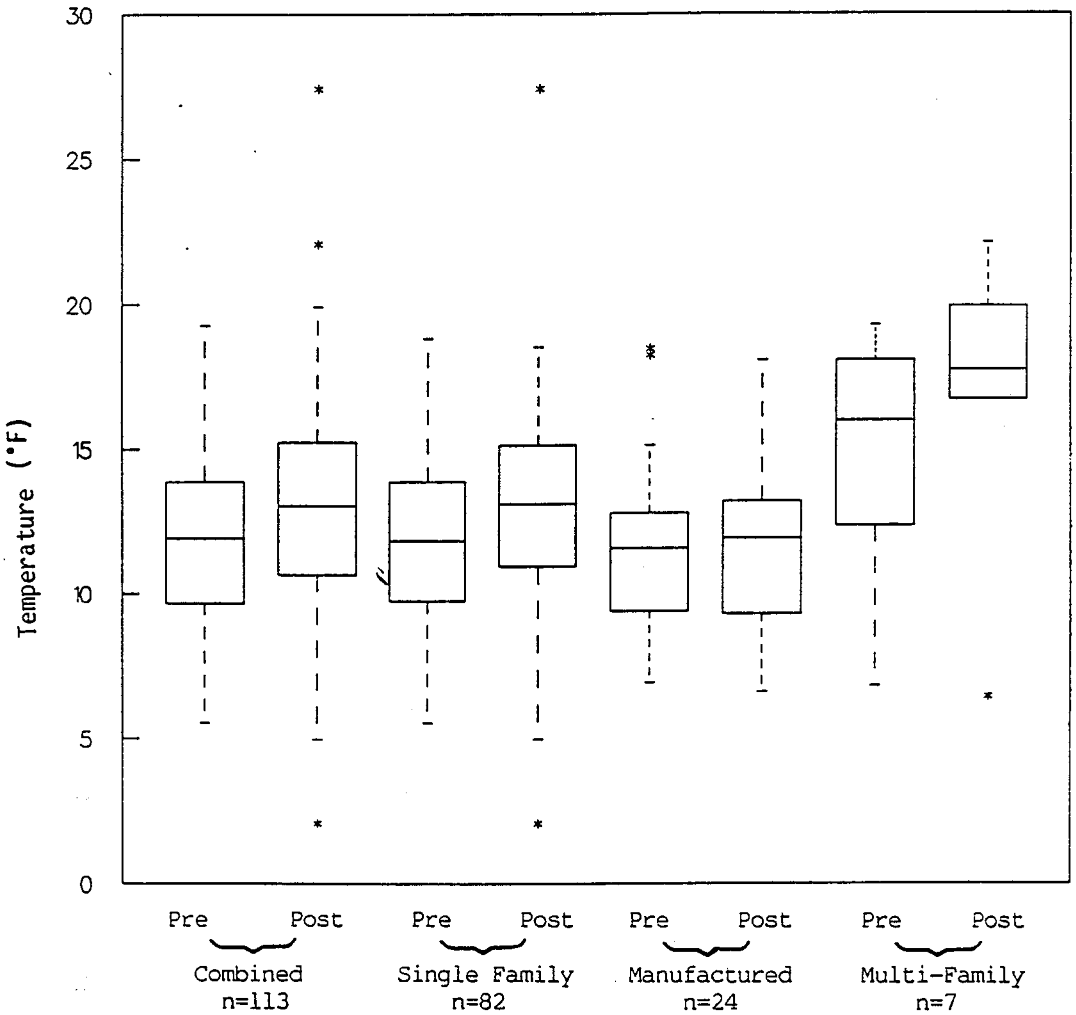

FIGURE 4.6. Balance Delta Temperatures from the Robust Linear Fits for 113 Hood River Homes - Before and After Retrofitting

$$E = UA * HDD \quad (1)$$
$$d(E) = d(UA) * HDD + d(HDD) * UA \quad (2)$$
$$d(E)/E = d(UA)/UA + d(HDD)/HDD \quad (3)$$

In Equation (3), the term d(E)/E is interpreted as the percentage change in total consumption for the two heating season estimates. The term d(UA)/UA is interpreted as the percentage change in as-operated UA. The percentage change in effective heating-degree days, represented by the term d(HDD)/HDD, must be computed from the balance temperature difference, the mean inside air temperature, and the Hood River weather year. Subtracting the balance temperature difference from the mean inside air temperature provides a balance outdoor temperature. This balance outdoor temperature is then used as a base for computation of effective heating-degree days. This effective heating-degree day computation is performed for each building type, using the same weather year for each pre- and post-retrofit parameter set. Table 4.3 summarizes the percentage changes in effective heating-degree days for the combined, single-family, multifamily, and manufactured home sample.

Substituting the percentage changes from Table 4.2 for the total AEC and the as-operated UAs into Equation (3), along with the percentage change column from Table 4.3 for each of the building-types, yields Table 4.4.

There is very close agreement between the results from the AEC numbers and those parameters derived from the robust linear fit. The percentage changes for as-operated UAs and balance outdoor temperatures sum to within 1 or 2 percentage points of the percentage change in total AEC for each of the building groups displayed. Moreover, for all home samples except the manufactured homes, the reduction in total kWh for space heating is about 80% of the reductions in as-operated UA and 20% of 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. Not only do the manufactured homes experience less savings in AECs than do the single-family and the multifamily units, but the savings that do occur are in different proportions of the UA and the effective HDD.

TABLE 4.3. Changes in Effective Heating Degree-Days Using Most Typical Hood River Weather Year - Pre- and Post-Retrofit Parameter Set

Building Type	Balance Outdoor Temp(°F) Pre	Post	Effective HDD Pre	Post	Percentage Change
Combined	59.0	58.2	3800	3599	5.3
Single Family	59.1	58.2	3826	3599	5.9
Manufactured	59.0	58.9	3800	3775	0.7
Multifamily	59.1	58.2	3826	3599	5.9

TABLE 4.4. Substitution by Building Type
d(E)/E = d(UA)/UA + d(HDD)/HDD

Building Type	d(E)/E	d(UA)/UA + d(HDD)/HDD	d(UA)/UA	d(HDD)/HDD
Combined	24	25	20	5
Single Family	30	29	23	6
Multifamily	30	28	22	6
Manufactured	11	11	10	1

4.4 INSIDE AIR TEMPERATURE

When a major home-tightening program results in less savings than was originally anticipated, it is often postulated that occupants, aware that their homes are now more energy-efficient, become less concerned with energy conservation and negate some of the energy savings by increasing the use of comfort and convenience devices. "Takeback," as this phenomenon is commonly termed, can take on several forms but is most commonly attributed to changes in zoning behavior or thermostat usage. Zoning is the practice of not heating unused rooms. An occupant who previously closed off unused rooms might cease to do so when the house becomes more efficient. Similarly, thermostat settings might be increased, keeping the homes warmer after the retrofits.

The issue of zoning is difficult to resolve because of limitations of the data collected from each house. An in-depth discussion of zoning appears in Section 6.0 and presents a plausible explanation of how the unrealized HRCP savings might be related to zoning behavior. Thermostat settings are investigated more easily because each end-use metered home has an indoor air temperature sensor. The results of the thermostat investigations are presented in this section.

Inspection of indoor temperature data does not reveal conclusive evidence that occupants increased temperatures in the main living area for these homes. Figure 4.7 displays the distribution of the mean heating season indoor temperature for each sample both before and after retrofit. Although there is a slight upward trend 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

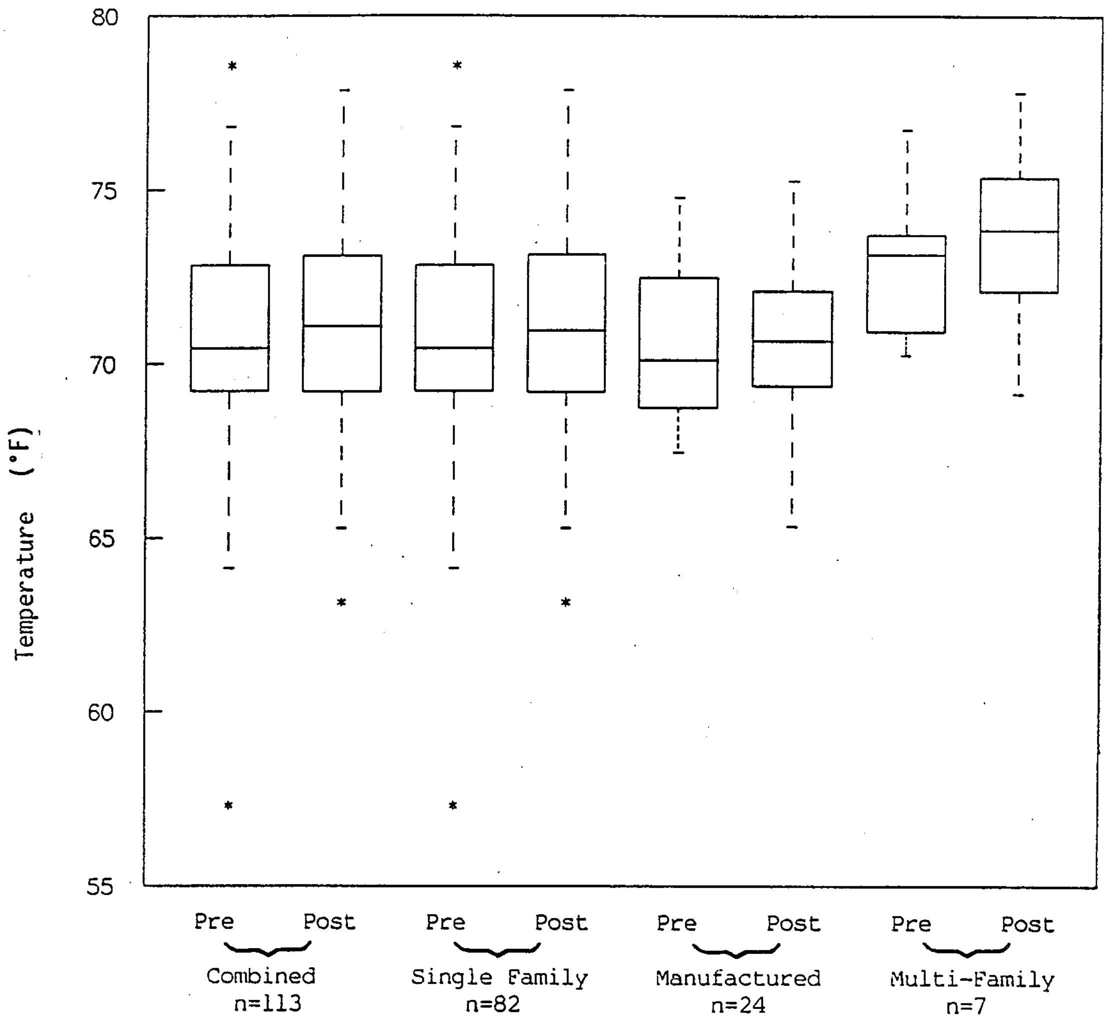

FIGURE 4.7. Mean Indoor Temperatures for 113 Hood River Homes - Before and After Retrofitting

air temperature would be indicative of changes in thermostat usage, thermostat set points were investigated in on several thermal simulations. The goal of the simulations was to produce an estimate of inside temperature over the heating season given a set of UAs similar to the pre- and post-retrofit as-operated UAs. We constructed a simple thermal network model representing a single-zone building. The model includes a single indoor air node, a pure resistance to heat flow between inside and outside, and a thermal mass node connected to the air via a simple thermal resistor. Using finite difference techniques, we modeled the indoor temperature assuming the house was equipped with a thermostatically controlled heating system. The thermal mass parameters used in the simulation were derived from regression analyses of metered data from several homes and represent thermal storage capacities typical of residential structures.

In the absence of Hood River TMY data, Portland TMY outside weather and solar data were used in the test cases. Using Portland TMY data tends to underestimate the changes in mean inside air temperature that would be observed using Hood River data because Portland has less HDD than Hood River.

The home is initially simulated with a UA of 385 Btu/hr-°F and then with a 20%-reduced UA of 307 Btu/hr-°F. The difference in average indoor air temperatures was compared for three distinct thermostat set point control strategies. The strategies used were 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 heating system used in the simulation was electric resistance heat with no air conditioning. The simulator generated hourly inside temperature data from September through May. The averaged results are presented in Table 4.5. Note the interplay of the two separate effects from Table 4.5. There is the expected effect of the average temperature decreasing as the more dramatic setback activity takes place. Also, as UA decreases, the mean inside air temperature increases. Part of this increase is because of the effect of the heating season shoulder months appearing in the data. During these months, space heating equipment is used very little, and the inside air temperature is often floating above the set point as evidenced by the average temperatures exceeding the set point in the constant-set point scenario. No air conditioning or venting was used in the simulation runs. The lower-UA home loses heat from the inside air in the living space to the outside more slowly. The other part of the UA-related effect is that during the periods of setback, the temperature of the inside air for the lower-UA homes is decaying more slowly than that for the higher-UA home.

TABLE 4.5. Mean Simulated Inside Air Temperatures (September through May) for Two Homes and Three Thermostat Control Strategies

Control Strategies	UA = 385	UA = 307
Constant thermostat set point	72.3	72.7
Single-evening setback	69.3	69.9
Morning and evening setbacks	67.3	68.2

It is clear from these simple simulations that modifying a building's UA can increase its average heating season temperature by at least as much as was observed in the HRCP homes. This is true even for the constant-set point thermostat strategy but is more pronounced when some setback behavior is evident. The hypothesis that thermostat takeback is partially responsible for the lower-than-expected savings in the Hood River project is not supported by the data.

4.5 COMPARISON TO THE ELCAP HOMES

Bonneville has also funded a collection of end-use metered data, through ELCAP, for a large group of homes throughout the Northwest region. Previous analyses of the ELCAP Base sample[b] and ELCAP Residential Standards Demonstration Program (RSDP) sample (Drost et al. 1987) use the same methodology as the Hood River end-use metered thermal characterization and invite performance comparisons between the ELCAP samples and Hood River homes.

The mean annual space heating estimates shown in Table 4.6 are for the ELCAP-monitored homes that participated in the RSDP and for the ELCAP base homes. The Model Conservation Standards (MCS) homes are those homes built to aggressive building standards proposed by the Northwest Power Planning Council. The control homes are those built to represent current construction practices of new homes as part of the RSDP. The base homes are roughly representative of the existing single-family, owner-occupied, electrically heated homes in the region. The electrical space heating consumption estimates for the ELCAP homes located in regions having less than 6000 base

(b) 1990 draft report, Pacific Northwest Laboratory, Richland, Washington.

65 HDD were computed using Seattle TMY data and the occupants' average measured inside temperatures. Seattle TMY data was selected because those AEC's were readily available.

Table 4.6 displays Hood River pre-retrofit consumption for the single-family sample as 6.94 kWh/ft^2-yr. This level is fairly close to that of the ELCAP base sample. Post-retrofit end-use metered Hood River consumption for the single-family sample is closest to that of the control homes. If the mean post-retrofit consumption estimate for the single-family homes (4.81 kWh/ft^2-yr) is compared to that of the ELCAP control homes (4.76 kWh/ft^2-yr), the Hood River retrofits can be viewed as bringing the homes up to current construction practice on the average.

TABLE 4.6. ELCAP and Hood River Homes' AEC Using Seattle TMY Weather Data

AEC	MCS	ELCAP Control	Base	Hood River Pre-retrofit	Single-Family Post-retrofit
kWh/ft^2-yr	3.32	4.76	7.41	6.94	4.81

5.0 WOOD STOVE USAGE

About 60% of the end-use metered homes are not included in the thermal performance characterizarions cited in Section 4.0. The predominant reason for excluding these homes is that burning wood creates a significant non-electric source of space heating energy. Because this analysis 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 excluded sites. (Only 14% of the homes with wood-stove sensors are included in the previously stated results. For these homes, days with wood-stove usage are excluded prior to the thermal characterizations.) However, the wood-burning homes did provide a way to estimate the amount of expected HRCP savings not realized because of electric heat displacement by the alternate fuel. It is reasonable to expect that subsequent to the retrofits, less burning of wood would be required to heat these homes. Indeed, post-retrofit wood-use surveys indicated that HRCP homeowners reduced wood consumption by an average 0.4 chords between the pre- and post-retrofit winters (Hirst 1987).

For the homes with functional wood-stove sensors a very simple analysis was performed to answer three questions:

1. Did the total number of days of wood-stove usage decrease post-retrofit?
2. Did the total number of days of heating system usage increase post-retrofit?
3. Did the intensity of wood-stove usage, as represented by the total number of hours the stove was used or the average amount of heat output by the stoves, decrease post-retrofit?

The magnitude of the Hood River wood-stove signal is proportional to the heat output. For each single-family home with a reliable wood-stove sensor having data for at least 90% of the November-through-March period of 1984 through 1985 and 1985 through 1986 (a total of 43 homes) a mean daily wood-stove signal was created by averaging each of the 15-min records for the day. 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 is noted in mean outdoor air temperature for the two 5-month periods. The total number of days during which the wood stove is in use during the 5-month period is counted for each site. Those numbers are then averaged for all sites for each heating season. The total number of days during which the electric heating system equipment is in use is also counted for each site. These numbers are then averaged for all sites. These means can be found in Table 5.1.

The means in Table 5.1 indicate very little change in the number of days when 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. Mean pre- and post-retrofit heater usage are the same. The average wood-stove signal over the November through March period is presented in Table 5.1. The mean heater load over the same period is also shown. Wood-stove usage drops 27% in the post-retrofit period in the sample mean. While it is conceivable that some of this reduction could be caused by wood-stove sensors becoming dirty with time or failing for other reasons, the magnitude of the change makes this explanation unlikely. The reduction is consistent with the occupant survey results and is further supported by the wood-burning intensity tests described below. The mean heater load drops only 17%.

To address the third question, on wood-burning intensity changes, the mean wood-stove signal for each day in the heating season is binned according to the magnitude of the signal. Hence, each site has a certain number of days in wood-burning categories denoted as low, medium, medium high, and high. Averages for each of these categories are taken for all sites and are summarized in Table 5.2.

TABLE 5.1. Hood River Single-Family Wood-Stove Usage Summary for 43 Homes--No Weather Normalization (November through March)

Intensity	Wood Stove Mean Days in Use	Space Heat Mean Days in Use	Mean Wood-Stove Signal	Mean Space Heat Load, kWh/day
Pre-retrofit	127	51	1640	25.8
Post-retrofit	120	51	1202	21.4
Change, %	-6	0	-27	-17

TABLE 5.2. Mean Number of Days in Each Burn Category for 43 Single-Family Homes

Intensity	Burn Category			
	Low	Medium	Medium-High	High
Pre-retrofit	17	22	39	48
Post-retrofit	24	23	37	32
Change, %	+41	+5	-5	-33

Figure 5.1 displays the information found in Table 5.2 in graphical form. These pie charts dramatically demonstrate a decrease in the mean number of days associated with the greatest wood-stove usage in the post-retrofit period as compared to the pre-retrofit period.

For the 43 single-family homes analyzed, the wood-stove usage did appear to drop by 27% after the installation of weatherization measures. The heater usage also went down but about 14%. For this group of homes, it appears that the greatest savings was seen in reduced wood-stove usage, although a significant reduction in space heating was also observed. The total number of days during which the wood stove was used dropped about 6% post-retrofit, and the total number of days during which the heater was used stayed about the same.

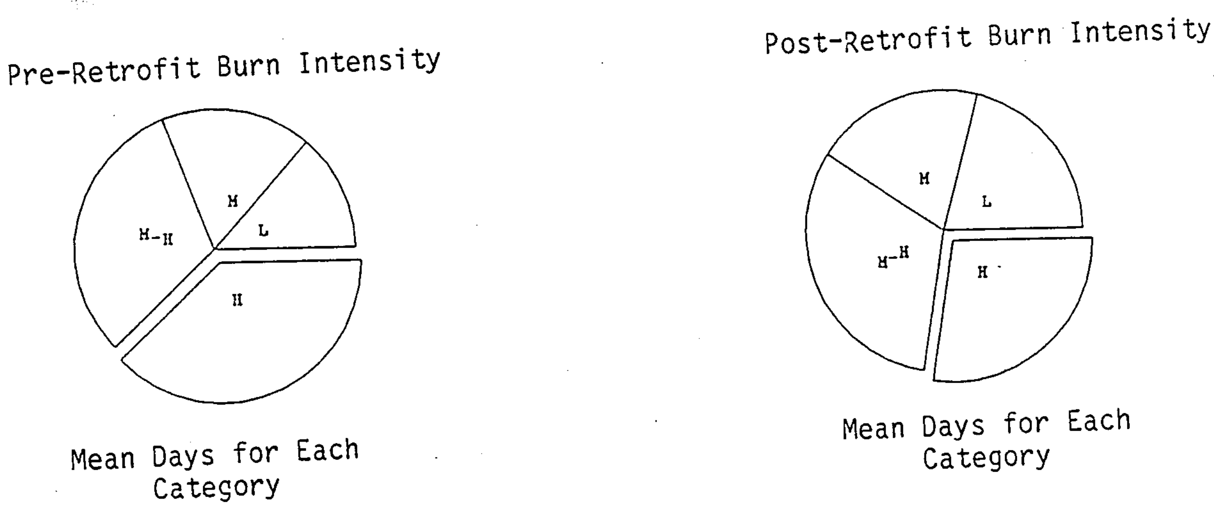

FIGURE 5.1. Pre- and Post-Retrofit Mean Shares of Total Days for Each of Four Burning-Intensity Categories for 43 Single-Family Homes During the November 1 Through March 31 Period

In the context of the HRCP savings estimates, which are based on an assumption of no wood-stove use, the reduction in post-retrofit wood-stove use is a type of takeback, in that occupants "diverted" some of the savings away from reduced electric bills. However, an analysis of the ELCAP wood-burning homes (Le Baron 1988) suggests that at least part of the disproportionate reduction in wood-stove use is unintentional on the part of the occupants. Le Baron showed that wood use is most intense in the evening hours, which are relatively warm compared to the night and early morning hours. Increased insulation in the post-retrofit HRCP homes could slow indoor temperature decay such that wood heating is simply not required until much later when occupants are sleeping and the electric heating system must meet the heating demand.

6.0 MISSING SAVINGS

Our analyses of the HRCP end-use metered homes show actual retrofit savings considerably lower than those projected at the inception of the project. This finding is consistent with that of Hirst (1987). Of the anticipated 6100 kWh/yr total savings per house, Hirst observed achieved savings of only 43%. Hirst postulates a number of potential reasons for the discrepancy. In this section, we discuss Hirst's hypotheses in the context of our analyses. Where appropriate, we examine some of these issues in more detail or provide additional complementary or contrasting theories.

Note that many of the comparisons in this section are based on estimated, not measured, energy consumption values. We have taken the liberty of approximating values that were not originally calculated in our analyses or those of Hirst (1987) to make the comparisons more meaningful.

6.1 COMPARISON OF OUR RESULTS

A comparison of our results with those of Hirst (1987) is complicated by the fact that the savings estimates produced in the two reports only overlap for two classes of building among the six classes implicitly defined, as shown in Table 6.1. Further, audit projections of retrofit savings are only

TABLE 6.1. Building Classes Analyzed in Two Hood River Studies

Building Class	Building Type	Fuels	Results Available? Hirst	Results Available? Ours	Audit Projected Savings?
All buildings	All homes	All	Yes	No	Yes
Electric buildings	All homes	Electric	Yes	Yes	No
Wood buildings	All homes	Wood	No	No	No
All SFDs[a]	Single Family	All	Yes	No	No
Electric SFDs	Single Family	Electric	Yes	Yes[b]	No
Wood SFDs	Single Family	Wood	No	Yes	No

(a) Single-family detached homes.

(b) Data were not weather normalized.

readily available for one class, the entire Hood River housing population that received retrofits, which is not one of the two classes common to both analyses.

This lack of overlap occurs because of the nature of the analytical techniques used. The Princeton Scorekeeping Method (PRISM) billing data analysis technique used by Hirst to obtain space heating estimates can only be expected to yield accurate results when the actual total space heating fuel consumption is reflected in the billings (as wood is not). Sites that exhibited a high degree of scatter were presumed by Hirst to be wood burning and results were not presented for these homes, although estimates are provided for the populations using both fuels (single-family or all housing types).

The techniques we use to examine heating savings explicitly remove wood-burning days to develop savings estimates as if each home was heated purely by electricity. Only homes with very heavy wood burning or other random behavior that precludes characterizing daily loads with indoor and outdoor temperatures are excluded from the analysis. This is essentially the same criterion used by Hirst, except at the daily instead of monthly level. Applying the filter at the daily level allowed us to eliminate fewer homes from the analysis. We performed a separate analysis of electrical consumption by heavy wood-burning single-family homes. This wood use analysis was not weather normalized, but the two weather years analyzed were quite similar to one another.

6.1.1 Methodology for Comparison

Because of the lack of overlap between our study and Hirst's, we have estimated values for the building classes not common to the two reports. In Hirst's work, we estimate values for the two classes of wood-burning homes by applying appropriate proportions to the total data population given in his report. For example, Hirst shows that there were 2362 total homes in the study and 615 electric homes; therefore, there must be 1747 wood-burning homes. Hirst shows that the 2,362 homes use an average 18,600 kWh/yr, while the electric homes use 21,000 kWh/yr. We calculated that the wood-burning homes must average 17,755 kWh/yr to be consistent with these values.

Because this section is merely a discussion of the missing savings issues, we have done no additional analyses of the end-use metered homes. Therefore, a similar estimation process was applied to fill some of the gaps in our results. In this case, we combined the average consumption of electric SFD homes with the average consumption of wood-burning SFDs to obtain total SFD population consumption estimates. In doing so, we use Hirst's ratio of the number of electric SFDs to the number of wood-burning SFDs because he analyzed a larger, more representative sample of homes. By assuming that the ratio between electric consumption and wood-burning consumption for other (non-SFD) homes is identical to that of SFD homes, we estimated electrical consumption for all classes of wood-burning homes. Finally, using Hirst's electric/wood population ratio, we estimate consumption for the entire population.

Table 6.2 displays these various observed and estimated data. Note that our analysis of wood-burning homes' electrical consumption included only the months of November through March. For this comparison, we have scaled these values upward by a factor of 1.34, the ratio of heating degree days (base 60°F) for the entire year and the November-through-March period for Olympia, Washington. Among the regional TMY sites, Olympia has the seasonal temperature pattern most like that of Hood River. Obviously, this provides only an approximation of the annual electric loads in these buildings. However, in contrast to the vast differences between predicted and observed savings in the HRCP homes, the errors introduced by this approximation are reasonably small.

The data derived from the Hirst analysis in Table 6.2 show that the electric space heat savings estimates for the wood sites are apparently larger than for the electrically heated sites. This is probably a result of inaccuracies in PRISM estimates for the wood sites, as would be expected given the degree of scatter introduced in monthly billings by wood-burning behavior. Hirst points out that for the All Building and All SFD classes, there is a slightly higher estimated space heating savings than total savings, incorrectly implying that savings taken by hot water measures were negative. This was attributed to inaccuracies in PRISM estimates, so the total savings

TABLE 6.2. Raw Data and Population Estimates

	HIRST, et al. (1982/83 vs. 1985/86)					
	ALL BUILDINGS	ELECTRIC BUILDINGS	WOOD* BUILDINGS	ALL SFDs	ELECTRIC SFDs	WOOD* SFDs
NUMBER IN SAMPLE	2,382	615	1,747	1,545	362	1,183
FLOOR AREA	1,350	1,360	1,348	1,560	1,670	1,526
SPACE HEAT, BEFORE	7,500	9,200	6,902	7,600	10,300	6,774
SPACE HEAT, AFTER	4,800	6,600	4,166	4,600	7,000	3,866
SPACE HEAT SAVINGS	2,700	2,600	2,735	3,000	3,300	2,908
HEAT SAVINGS, %	36%	28%	40%	39%	32%	43%
TOTAL, BEFORE	18,600	21,000	17,755	20,400	24,400	19,176
TOTAL, AFTER	16,000	17,800	15,366	17,500	20,400	16,613
TOTAL SAVINGS	2,600	3,200	2,389	2,900	4,000	2,563
TOTAL SAVINGS, %	14%	15%	13%	14%	16%	13%

	MILLER, et al. (1984/85 vs. 1985/86)					
	ALL* BUILDINGS	ELECTRIC BUILDINGS	WOOD* BUILDINGS	ALL* SFDs	ELECTRIC SFDs	WOOD SFDs (ELECTRIC)
NUMBER IN SAMPLE	N/A	113	N/A	N/A	82	43
FLOOR AREA	N/A	1,293	N/A	N/A	1,422	N/A
SPACE HEAT, BEFORE	6,419	10,111	5,119	6,415	10,315	5,222
SPACE HEAT, AFTER	5,317	7,679	4,486	5,054	7,415	4,331
SPACE HEAT SAVINGS	1,101	2,432	633	1,361	2,900	891
HEAT SAVINGS, %	17%	24%	12%	21%	28%	17%

(* Indicates Estimated Values for this Building Population)

OLYMPIA TMY USED FOR HOOD RIVER IN ADJUSTING WOOD ANALYSIS SEASON TO YEAR		WOOD SFDs (WOOD)	APPARENT WOOD SENSOR CALIBRATION
DAYS IN NOV-MAR =	151	43	
DD60 IN NOV-MAR =	2,732	N/A	
DD60 IN YEAR =	3,662		
DD60 YR/NOV-MAR =	1.34	331,939	0.0153
		243,287	0.0127
		88,652	
		27%	

were used in the analysis of Hirst (1987). However, this implicitly assumes that the savings resulting from the hot water measures were small, a conclusion not supported by the apparent hot water savings (the difference between the space heat savings and total savings for all types of electric homes or the electric SFDs, 600 kWh/yr and 700 kWh/yr, respectively).

We did not explicitly examine the water heating savings in the end-use metered homes, but there appeared to be sizeable savings in nearly all the homes examined. Our analysis is specifically confined to space heating, restricting the comparison with Hirst to space heating results and derivatives thereof at this time. However, the data do not indicate explicitly whether the comparison is better made using the space heating or total savings estimates from Hirst. We have somewhat arbitrarily chosen to use the space heating savings at this time (note this was **not** the decision of Hirst). We believe that this is justified for the population of electric homes, the one population that is directly comparable to our results.

6.1.2 Comparisons of Basic Heating Results

The estimated heating consumption from the two analyses for each of the six populations are compared side-by-side in Table 6.3. That table simply replicates the heating data from Table 6.2 but in side-by-side fashion to facilitate comparisons.

First, it is important to establish that the populations analyzed by the two studies are relatively similar. The only indicators available are floor area and absolute consumption before and after the retrofits. On the basis of floor area, the only valid points of comparison are for all the electrically heated homes and the electrically heated SFDs. The electric SFDs of our analysis are somewhat smaller (15%) than those of Hirst. This suggests the possibility of normalizing by floor area, but space heating is more a function of surface area than floor area, so the benefit of doing this is probably marginal. The floor areas of all types of electrically heated homes are seen to be remarkably comparable, differing by only 5%.

TABLE 6.3. Comparison of Savings Estimates Based on Metered Data and Fuel Bill Analysis

	ALL BUILDINGS		ELECTRIC BUILDINGS		WOOD BUILDINGS		ALL SFDs		ELECTRIC SFDs		WOOD SFDs	
	HIRST	MILLER*	HIRST	MILLER	HIRST*	MILLER*	HIRST	MILLER*	HIRST	MILLER	HIRST*	MILLER
NUMBER IN SAMPLE	2,362	N/A	615	113	1,747	N/A	1,545	N/A	362	82	1,183	43
FLOOR AREA	1,350	N/A	1,360	1,293	1,346	N/A	1,560	N/A	1,670	1,422	1,526	N/A
SPACE HEAT, BEFORE	7,500	6,419	9,200	10,111	6,902	5,119	7,600	6,415	10,300	10,315	6,774	5,222
SPACE HEAT, AFTER	4,800	5,317	6,600	7,679	4,166	4,486	4,600	5,054	7,000	7,415	3,866	4,331
SPACE HEAT SAVINGS	2,700	1,101	2,600	2,432	2,735	633	3,000	1,361	3,300	2,900	2,908	891
HEAT SAVINGS, %	36%	17%	28%	24%	40%	12%	39%	21%	32%	28%	43%	17%

(* Indicates Estimated Values for this Building Population)

Both the space heating consumption and the savings estimates of these two groups of homes are also very similar. This lends confidence to the conclusion that the two analyses were conducted using essentially comparable groups of homes. In each case the savings estimates agree to within 12% (fractional savings of 28% to 24% and 32% to 28% of space heat for all electric homes and electric SFDs, respectively). Thus, the basic conclusions of the two analyses regarding space heat savings for the population of electrically heated homes are mutually supportive.

The results in Table 6.3 are not as encouraging for the other four building classes, however. The basic problem is the difference in estimates for the wood-burning population, where the savings indicated by Hirst are dramatically larger than ours. This difference carries through into the population estimates for the SFDs and all homes. Note that this difference is greatly reduced if the total savings estimates from Hirst are used and 600 to 700 kWh/yr of savings are subtracted for the hot water retrofits, yet a difference of over 100% would still remain. This indicates that substantial insight could be gained by a detailed analysis of all the end-use metered wood-burning homes (those we didn't analyze using the AEC characterizations), matching the classification scheme of Hirst, to refine our wood-burning population estimates.

6.1.3 Comparison of Heating Results Modified to Account for Wood Burning

The issue of displacement by wood burning in Hood River appears to be major, as indicated by both our work and Hirst's. The data in Table 6.3 can be used to estimate displacement by wood and combined with electrical space heat, to estimate a total space heating load that should be more comparable with the load estimated by the original audits. This is displayed in Table 6.4. Note that the data for the electrically heated homes remains unchanged, but we assume that the wood-burning homes use the same quantity of space heat as the electric homes, yet use it from two sources. In this fashion, estimates of the contribution of wood to the total space heating load are developed for the other classes of homes both before and after the retrofits.

Note that the row labelled "Total Savings %" in Table 6.4 refers to savings as a percentage of the pre-retrofit total heating estimate. We use fractional savings rather than absolute savings in the comparisons to minimize differences resulting from differing baseline assumptions. Percentages also facilitate better comparisons with the original audit savings estimates because the pre- and post-retrofit consumption projections are not included in the Hood River audit database; only the differences between the two (the savings) were retained.

Note that the savings in wood estimated from Hirst's data are actually negative for the three All Buildings classes, and much smaller than our estimates for SFDs (see Table 6.2). By examining the basic data in Table 6.2, this savings is seen to result from the higher savings for the wood-burning buildings than the electric buildings. This is contradictory to the observed takeback effect in wood-burning behavior, and would no longer hold if the savings estimated from Hirst's data were based on the total electric bills instead of PRISM space heating estimates as discussed previously (Section 6.1). The adjustment for hot water savings then becomes critical, however.

The predicted and actual savings adjusted for wood displacement can now be compared. At this point, the six building type classes in Table 6.4 become redundant so only the two classes of interest (All Buildings and Electric

TABLE 6.4. Adjusted Savings Estimates Based on Analysis of Metered and Billing Data

	ALL BUILDINGS N = 2,362		ELECTRIC BUILDINGS N = 615		WOOD BUILDINGS N = 1,747		ALL SFDs N = 1,545		ELECTRIC SFDs N = 362		WOOD SFDs N = 1,183	
	HIRST	MILLER*	HIRST	MILLER	HIRST*	MILLER*	HIRST	MILLER*	HIRST	MILLER	HIRST*	MILLER
BASELINE ESTIMATES:												
ACTUAL ELECTRIC HEAT	7,500	6,419	9,200	10,111	6,902	5,119	7,600	6,415	10,300	10,315	6,774	5,222
ESTIMATED WOOD HEAT	1,700	3,692	0	0	2,298	4,992	2,700	3,900	0	0	3,526	5,093
ESTIMATED TOTAL HEAT	9,200	10,111	9,200	10,111	9,200	10,111	10,300	10,315	10,300	10,315	10,300	10,315
POST-RETROFIT ESTIMATES:												
ACTUAL ELECTRIC HEAT	4,800	5,317	6,600	7,679	4,166	4,486	4,600	5,054	7,000	7,415	3,866	4,331
ESTIMATED WOOD HEAT	1,800	2,362	0	0	2,434	3,193	2,400	2,361	0	0	3,134	3,084
ESTIMATED TOTAL HEAT	6,600	7,679	6,600	7,679	6,600	7,679	7,000	7,415	7,000	7,415	7,000	7,415
RESULTS:												
ELECTRIC SAVINGS, %	36%	17%	28%	24%	40%	12%	39%	21%	32%	28%	43%	17%
WOOD SAVINGS, %	-6%	36%	0%	0%	-6%	36%	11%	39%	0%	0%	11%	39%
TOTAL SAVINGS, %	28%	24%	28%	24%	28%	24%	32%	28%	32%	28%	32%	28%
PROJECTED SAVINGS	6,100	6,704	6,100	6,704	6,100	6,704	6,829	6,839	6,829	6,839	6,829	6,839
ADJUSTED SAVINGS	2,600	2,432	2,600	2,432	2,600	2,432	3,300	2,900	3,300	2,900	3,300	2,900
"MISSING" SAVINGS	3,500	4,272	3,500	4,272	3,500	4,272	3,529	3,939	3,529	3,939	3,529	3,939
ACHIEVED SAVINGS, %	43%	36%	43%	36%	43%	36%	48%	42%	48%	42%	48%	42%
"MISSING" BASELINE	12,385	17,761	12,385	17,761	12,385	17,761	11,016	14,012	11,016	14,012	11,016	14,012
"APPARENT" BASELINE	21,585	27,872	21,585	27,872	21,585	27,872	21,316	24,327	21,316	24,327	21,316	24,327

(* Indicates Estimated Values for this Building Population)

SFDs) are displayed in Table 6.5 for clarity. The original audit projection of savings for each home in the All Buildings class is 6100 kWh/yr. This estimate corresponds to the data in the first column of Table 6.5. The other three columns represent subsamples that do not correspond directly to the sample on which the 6100 kWh/yr projection is based. Therefore, we adjust the projected savings in each of those columns by the ratio between its estimated total pre-retrofit heating consumption and the savings in column one.

TABLE 6.5. Summary of Adjusted Savings Estimates Based on Metered and Billing Data

	ALL BUILDINGS N = 2,362		ELECTRIC SFDs N = 362	
	HIRST	MILLER*	HIRST	MILLER
BASELINE ESTIMATES:				
ACTUAL ELECTRIC HEAT	7,500	6,419	10,300	10,315
ESTIMATED WOOD HEAT	1,700	3,692	0	0
ESTIMATED TOTAL HEAT	9,200	10,111	10,300	10,315
POST-RETROFIT ESTIMATES:				
ACTUAL ELECTRIC HEAT	4,800	5,317	7,000	7,415
ESTIMATED WOOD HEAT	1,800	2,362	0	0
ESTIMATED TOTAL HEAT	6,600	7,679	7,000	7,415
RESULTS:				
ELECTRIC SAVINGS, %	36%	17%	32%	28%
WOOD SAVINGS, %	-6%	36%	0%	0%
TOTAL SAVINGS, %	28%	24%	32%	28%
PROJECTED SAVINGS	6,100	6,704	6,829	6,839
ADJUSTED SAVINGS	2,600	2,432	3,300	2,900
"MISSING" SAVINGS	3,500	4,272	3,529	3,939
ACHIEVED SAVINGS, %	43%	36%	48%	42%
"MISSING" BASELINE	12,385	17,761	11,016	14,012
"APPARENT" BASELINE	21,585	27,872	21,316	24,327

The Adjusted Savings is the combined estimate of electric and wood savings for the class, and the Achieved Savings is the percentage of projected savings as indicated. For the population as a whole, Hirst's data show an achieved fraction of projected savings of 43%. Similarly, our data indicate a 36% fraction. For electric SFDs, our achieved fraction of projected savings is 48% compared to Hirst's 42%. Therefore, after accounting for wood use, both studies indicate that more than one-half the projected savings were not achieved. Incorporating accurate hot water savings estimates might raise the achieved percentages, but Hirst's analyses indicate that the adjustments would be small.

6.2 HYPOTHESES REGARDING THE MISSING SAVINGS

The overall population average savings estimate based on energy audits of each HRCP site was 6100 kWh/yr. Even for the electrically heated sites, where both studies agree closely and savings would be expected to be highest, less than half of the expected savings were actually achieved. There are several basic conclusions and/or hypotheses drawn by Hirst (1987) regarding why the expected savings were not achieved. These can be summarized as follows:

- typical discrepancies between predicted and achieved savings
- reduced pre-retrofit baseline energy consumption
- post-retrofit increases in thermostat settings
- disproportionately larger post-retrofit decreases in use of wood for heating.

The first conclusion, that there are typically unrealized savings from retrofit programs, is undoubtedly true. However, this observation is central to the research questions that the HRCP was designed to answer and demands further examination and explanation.

Low pre-retrofit consumption was concluded to be the major contributor to the low achieved savings. Because the actual pre-retrofit heating load was dramatically below expectations, actual savings might be expected to be proportionally lower than predicted. Hirst states that pre-retrofit energy consumption in the Hood River SFDs was about 20,400 kWh/yr; 7600 kWh/yr of which was because of heating. He cites the typical regional average total consumption at about 25,000 kWh/yr with 13,000 kWh/yr for heating. The low HRCP consumption relative to the regional average was concluded to result from recent increases in local fuel prices, a recent local economic downturn, and participation by residents in other conservation programs.

However, the energy consumption observed in the ELCAP residences suggests that Hirst's region-wide consumption estimate of 25,000 kWh/yr is too high. The ELCAP homes in the same climate zone as Hood River averaged 21,800 kWh/yr total consumption, 8100 of which was used for heating. These observed consumption levels, while higher than the actual HRCP pre-retrofit levels, are not as dramatically different as Hirst's data suggest. Unfortunately, the pre-retrofit energy consumption predicted by the HRCP audits cannot be compared with these numbers because they were not retained in the audit database. Nonetheless, there is evidence that part of the missing savings are attributable to misestimation of baseline loads.

Hirst's last two conclusions, regarding higher post-retrofit indoor temperatures and lower post-retrofit wood use, were discussed in previous sections. While there was an increase in post-retrofit indoor temperatures, we have shown it to be within the range expected as a result of increased thermal integrity of the homes. There is insufficient evidence to conclude that occupants knowingly raised their thermostat set points. At any rate, Hirst's estimate of the savings attributable to temperature takeback was small--300 kWh/yr.

The conclusion that some of the retrofit savings were taken in reduced wood use is confirmed by our analyses, which show that twice as much savings went toward reductions in wood use as went toward reductions in electricity. Indeed, after accounting for wood use, our analyses still show an achieved savings fraction of around 40%.

6.2.1 Hypotheses Regarding Misestimation of Baseline Loads

There are four fundamental reasons why baseline space heat consumption (and savings) might be overpredicted by audits based on Bonneville's Standard Heat Loss Methodology (SHLM):

- The audits do not account for displacement by wood burning.
- The audits implicitly assume a room temperature and thermostat strategy.
- The audits implicitly assume a level and utilizability of internal heat gains (e.g., from lights and plug loads).
- The audits implicitly assume a level of room closures and/or zoned heating systems.

We have already addressed the first two reasons. The third, regarding internal and solar gain levels, relates to the "C-factor," a simple degree-day multiplier in the SHLM. The C-factor adjusts standard (base-65°F) degree days to account for nominal assumptions about internal and solar heat gains, thermostat settings, and setback behavior. Poor assumptions regarding non-HVAC heat gains could result in an overprediction of savings, but the C-factor would have to be incorrect by a factor of two to account for the missing savings. It is unlikely that the effective number of degree days was miscalculated that badly. The remaining issue is zoning.

In the absence of room-by-room temperature data it is not possible to confidently estimate the prevalence and magnitude of zoning in the HRCP homes. However, to provide a context for discussion, we have examined the potential magnitude of zoning effects on a purely theoretical basis. We define a reasonable house geometry (see Figure 6.1) and vary its size (see Table 6.6), insulation levels (see Table 6.7), and zoning strategy (see Table 6.8). For each combination, we compute the effective reduction in envelope conductance

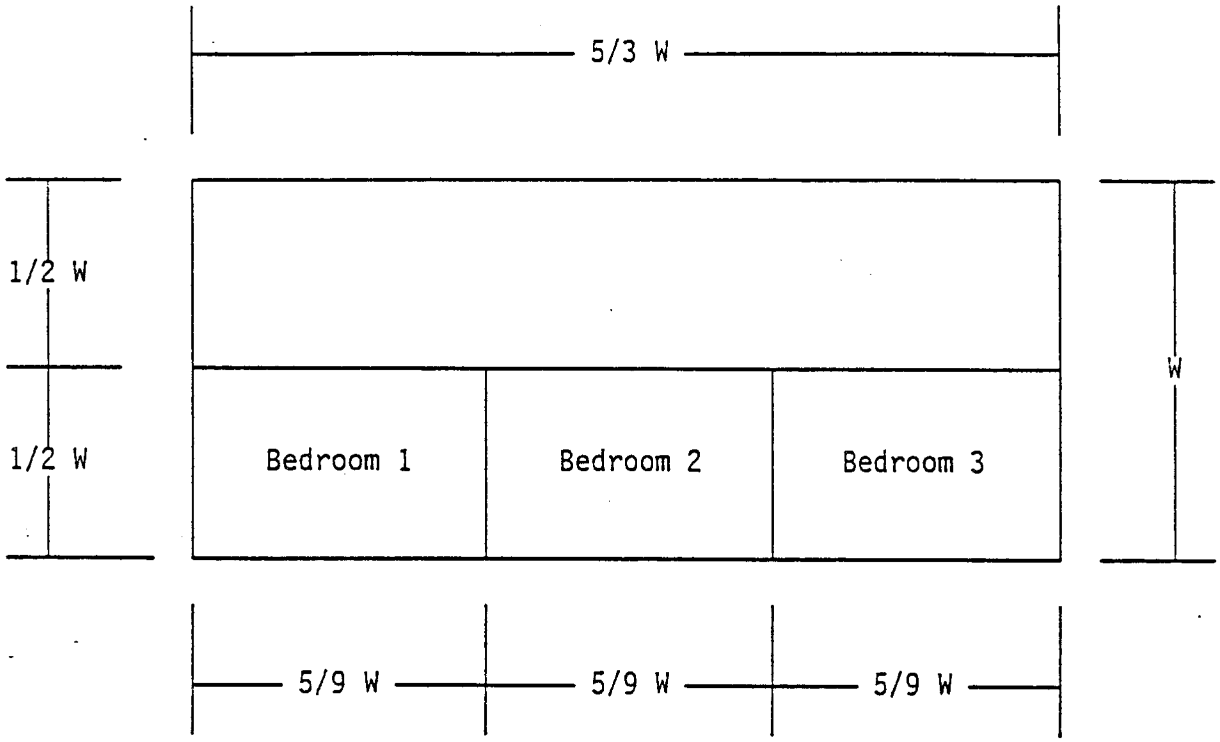

FIGURE 6.1. House Geometry

TABLE 6.6. House Dimensions

	Design #				
	1	2	3	4	5
Width, ft	25	30	35	40	45
Length, ft	42	50	58	67	75
Floor Area, sqft	1042	1500	2042	2667	3375
Height, ft	8	8	8	8	8
Volume, cuft	8333	12000	16333	21333	27000
Windows, % floor	10%	10%	10%	10%	10%
Doors, sqft	120	120	180	180	240
Net Wall, sqft	843	1010	1109	1260	1343

TABLE 6.7. House Construction

Component	Insulation Levels (R-Values) 1	2	3	4	5
Walls	4.0	11.0	19.0	19.0	26.0
Windows	1.0	1.0	2.0	2.0	3.0
Ceiling	4.0	19.0	30.0	38.0	60.0
Infiltration	1.0	1.0	0.4	0.4	0.2
Floor	4.0	11.0	19.0	24.0	38.0
Doors	1.5	1.5	2.5	4.0	7.0
Partitions	3.0	3.0	3.0	3.0	3.0

TABLE 6.8. Zoning Strategy

Type	#	Floor Area Zoned	Wall Area Zoned	Partion Area (% of W)
None	0	0%	0%	0%
Bedroom 1	1	17%	20%	106%
Bedrooms 1 & 2	2	33%	30%	161%
Bedrooms 1-3	3	50%	50%	167%

(UA) because of the closed-off rooms. (When a room is not heated, its interior walls act as an additional R-value between the thermostat and the outside air.)

The UA calculations, by component, are displayed in Table 6.9. The whole-house UAs are further summarized in Table 6.10 and presented as percentages of the nominal (non-zoned) UAs in Table 6.11. The effect of zoning half the floor space of a house results in UAs that range from 55% to 83% of the nominal level in uninsulated and superinsulated houses, respectively. A more modest level of zoning roughly corresponding to closing

TABLE 6.9. Heat Loss Coefficient Calculation as a Function of Insulation Level, Size, and Zoning Strategy

Heat Loss Coefficeint for House Geometry (Btu/hr-F)

Insulation Level	Design # 1 Zoning Strategy				Design # 2 Zoning Strategy				Design # 3 Zoning Strategy				Design # 4 Zoning Strategy				Design # 5 Zoning Strategy			
	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
	1 = Insulation Level				1 = Insulation Level				1 = Insulation Level				1 = Insulation Level				1 = Insulation Level			
Wall	211	169	147	105	253	203	176	126	277	222	194	139	315	253	220	158	338	269	234	168
Windows	104	84	73	52	150	120	105	75	204	164	142	102	267	214	186	133	338	271	236	169
Ceiling	260	217	174	130	375	313	250	188	510	425	340	255	667	556	444	333	844	703	563	422
Infilt.	150	125	100	75	216	180	144	108	294	245	196	147	384	320	256	192	486	405	324	243
Floor	260	217	174	130	375	313	250	188	510	425	340	255	667	556	444	333	844	703	563	422
Door	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80
Main Subtotal	1066	892	747	573	1449	1208	1005	764	1876	1562	1293	978	2379	1978	1631	1230	2927	2431	1999	1503
Partition	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111
Zoned Subtotal	0	50	80	91	0	54	86	96	0	58	91	99	0	60	94	101	0	62	96	103
TOTAL UA	1065	942	827	663	1448	1262	1091	860	1876	1619	1383	1077	2379	2038	1725	1331	2926	2493	2095	1606
	2 = Insulation Level				2 = Insulation Level				2 = Insulation Level				2 = Insulation Level				2 = Insulation Level			
Wall	77	61	53	38	92	74	64	46	101	81	70	50	115	92	80	57	122	98	85	61
Windows	104	84	73	52	150	120	105	75	204	164	142	102	267	214	186	133	338	271	236	169
Ceiling	55	46	37	27	79	66	53	39	107	90	72	54	140	117	94	70	178	148	118	89
Infilt.	150	125	100	75	216	180	144	108	294	245	196	147	384	320	256	192	486	405	324	243
Floor	95	79	63	47	136	114	91	68	186	155	124	93	242	202	162	121	307	256	205	153
Door	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80
Main Subtotal	560	475	406	320	753	633	536	417	972	814	684	526	1228	1025	857	654	1510	1257	1048	795
Partition	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111
Zoned Subtotal	0	39	63	76	0	44	72	84	0	49	78	89	0	52	83	93	0	55	87	96
TOTAL UA	560	513	469	396	753	678	608	500	972	863	762	615	1228	1077	941	747	1510	1312	1135	891

TABLE 6.9. (contd)

Heat Loss Coefficeint for House Geometry (Btu/hr-F)

Insulation Level	Design # 1 Zoning Strategy				Design # 2 Zoning Strategy				Design # 3 Zoning Strategy				Design # 4 Zoning Strategy				Design # 5 Zoning Strategy			
	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
	3 = Insulation Level				3 = Insulation Level				3 = Insulation Level				3 = Insulation Level				3 = Insulation Level			
Wall	44	36	31	22	53	43	37	27	58	47	41	29	66	53	46	33	71	57	49	35
Windows	52	42	36	26	75	60	52	38	102	82	71	51	133	107	93	67	169	135	118	84
Ceiling	35	29	23	17	50	42	33	25	68	57	45	34	89	74	59	44	113	94	75	56
Infilt.	60	50	40	30	86	72	58	43	118	98	78	59	154	128	102	77	194	162	130	97
Floor	55	46	37	27	79	66	53	39	107	90	72	54	140	117	94	70	178	148	118	89
Door	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Main Subtotal	294	250	215	171	392	330	281	220	502	421	355	275	630	527	443	339	772	644	538	410
Partition	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111
Zoned Subtotal	0	27	46	58	0	33	54	67	0	38	62	75	0	42	68	80	0	45	74	85
TOTAL UA	294	277	261	229	392	363	335	287	502	459	417	349	630	569	511	420	772	689	612	495
	4 = Insulation Level				4 = Insulation Level				4 = Insulation Level				4 = Insulation Level				4 = Insulation Level			
Wall	44	36	31	22	53	43	37	27	58	47	41	29	66	53	46	33	71	57	49	35
Windows	52	42	36	26	75	60	52	38	102	82	71	51	133	107	93	67	169	135	118	84
Ceiling	27	23	18	14	39	33	26	20	54	45	36	27	70	58	47	35	89	74	59	44
Infilt.	60	50	40	30	86	72	58	43	118	98	78	59	154	128	102	77	194	162	130	97
Floor	43	36	29	22	63	52	42	31	85	71	57	43	111	93	74	56	141	117	94	70
Door	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Main Subtotal	257	216	186	144	347	290	245	188	447	372	313	238	565	469	393	297	693	575	480	362
Partition	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111
Zoned Subtotal	0	26	43	56	0	31	52	65	0	36	60	72	0	40	66	78	0	44	71	83
TOTAL UA	257	242	228	200	347	321	297	254	447	409	373	311	565	510	459	376	693	619	551	445
	5 = Insulation Level				5 = Insulation Level				5 = Insulation Level				5 = Insulation Level				5 = Insulation Level			
Wall	32	26	23	16	39	31	27	19	43	34	30	21	48	39	34	24	52	41	36	26
Windows	35	28	24	17	50	40	35	25	68	55	47	34	89	71	62	44	113	90	79	56
Ceiling	17	14	12	9	25	21	17	13	34	28	23	17	44	37	30	22	56	47	38	28
Infilt.	30	25	20	15	43	36	29	22	59	49	39	29	77	64	51	38	97	81	65	49
Floor	27	23	18	14	39	33	26	20	54	45	36	27	70	58	47	35	89	74	59	44
Door	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
Main Subtotal	159	133	114	88	214	178	151	115	274	228	192	146	346	287	241	182	424	351	293	220
Partition	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111	0	70	107	111
Zoned Subtotal	0	19	32	43	0	24	40	52	0	28	47	60	0	32	53	66	0	36	59	72
TOTAL UA	159	152	146	131	214	202	191	168	274	256	239	205	346	319	294	248	424	386	352	292

TABLE 6.10. Heat Loss Coefficient as a Function of Insulation Level, Size, and Zoning Strategy

Heat Loss Coefficeint for House Geometry (Btu/hr-F)

Insulation Level	Design # 1 Zoning Strategy				Design # 2 Zoning Strategy				Design # 3 Zoning Strategy				Design # 4 Zoning Strategy				Design # 5 Zoning Strategy			
	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
1	1066	942	827	663	1449	1262	1091	860	1876	1619	1383	1077	2379	2038	1725	1331	2927	2493	2095	1606
2	560	513	469	396	753	678	608	500	972	863	762	615	1228	1077	941	747	1510	1312	1135	891
3	294	277	261	229	392	363	335	287	502	459	417	349	630	569	511	420	772	689	612	495
4	257	242	228	200	347	321	297	254	447	409	373	311	565	510	459	376	693	619	551	445
5	159	152	146	131	214	202	191	168	274	256	239	205	346	319	294	248	424	386	352	292

TABLE 6.11. Effect of Zoning Strategy in Reducing Overall Heat Loss Coefficient

Reduction in Overall Heat Loss Coefficient Due to Zoning Strategy

Insulation Level	Design # 1 Zoning Strategy				Design # 2 Zoning Strategy				Design # 3 Zoning Strategy				Design # 4 Zoning Strategy				Design # 5 Zoning Strategy			
	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
1	100%	88%	78%	62%	100%	87%	75%	59%	100%	86%	74%	57%	100%	86%	72%	56%	100%	85%	72%	55%
2	100%	92%	84%	71%	100%	90%	81%	66%	100%	89%	78%	63%	100%	88%	77%	61%	100%	87%	75%	59%
3	100%	94%	89%	78%	100%	93%	86%	73%	100%	91%	83%	70%	100%	90%	81%	67%	100%	89%	79%	64%
4	100%	94%	89%	78%	100%	93%	86%	73%	100%	91%	83%	70%	100%	90%	81%	67%	100%	89%	79%	64%
5	100%	96%	92%	83%	100%	94%	89%	78%	100%	93%	87%	75%	100%	92%	85%	72%	100%	91%	83%	69%

off two bedrooms can result in UA reductions to about 80% of the nominal value in modestly insulated homes. Note that this roughly corresponds to the difference in nameplate and as-operated UAs observed in ELCAP homes. However, it does seem unlikely that zoning behavior is so predominant as to reduce theoretical baseline space heat consumption by 50%, enough to account for the missing savings.

6.2.2 Hypotheses Regarding Misestimation of Energy Benefits

The potential contributors to overpredicted retrofit benefits that have not yet been discussed are zoning and in-situ thermal performance of the retrofit materials. In addition to its effect on baseline loads, zoning has an effect on retrofits that is not widely recognized. The benefit of zoning can be conceptualized as the additional R-value provided by the interior partition wall acting in series with the exterior envelope insulation in the zoned part of the house. In an uninsulated (or very poorly insulated) house, the R-value of this partition is about equal to that of the envelope and adds significantly to the effective overall R-value of the zoned rooms. When the envelope is insulated, however, the relative benefit of zoning is decreased because the R-value of the partition wall is small in comparison, and adds only marginally to the overall R-value of the zoned area. It is important to note that this appears just like takeback to an energy analyst--even if the zoning behavior does not change after the retrofit.

Table 6.12 displays the effect of zoning in reducing the actual UA changes caused by a retrofit. For modest levels of zoning, the effect can account for reduced benefits of 30% in an uninsulated home. The reduction is lower, about 15% to 20%, for a home with some insulation originally. When combined with the initial error in baseline consumption because of similar levels of zoning, the potential impact on absolute savings rises to the range of 35% to 50%. If all homes use zoning at this level, the potential magnitude is large enough to account for the majority of the "missing savings" in Hood River.

The remaining possible explanation for the missing savings involves the in-situ thermal performance of the retrofit materials. These materials are laboratory-tested and have long been the subject of research, so poor installation seems to be a more likely contributor to reduced savings. Despite the quality assurance inspections performed in Hood River, it is possible that field conditions are such that fully effective performance could not be achieved. However, this hypothesis is difficult to defend (or refute) with the available data.

TABLE 6.12. Reduction in Retrofit Benefits as a Result of Zoning Strategy

Fraction of Achieved Change in UA vs. Expected Change in UA Due To Zoning Strategy

Insulation Level	Design # 1 Zoning Strategy				Design # 2 Zoning Strategy				Design # 3 Zoning Strategy				Design # 4 Zoning Strategy				Design # 5 Zoning Strategy			
	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
From: 1																				
To: 2	100%	85%	71%	38%	100%	84%	69%	52%	100%	84%	69%	51%	100%	83%	68%	51%	100%	83%	68%	50%
...... 3	100%	86%	73%	41%	100%	85%	72%	54%	100%	84%	70%	53%	100%	84%	69%	52%	100%	84%	69%	52%
...... 4	100%	87%	74%	42%	100%	85%	72%	55%	100%	85%	71%	54%	100%	84%	70%	53%	100%	84%	69%	52%
...... 5	100%	87%	75%	43%	100%	86%	73%	56%	100%	85%	71%	54%	100%	85%	70%	53%	100%	84%	70%	53%
From: 2																				
To: 3	100%	89%	78%	63%	100%	87%	75%	59%	100%	86%	73%	56%	100%	85%	72%	55%	100%	84%	71%	54%
...... 4	100%	89%	80%	65%	100%	88%	76%	61%	100%	86%	74%	58%	100%	86%	73%	56%	100%	85%	71%	55%
...... 5	100%	90%	81%	66%	100%	88%	77%	62%	100%	87%	75%	59%	100%	86%	73%	57%	100%	85%	72%	55%
From: 3																				
To: 4	100%	95%	89%	80%	100%	93%	85%	75%	100%	91%	82%	70%	100%	90%	79%	67%	100%	89%	77%	64%
...... 5	100%	93%	85%	73%	100%	91%	81%	67%	100%	89%	79%	63%	100%	88%	76%	60%	100%	87%	75%	58%

7.0 CONCLUSIONS

The thermal analysis on the Hood River end-use metered data leads to several conclusions. This sample includes single-family homes (about 73%), multifamily residences (about 6%), and manufactured homes (about 21%). The homes with enough data to permit thermal characterization tend to be those that are reportedly relying on electric space heat. Of the end-use metered homes in the HRCP, about 60% could not be characterized--predominantly because of the large number of days that wood-burning equipment appears to be in use. Several conclusions were reached concerning the 113 sites characterized using the metered data:

- The difference in annualized estimated consumption (ACE) for space heating per square foot of conditioned floor area, before and after retrofit for the combined sample, represents a 24% reduction in consumption in the pre-retrofit level of space heating requirements. The single-family homes and multifamily homes show the greatest reduction (approximately 30% each) in kWh/ft^2-yr post-retrofit. Manufactured homes show only one-third the savings of a a single-family home.

- The changes in heat loss coefficients (UA) and effective heating-degree-days, derived from the linear fits of the heating data to inside-outside temperature difference show a total savings similar to that of the AEC estimates.

- The mean difference in floor area-normalized space heating requirements for the combined sample is 2.05 kWh/ft^2-yr. Single-family reductions averaged 2.24 kWh/ft^2-yr, multifamily units averaged 2.48 kWh/ft^2-yr, and manufactured homes averaged 1.28 kWh/ft^2-yr.

- The mean reduction in total consumption for the combined sample is 2432 kWh/yr. Single-family reductions averaged 2899 kWh/yr, multifamily units 1900 kWh/yr, and manufactured homes 991 kWh/yr.

- Space heating consumption estimates performed using Seattle TMY data for the Hood River single-family homes show that pre-retrofit levels of consumption are similar to those for the ELCAP climate zone-1 Residential Base homes, and that post-retrofit consumption levels are very similar to those for the ELCAP climate zone-1 RSDP control homes that represent current construction practice.

- The change in the as-operated UAs for the combined sample is a 20% reduction over the mean pre-retrofit level. The shift upward in balance temperature difference represents a 9% increase for the combined sample. The changes in as-operated UA and balance temperature differences for the single-family homes and multifamily units are greater than those of the combined sample by several percentage points. The manufactured homes show less than half the decrease observed in the single-family, as-operated UAs and demonstrate little change in the balance temperature differences over pre-retrofit levels.

- Although a change upward is noted in the mean heating season inside temperatures, it is less than 0.5°F. Given the change in as-operated UAs, this temperature change is not large enough to suggest higher thermostat set points in the post-retrofit heating season.

- In homes that burned wood, wood usage dropped by 27% after the installation of weatherization measures. Heater usage also went down but only by about 14%. For this group of homes it appears that the greatest share of the savings was receovered in reduced wood-stove usage, although a significant reduction in space heating was also observed.

- Mean annual electrical space heat savings are less than half of the savings initially projected. The weather normalized estimates provided by this work are for homes assuming no wood-stove usage.

7.1 RECOMMENDED ADDITIONAL ANALYSES

Our analyses show that reduction in wood use is a factor contributing to the low achieved savings fraction and that thermostat takeback is not likely. However, our discussions about zoning are, at best, plausible explanations and, at worst, pure speculation. The vast unexplained difference between predicted and actual savings demands further explanation. We suggest several additional analyses to further the understanding of the Hood River homes. These additional analyses follow, in roughly prioritized order:

1. Reproduce the pre- and post-retrofit UAs and space heating consumption estimates for the end-use metered Hood River homes using the SHLM. The lack of this information largely limits examinations of baseline estimates to conjecture. By comparing the predicted loads with measured loads, the contribution of errors in baseline consumption estimates could be placed in proper perspective. Additionally, comparing theoretical and empirical UAs would shed light on the issues of in-situ retrofit performance.

2. Estimate the hot water savings in the end-use metered homes. This would result in more accurate space heat savings estimates from Hirst's data on billing totals.

3. Evaluate total pre- and post-retrofit consumption in the end-use metered homes. This would ensure that our analyses of space heating in those homes were not influenced by changes in other end uses.

4. Evaluate the electric space heating consumption in the end-use metered homes not included in this report (the wood-burning homes). This would allow a closer match to Hirst's definitions of wood-burning building classes and strengthen the conclusions regarding wood displacement.

5. Analyze, in detail, the hourly and seasonal wood heating and indoor air temperature patterns in the end-use metered homes. This would further verify or refute our conclusions regarding wood heating takeback, and provide additional knowledge as to the nature of the phenomenon and how it might be accounted for in future conservation projects.

8.0 REFERENCES

Drost, M. K., P. W. Zimmerman, R. J. Skarda, and E. W. Pearson. 1987. Analysis of Thermal Performance Data Taken Under the Residential Standards Demonstration Program. PNL-6021, Pacific Northwest Laboratory, Richland, Washington.

Fels, M. F. 1984. The Princeton Scorekeeping Method: An Introduction. PU/CEES-163, Princeton University, Center for Energy and Environmental Studies, Princeton, New Jersey.

Hirst, E. 1987. Cooperation and Community Conservation. DOE/BP-11287-18, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Le Baron, B. A. 1988. Wood Stove Use in the ELCAP Residential Base Sample. PNL-6713, Pacific Northwest Laboratory, Richland, Washington.

Stovall, T. K. 1987. Hood River Conservation Project Load Analysis. ORNL/CON-240, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

DISTRIBUTION

No. of
Copies

OFFSITE

2 DOE/Office of Scientific and
Technical Information

2 R. A. Gillman
Bonneville Power Administration
End-Use Research Section
P.O. Box 3621-RPEE
Portland, OR 97208

M. E. Taylor
Bonneville Power Administration
End-Use Research Section
P.O. Box 3621-RPEE
Portland, OR 97208

W. M. Warwick
Battelle Portland Office
500 NE Multnomah, Suite 650
Portland, OR 97232

No. of
Copies

ONSITE

13 Pacific Northwest Laboratory

N. E. Miller
R. G. Pratt
W. F. Sandusky (4)
G. M. Stokes
Publishing Coordination
Technical Report Files (5)