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An Analysis of Predicted vs. Monitored Space Heat Energy Use in 83 Homes

Residential Construction Demonstration Project

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Introduction

In 1980 Congress passed the Northwest Electric Power Planning and Conservation Act which established the Northwest Power Planning Council (NWPPC) and directed it to create a set of model conservation standards (MCS) based on cost effective conservation measures for residential and commercial construction.

In 1983 the NWPPC directed the Bonneville Power Administration to create the Residential Standards Demonstration Program to demonstrate actual construction using the MCS and to collect cost and thermal data in residential structures. Much information was gained from that program, and as a consequence, the MCS were reevaluated and updated. A second program, the Residential Construction Demonstration Project was created to further investigate residential energy efficiency measures for both cost and thermal performance. The Residential Construction Demonstration Project was administered by the Washington State Energy Office in conjunction with the Idaho Department of Water Resources, the Montana Department of Natural Resources and Conservation, and the Oregon Department of Energy. This analysis is based upon information collected during the [illegible] phase of the Residential Construction Demonstration Project (RCDP).

The MCS is a set of performance requirements that vary depending on climate. Three climate zones defined by heating degree days (Fahrenheit) were established. Table 1 contains a list of climate zones and corresponding degree days.

Table 1
Pacific Northwest Climate Zones

Climate Zone	Heating Degree Days
Zone 1	<6000
Zone 2	6000-8000
Zone 3	>8000

The Model Conservation Standards are based on simulated performance of homes using the SUNDAY thermal simulation program. Several studies have been undertaken to assess the ability of SUNDAY to predict space heat energy consumption. The Washington State Energy Office found good agreement between SUNDAY predictions and monitored performance for [illegible] homes located in Washington State which were constructed in the Residential Standards Demonstration Program (Byers, 1988). Other studies have shown SUNDAY predictions to be high by as much as 30% (Yoder, 1986). Controversy persists surrounding SUNDAY's ability to accurately predict space heat energy consumption without bias.

The purpose of this study is to examine the relationship between SUNDAY predicted and monitored [illegible] heat consumption in RCDP houses. Specifically, this analysis will determine the degree to which SUNDAY predictions agree with monitored use; examine the correlations (if any) between the degree of agreement with such factors as house size, architecture, heating system type, and location; and determine which estimated SUNDAY inputs lead to the most consistent comparisons between predicted and actual performance.

This analysis is separated into two primary sections. The first section contains a description of calculated and estimated SUNDAY input variables. In this section methodologies used to collect and calculate physical inputs are described. A brief summary of each of these characteristics is also included. The second section contains an analysis of predicted and monitored performance including variables that are not included in the simulation model but may impact energy consumption.

SUNDAY Input Variables

Many complex inputs are required to perform a prediction of space heat energy consumption. Methodologies used to calculate or estimate these inputs are described below. Model variables include overall building heat loss coefficient, internal heat gains from people and appliances, structural heat storage capacity, internal temperature set points and schedule, glazing orientation and transmissivity, and local weather. Overall building heat loss is broken into three components: conduction heat loss, mechanical convection heat loss and natural convective heat loss.

Inputs which are either inaccurate or imprecise may negate any analysis of simulated performance. Effort has been made to ensure that data does not contain systematic errors.

Conduction Heat Loss Coefficients

Standardized heat loss coefficients for wall, ceiling, and floor components were taken from a set of standardized U-values created for the Super Good Cents program and were calculated with standard ASHRAE procedures (Baylon and Heller, 1988). Basements were modeled with heat loss through the below grade walls and heat loss through the below grade slab. Heat loss coefficients for doors were assumed to be 0.33 Btu/hr SF F and 0.19 Btu/hr SF F for solid core wood and insulated metal doors respectively.

Glazing heat loss coefficients were extracted from tested data available in the April 1987 Glazing Test Report List (Hogan, 1987). Windows were categorized by frame type, number of glazings, air space width, coating type and filled gas type. Mean heat loss coefficients were then calculated for each category.

Component areas were examined for extreme values. Any extreme values were checked against construction blueprints and corrected if needed. A total of seven corrections were made. Three basement perimeter lengths and four glazing areas were incorrectly recorded and subsequently corrected. Component areas and descriptions were extracted from house plans and were verified through a series of construction inspections. The methodology for collecting component data (plans check and inspection process) was similar to that used in the Residential Standards Demonstration Program. This methodology was examined by WSEO and found to provide data which were accurate and relatively free from errors (Downey, 1988).

The overall conduction heat loss coefficient was calculated with Equation 1.

Equation 1

$$UA_c = U_1 A_1 + U_2 A_2 + \ldots + U_n A_n + F_s P_s$$

where:

UAc = the overall conduction UA in Btu/hr F

Un = the conduction heat loss coefficient for component n in Btu/hr SF F

An = the area of component n in SF

Fs = the conduction heat loss coefficient for slab in Btu/hr ft F

Ps = the perimeter of slab in lineal feet

Table 2 contains summary statistics of the conductive heat loss coefficient calculated for the 83 homes examined in this analysis. Because different thermal standards were required depending on the climate zone where the structure was located, this table is cross tabulated by the three climate zones. Figure 1 contains histograms of these data.

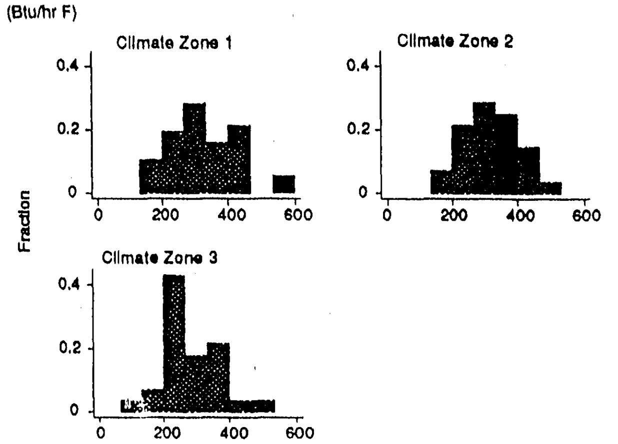
Table 2

Conduction Heat Loss Coefficients by Climate Zone

Climate Zone	Mean	Median	Standard Deviation	Frequency
1	318.6	290.6	111.0	41
2	299.7	297.8	73.4	22
3	271.5	255.9	75.8	20
Overall	302.2	283.8	95.3	83

Figure 1

Conduction Heat Loss by Climate Zone



Convection Heat Losses

Convective losses are problematic for the simulation software used in this analysis since they can not be scheduled. Consequently, convective heat loss must be condensed into an annual figure. Since all of the test homes were equipped with mechanical heat recovery ventilation (i.e., air-to-air heat exchangers), convective heat loss is broken into two components: mechanical and natural convective losses.

Mechanical Convection Losses

Each home in the program was equipped with heat recovery ventilation (HRV) in the form of air-to-air heat exchangers. Two types of air-to-air heat exchangers were used: plate exchangers with a core constructed of plastic or metal and rotary wheel exchangers with the core consisting of a plastic wheel rotating through the exhaust and intake air streams. Heat exchanger air flow rates and electrical current draw were measured during a single site survey. The field technician attempted to balance supply and exhaust flows during the site survey. In some instances the technician found it impossible to either measure flows or balance the HRV unit due to poorly located supply and exhaust vents, inaccessible flow dampers or minimal flow capacity. Amp draw was recorded on both high and low speeds if the heat exchanger unit was equipped with a multiple or variable speed fan.

Mechanical convection losses were broken into two separate components: effective convection losses and unbalanced convection losses. The effective convection loss coefficient was calculated with the following formula. Unbalanced convection losses are addressed with natural convection losses.

Equation 2:

$$UA_m = (\dot{M}_h (1 - W) + \dot{M}_l W)\, eCp_a\, o$$

where:

UAm = the heat loss due to mechanical ventilation in Btu/hr F

$\dot{M}h$ = the exhaust flow rate on high speed in CFM

$\dot{M}l$ = the exhaust flow rate on low speed in CFM

w = the average fan speed factor (dimensionless)

e = the calculated effectiveness of heat removal from the exhaust stream (dimensionless)

Cp_a = the heat capacity of air in Btu/CF F

o = the daily hrv operation factor (dimensionless)

Some HRV's were equipped with two-speed or variable-speed fans. Amp draw was measured on both high speed and low speed during site survey and at three-minute intervals with the data logger equipment. Fan flow curves were assumed to be linear between high and low speeds. Equation 3 was used to calculate the fan speed factor.

Equation 3:

$$W = \frac{(Amp_a - Amp_h)}{(Amp_h - Amp_l)}$$

where:

w = the average fan speed factor: dimensionless)

Amp_a = the average amp draw: amps

Amp_h = the amp draw on low speed: amps

Amp_l = the amp draw on high speed: amps

Heat recovery ventilation effectiveness was calculated with monitoring equipment. The data logger monitored exhaust temperature downstream from the unit and indoor and outdoor temperatures. The data logger automatically calculated the effectiveness of the AAHX unit on a three-minute time interval and stored that figure in memory. The weekly mean effectiveness was then recorded by the home occupant. Effectiveness was calculated as the ratio of the differential between indoor temperature and exhaust stream temperature to indoor temperature and outdoor temperature. See Equation 4.

Equation 4:

$$e = \frac{\left(\sum_{1}^{N} \frac{\left(\sum_{1}^{n} \frac{T_i - T_e}{T_i - T_o} \right)}{n} \right)}{N}$$

where:

e = the calculated effectiveness of heat removal from the exhaust stream (dimensionless)

T_{in} = Indoor Temperature

T_{ex} = Exhaust stream temperature

T_{out} = Outdoor Temperature

n = the number of effectiveness calculations between occupant recordings

N = the number of occupant recordings

Several problems have been identified with this monitoring scheme. HRV effectiveness is not equivalent to overall system efficiency. Since only the exhaust temperature was used in the calculation of effectiveness, an HRV which was out of balance (more flow in either the exhaust or supply stream) would provide an inaccurate reading of efficiency. If the exhaust flow was greater than the supply flow, the recorded unit effectiveness as calculated by the data logger would be less than true unit efficiency because the temperature differential on the exhaust stream would be less than in a balanced unit. Conversely, if the supply flow was greater than the exhaust flow, unit effectiveness would appear greater than true efficiency.

In order to calculate true unit efficiency in an unbalanced HRV both supply and exhaust temperature differentials and flows must be known. While downstream supply, indoor and outdoor temperatures were recorded, system efficiency cannot be calculated because these temperatures were recorded at different time intervals. Downstream supply temperatures were recorded at three-minute time intervals while indoor and outdoor temperatures were recorded at hourly intervals. All data were then aggregated to weekly levels.

Sixty-five percent of the HRV units in this study were more than 10% out of balance. Of those systems which were out of balance, 54 units or 83% had greater exhaust than supply flow. The mean effectiveness for all units was 49.6 % with a standard deviation of 14.3 % which is lower than manufacturers' estimates. No correlation between heat exchanger system balance and measured effectiveness could be found.

A second problem with the monitoring scheme was the manner in which the data logger recorded effectiveness. Instead of recording temperature differentials and calculating the effectiveness at the end of the monitoring period, effectiveness was calculated on three-minute time intervals. These ratios were then summed and averaged on a weekly basis. Consequently the number reported as HRV effectiveness is an average of the ratios of temperature differentials instead of a ratio of the average temperature differentials (Lubliner et al., 1988). This recording scheme will diminish the accuracy of the data and has introduce systematic bias. While this monitoring technique has introduced systematic bias to the HRV effectiveness figures, quantifying this bias is difficult and may require additional research.

Natural Convective Losses

Natural convective losses are influenced by natural ventilation rate and any unbalanced mechanical ventilation. Natural ventilation was estimated from blower door data with Sherman's simplified leakage-infiltration ratio (Sherman, 1986). This technique employs the measured blower door air change rate at 50 Pascal and then modifies this number to estimate an annual air change rate under natural conditions. Four figures are used in the development of this figure. They include the leakage-infiltration ratio and stack, shielding, and crack effect correction factors. The leakage-infiltration ratio is based on empirical data and is dependent on climate conditions. Sherman has mapped leakage-infiltration ratio figures (Sherman, 1986). The stack effect factor depends on building geometry. Shielding depends on local geographical conditions. Crack effects directly relate to the effective leakage area discovered during the blower door test. All of these data were acquired during the blower door site visit. Equation 5 was used to calculate natural ventilation in these homes.

Equation 5:

$$\dot{M}_n = \frac{\dot{M}_{d50}}{L f_1 f_2 f_3}$$

where:

Mn = natural ventilation in CFM
Md50= depressurized blower door reading at 50 Pascal in CFM
L = Leakage-infiltration ratio (dimensionless)
f1 = correction factor for stack effects (dimensionless)
f2 = correction factor for shielding effects (dimensionless)
f3 = correction factor for crack effects (dimensionless)

Leakage-infiltration ratios of 21, 20, and 18 were used for climate zones 1 ,2, and 3 respectively. The stack effect correction factor assumes values between 1.0 and 0.8 with 1.0 being equivalent to a single-story home, and 0.8 equivalent to a two-story home. The shielding correction factor assumes values between 1.2 for well shielded structures and 0.9 for exposed structures. The crack correction factor falls between 1.4 for a tight home with small cracks to 0.7 for loose construction with large holes. Stack, shielding and crack correction factors are summarized in Table 3.

Table 3
Blower Door Air Change Rate Correction Factors

Correction Factor	Mean	Standard Deviation
Stack	0.93	0.08
Shielding	0.98	0.05
Crack	0.92	0.19

Modeling the relationship between unbalanced mechanical ventilation and natural ventilation is controversial (Lubliner et al.,1988). Two methods were examined for modeling the combined effect of natural and unbalanced mechanical ventilation. The first method was postulated by Douglass (reference) and models the effect of unbalance mechanical ventilation through a series of five pressure planes in the home. The second method adds mechanical ventilation rate to natural ventilation rate in quadrature.

The first model has the potential to more accurately represent the interdependence of unbalanced mechanical and natural ventilation. However, input requirements for this model were greater than that of data collected during the study, consequently this model could not be supported by the data. Adding the unbalanced mechanical and natural ventilation in quadrature was deemed most appropriate for this analysis. By adding the two values in quadrature, the effect of the pressure differential caused by the unbalanced system is being modeled. Equation 6 was used to combine natural and unbalanced mechanical ventilation.

Equation 6:

$$UA_n = \left(\sqrt{(\dot{M}_u^2 + \dot{M}_n^2)} * o + \dot{M}_n * (1-o) \right) * 60 * Cp_a$$

where:

UAn = heat loss coefficient for natural and unbalance mechanical
$\dot{M}n$ = natural ventilation in CFM

Mu = unbalance flow in CFM
o = hrv on time factor
Cp_a = heat capacity of air in BTU/CF F

The total heat loss coefficient for each structure is composed of conductive heat loss, mechanical ventilation heat loss and natural convective heat loss. Equation 7 represents this figure. The mean heat loss coefficient per square foot of heated space was calculated for structures in each of the three climate zones. Table 4 summarizes these data.

Equation 7:

$$UA_t = UA_c + UA_m + UA_n$$

where:

UAc = Overall conduction UA in Btu/hr F
UAm = heat loss due to balanced mechanical ventilation in Btu/hr F
UAn = heat loss coefficient for combined natural and unbalance mechanical

Table 4
Overall Heat Loss Coefficient per Square Foot for 83 homes by Climate Zone Btu/hr F/SF

Climate Zone	Mean	Standard Deviation	Frequency
1	0.218	0.039	41
2	0.169	0.043	22
3	0.158	0.044	20

Figure 2 is a percentage bar chart representing the contribution of conduction, mechanical ventilation, and natural infiltration to the total heat loss coefficient. Natural infiltration was approximately equal to expected values for each heat loss category. Mechanical ventilation systems had the capacity to adequately ventilate the homes, but most systems were operated less than had been expected. Figure 3 contains a histogram of average mechanical ventilation system on-time for the 83 houses.

Figure 2
Percent UA Contribution from Conduction and, Natural and Mechanical Ventilation by UA Category

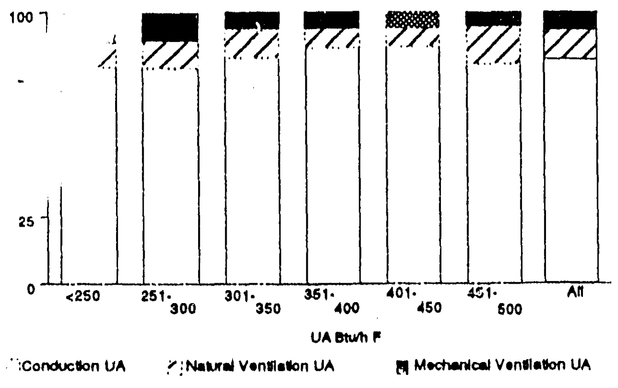
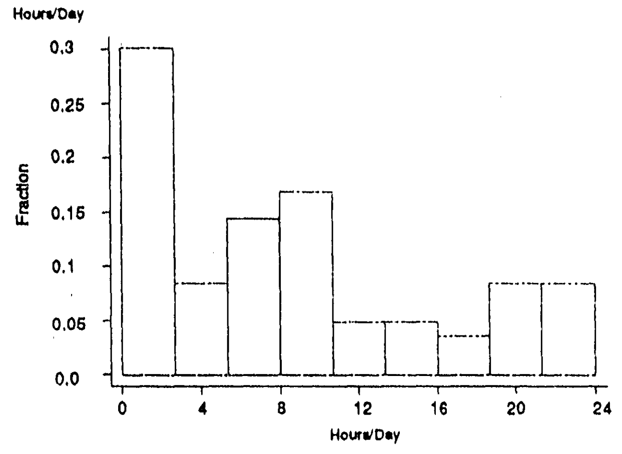


Figure 3
Average Heat Exchanger On-time



Structural Heat Capacity

Structural heat capacity was modeled assuming three types of construction: light frame; slab on grade; and basement construction. Light frame construction was assumed to contain 3.0 Btu/hr SF; slab construction was assumed to contain 7 Btu/hr SF; and homes with below grade walls were assumed to contain 11 Btu/hr SF (Ecklund and Baylon, 1984). Homes with more than one story that were built on a slab or basement were modeled with a combination of construction types. Table 5 describes different construction types found in the data set and their associated structural heat capacity.

Table 5
Structural Heat Capacity

Const.Type	# of Homes	Mean Heat Capacity Btu/hr	Std. Dev. Btu/hr
Lt. Frame	37	5269	2288
Slab	2	15180	6647
Lt. Frame+Bsmt.	25	16045	3813
Lt. Frame+Slab	6	12040	6277
Lt.Frame+Slab+Bsmt.	13	13034	3701
Total	83	10459	5911

Thermostat Set Point

Daytime and nighttime thermostat set points were primarily acquired from an occupant survey. Duration of nighttime thermostat set back was assumed to be ten hours. In those instances where thermostat set points were unavailable from the occupant survey, or where the average internal temperature was more than 2° F than the set point stated by the occupant, the average internal temperature was assumed to be the temperature set point. The daytime thermostat set point has a mean of 68.5 °F with a standard deviation of 3.0° F. Nighttime temperature has a mean of 63.9° F with a standard deviation of 6.3° F. Of the 83 houses with sufficient data for this analysis, 10 indicated that the heating system is turned off during the nighttime set back period. Nighttime temperature set point data from these homes were not incorporated into the calculation of mean nighttime temperature set point. These homes were modeled with a nighttime thermostat set point of 32° F.

Internal Heat Gains

Heat gains from appliances and occupants offset the need for space heat.

SUNDAY requires that an hourly average internal heat gain be specified. This figure cannot be scheduled. The methodology used to calculate internal gains was identical to that used in the analysis of RSDP data (Byers and Palmiter, 1988). Average hourly internal heat gains were estimated from appliance load, appliance type, and the number of people in the structure. Equation 8 was used to calculate hourly internal heat gains and is derived from appliance performance estimates.

Equation 8:

$$I = 0.8\,A\left(\frac{3413}{8760}\right) - 20.8W\ 467R - 311F + 150P + 284H$$

where:

I =	Internal heat gains in Btu/hr
A =	the monitored appliance energy usage in kWh/year
W =	the number of well pumps
R =	the number of refrigerators located outside
F =	the number of freezers located outside
P =	the number of occupants
H =	the number of water heaters

The factor of 80% is applied to account for electrical appliance use outside the heated space in addition to those appliances explicitly accounted for in the equation. This figure is arbitrary and may introduce systematic bias into the analysis but is the same figure used by Byers and Palmiter. Internal gains are summarized in Table 6 by UA category.

Table 6

Average Internal Gains by UA Category
Btu/hr

UA Btu/SF F	Mean	Internal Gains Median	Std. Dev.	Number
<250	2319	2346	892	8
251-300	2384	2313	639	17
301-350	2593	2320	1026	24
351-400	3317	3095	903	6
401-450	2687	2395	1296	8
451-500	3789	3287	1110	20
Total	2874	2545	1116	83

Glazing Orientation and Transmittance

Glazing areas were extracted from construction blueprints. Orientation was also taken from blueprints when possible, or was extracted from the solar site survey completed during the site visit by contracted technicians. SUNDAY requires that each window have a solar multiplier which accounts for glazing transmissivity. For the purposes of this analysis, the solar multiplier for double pane and triple pane windows were 0.95 and 0.85 respectively. This assumes no shading from overhangs or vegetation.

Weather Data

Required SUNDAY weather inputs include daily average temperature, available insolation, and hours of daylight. Temperature data were constructed from daily maximum and minimum temperature recordings into average daily temperatures with a cosine interpolation algorithm for 43 locations throughout the Pacific Northwest. Insolation data were not recorded at each locality, but were taken directly from typical meteorological year data (TMY) and may not be representative of real insolation levels experienced by these homes. Hours of daylight were calculated with algorithms outlined in Lunde (1980).

Simulation Results

All of the variables discussed above were used as inputs into the simulation model. Space heat was simulated for 83 homes and is compared to monitored energy consumption in Figure 4. A least squares regression analysis of these data indicated that 51.9 % of the variation in monitored space heat is explained by the simulated data. Data from two homes which were identified as outliers were excluded from the analysis. These two homes had less than half the monitored space heat than was predicted by the simulation. Space heat consumption in these homes were assumed to be supplemented with other fuels (most likely wood). Inclusion of these homes

Figure 4
Predicted versus Actual Space Heat

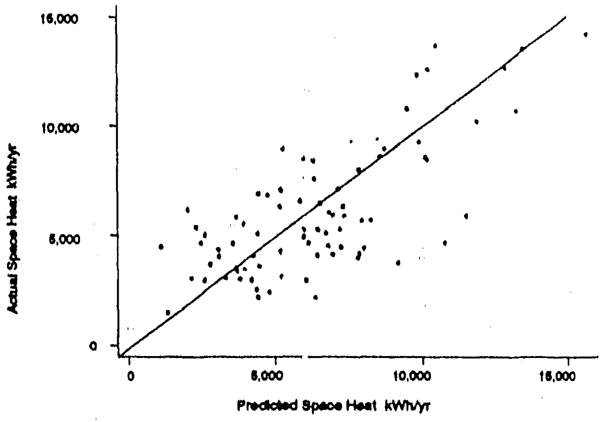
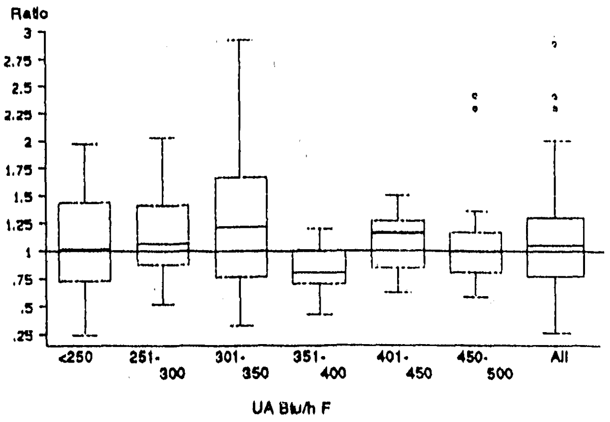


Figure 5
Ratio of Monitored to Predicted Space Heat by UA



decreased the coefficient of determination to 41.5%. A scatter plot with a 45 degree line is included in Figure 4.

Monitored and predicted space heat were categorized by heat loss coefficient bin as summarized in Table 7. Differences between means of monitored and predicted space heat were examined with paired t tests for each category and none were significantly different than zero (probability). While this indicated that there is no statistical difference between monitored and simulated space heat, this may be due in part to a combination of small sample size within each category combined with large coefficients of variation. These data are represented visually in Figure 5.

Several variables known to impact space heat energy consumption are not included in the simulation model. The simulation model does not include heating system efficiency or house type both of which have been shown by other researchers to affect space heat energy consumption (Byers and Palmiter, 1988). House size is another variable which is not explicitly included in the simulation model but has been correlated with space heat. However, house size is positively correlated to heat loss coefficient, heat capacity and internal heat gains all of which are included in the simulation model.

An analysis of covariance model was used to examine those factors which are not explicitly included in the simulation model. Predicted space heat and house size were included as continuous variables and categorical variables were created for heating system type and house type. Heating systems were categorized as forced air and radiant slab, zonal, and heat pump systems. Radiant heat systems were included with force air electric systems because both systems are controlled from a single central thermostat. House type was categorized as single story, single story with conditioned basement, two story, and two story with conditioned basement.

Other variables from the simulation were also analyzed on the covariance model. They included total UA, mass, internal gains, and effective solar glazing area. None of the variables explicitly included

Table 7
Monitored vs. Predicted Space Heat by UA Bin

UA BTU/hr F	n	Monitored kWh/SF/yr	Predicted kWh/SF/yr	Difference kWh/SF/yr	Ratio	Probability
<250	8	3792	4004	-212	1.06	0.77
251-300	17	5161	5337	-176	1.03	0.68
301-350	24	5394	6254	-860	1.16	0.10
351-400	6	7740	6581	1159	0.85	0.17
401-450	8	6420	6754	-334	1.05	0.59
451-500	20	8517	8607	-90	1.01	0.88
Total	83	6213	6488	-275	1.04	0.26

in the SUNDAY model were significant either by themselves or interacted with predicted space heat in the analysis of covariance model. This would suggest that the SUNDAY model adequately explained variation in energy consumption due to these coefficients.

Modification of predicted space heat with this analysis of covariance model increases the coefficient of determination from 51.9% to 61.2%. Model coefficients are included in Equation 9. Note that the constant figure in this equation is not significantly different from zero and may be dropped. The single-story house without basement and the zonal space heat are constants held at zero. A single-story home with basement produced the largest modification, a decrease of more than 2000 kWh/yr as compared to the single-story home with no basement. Forced air electric and radiant slabs heating systems use 13.3% more energy for space heat. Heat pump systems use 20.6% less energy for space heat as compared to zonal heated systems.

Equation 9:

$$S_m = 0.521\, S_p + 1.828h + a + bSp - 37$$

where:

S_m = Modified Sunday predicted spaceheat in kWh
Sp = SUNDAY predicted space heat in kWh/yr
h = House size in square feet
a = Construction type
  one story with basement = 2045
  two story no basement = 1389
  two story with basement = 484 *
b = Heating system type
  forced air electric = 0.133
  and radiant slab heat pump = 0.206

* The coefficient for two story houses with basements is not significant.

Figure 6 shows a ratio of modified predicted to monitored space heat energy consumption. Figure 7 is included as a comparison of predicted and modified predicted space heat to monitored space heat. In both figures the sample of houses is classed by heat loss category. As before there is no significant difference between modified predicted space heat use and monitored space heat use for either the aggregate sample or any of the sub-samples categorically defined by the heat loss coefficient.

Figure 6
Ratio of Monitored to Adjusted Predicted Space Heat

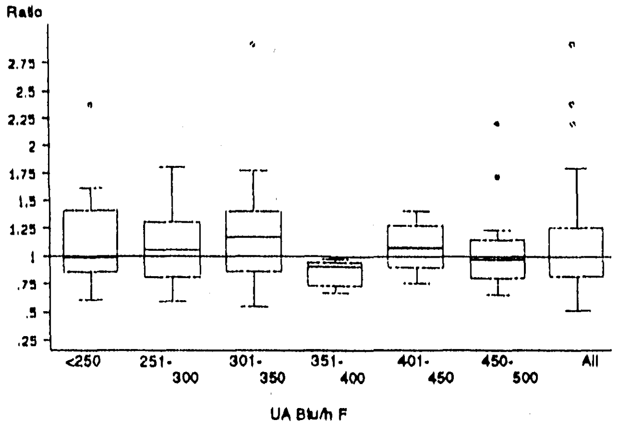
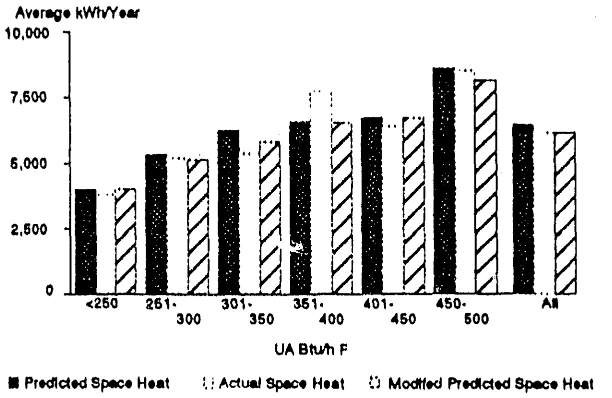


Figure 7
Predicted, Actual, and Modified Predicted Space Heat



Conclusion

The SUNDAY thermal simulation program was used to predict space heat energy consumption for 83 energy efficient homes. The predicted data were found to explain 51.9 % of the variation in monitored space heat consumption. Using a paired student's t test, no statistically significant difference could be found between mean predicted space heat and monitored space heat for the entire sample of homes or for sub-samples of homes categorized by six classes of total heat loss coefficient.

Several variables which were not included as inputs to the simulation were examined with an analysis of covariance model for their ability to improve the simulation's prediction of space heat. These variables included house size, construction type and heating system type. The model was able to increase the coefficient of determination from 0.519 to 0.611 - a 17.7% increase.

While the SUNDAY simulation program on aggregate is able to predict space heat consumption, it should be noted that there is a large amount of variation in both the monitored space heat consumption and the SUNDAY predictions. The ability of the program to accurately model an individual house will be constrained by the quality of input variables.

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