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HEATING SEASON PERFORMANCE AND THERMAL CHARACTERISTICS OF THE NCSU SOLAR HOUSE

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ABSTRACT

This paper presents an analysis of heating season performance of the North Carolina State University Solar House. A microcomputer based data acquisition system was used for detailed monitoring during four periods in the winter of 1982-1983. Measurements of 52 temperatures and 4 insolation values in and around the structure were recorded for subsequent analysis. Electrical usage was metered separately for lighting and appliances, domestic hot water, and auxiliary heat (heat pump). Manual logs were kept noting building occupancy and the operation of controllable building features. Using this information, experimental estimates were made of the building loss coefficient, balance point temperature, and other thermal parameters. Monthly building energy consumption was broken down into internal gains, auxiliary heat, and solar gains for both 1981-1982 and 1982-1983 heating seasons. Performance was consistent for the two seasons and the results presented here confirm the effectiveness of the house design.

1. INTRODUCTION

The NCSU Solar House is a fully furnished two-story residential building of traditional design located on the campus of North Carolina State University in Raleigh, NC. The site is at latitude 35°47' north, longitude 78°42' west, and elevation 132m(433 ft). The climate is temperate, with mild winters, warm humid summers, and much pleasant weather in the spring and fall. Serving as a research, demonstration, and educational facility, the house has been open to the public on weekdays since its dedication in September 1981. A discussion of the house design (1), construction costs (2), and performance results for the first year of use (3) have been reported previously. Further details and background on the results presented here may be found in reference (5).

1.1 Building Description

The house contains 158m^2 (1700ft^2) of living space plus 30m^2 (320ft^2) in the sunspace. Built into a south sloping site, the lower level north and west walls are earth sheltered. Upper level walls are of conventional 2x4 wood stud construction with fiberglass batt insulation and styrofoam sheathing for 3.3 m^2*°C/W (R-19) resistance. The ceiling is insulated with blown mineral wool to 5.3 m^2*°C/W (R-30). All windows are double pane glass, weatherstripped, with wood sash for a 0.30 m^2*°C/W (R-1.7) rating. The four windows on the north side have weatherstripped, operable insulating shutters. Exterior doors to the living space are foam filled metal doors, 0.88 m^2*°C/W (R-5), with spring bronze weatherstripping. Extensive silicone caulking was used during house construction to reduce air leakage through the building skin. An active solar domestic hot water system is installed, consisting of 6m^2 (60ft^2) of collector mounted on the south slope of the roof.

1.2 Passive Solar Heating System

The primary passive solar heating feature in the house is a two-story sunspace. The sunspace is enclosed in the living space, which wraps around it in a U-shaped fashion. Every room of the house may be opened to the sunspace by either windows or doors, permitting free movement of warm air from the sunspace to the rest of the house. The aperture of the sunspace consists of 24m^2 (260ft^2) of vertical south-facing double pane glass. Thermal mass is provided by 20cm (8in) thick brick walls on three sides and mass floor of 1.27cm (0.5in) quarry tile on a 2.54cm (1in) grout bed over a 15cm (6in) concrete slab. The sunspace may be ventilated by opening four awning windows along the bottom of the glass wall and by a manually controlled two-speed attic fan located in the sunspace ceiling. Shading of the sunspace during warmer months is provided by a 0.97m (3.17 ft) roof overhang spanning the width of the sunspace and by a system of drop-in wooden louvers supported with a 3.66m by 6.40m (12ft by 21ft) framework, which shades the lower portion of the glazing and the brick patio outside.

There are two Trombe walls, one-story high, in the lower level bedrooms. Each Trombe wall has $20m^2$ ($64ft^2$) of double pane glass separated by a 10cm (4in) air space from the masonry wall, which is 30cm (12in) thick. The Trombe walls are shaded by a 0.91m (3ft) overhang with removable wooden louvers at the top of each wall.

Each Trombe wall contains a window which, together with the two south facing windows on the upper level, comprise the direct gain solar heating features. Total direct gain window aperture is $2.7m^2$ ($29ft^2$).

1.3 Backup Heating and Air Conditioning

Auxiliary heating and cooling is provided by a water-to-air heat pump. This unit has a heating capacity of 7.3 kW (25000 Btuh) and a cooling capacity of 7.9 kW (27000 Btuh). The outside heat source/sink consists of 73m (240ft) of 10cm (4in) cast iron pipe buried through the septic field at a depth of about 1.5m (5ft). Water is the heat exchange fluid and is circulated through the pipe in a closed loop. The heating season coefficient of performance (COP) is 2.8 according to manufacturer's information; this value for the COP is used to estimate the auxiliary heat delivery for the analyses reported here. There is also a wood stove in the sunspace and a fireplace in the living room.

2. PERFORMANCE MONITORING

Detailed performance data was taken during four monitoring periods in the 1982-1983 heating season. These periods were

1. Jan 26 - Feb 2, 1983 (8 days)
2. Feb 7 - Feb 19, 1983 (13 days)
3. Mar 10 - Mar 14, 1983 (5 days)
4. Apr 16 - Apr 25, 1983 (10 days)

for a total of 36 full days of data. During these periods, 56 sensors were scanned at 5-minute intervals and hourly average temperatures and cumulative insolation were recorded. A log book was kept during the monitoring periods; in this were recorded sunspace and living room air temperatures, position (open or closed) of the doors between the sunspace and the living space, and other information related to the operation of the passive and auxiliary heating systems. Also available are watt-hour meter readings for total electrical usage, heat pump usage, and electric hot water heater usage; these were provided by the local electric utility company, Carolina Power and Light.

2.1 Controls During Monitoring

The house was operated normally during the January, March, and April monitoring periods. The building was open to the public on weekdays and occupied by a student during the evenings. The thermostat setting for the heat pump was 20°C (68°F). Sunspace doors (upstairs and downstairs) were opened when it was observed by the occupant that sunspace temperatures equaled or exceeded the living room temperature. The doors were closed when the sunspace temperature fell below the living room temperature. No fires were built in the wood stove or fireplace.

During the February monitoring period, the house was closed to the public so that controlled performance evaluation could be done. Auxiliary heat (the heat pump) was turned off at 8:00 PM on February 6 and remained off throughout the monitoring period. The solar domestic hot water system was shut down at 11:30 AM on February 7, and remained off for the remainder of the monitoring period. The solar hot water system is not monitored by the data acquisition hardware, so that thermal input from it into the living space cannot be evaluated. The electric hot water heater, which is separately metered, remained on, although hot water consumption by the single occupant was minimal. Sunspace doors were operated normally. Exterior insulating shutters on all north facing windows remained shut and the thermosiphon vents in the brick Trombe wall remained closed.

2.2 Instrumentation

Copper-constantan (type T) thermocouples are located throughout the house and are available for placement as needed for air temperature measurements. An Eppley pyranometer is installed above the roof for measurement of horizontal insolation. Three Licor pyranometers measure insolation on vertical south facing planes inside the sunspace, outside the sunspace, and outside the brick Trombe wall.

All sensors are connected to a central terminal board in the utility room from which they can be connected to a digital voltmeter. Automated monitoring of selected sensors is provided by a Hewlett Packard (HP) model 3054 data acquisition system. This consists of a microcomputer with tape drive and a digital voltmeter with 57 channels available for connection to sensors.

3. ESTIMATION OF BUILDING THERMAL PARAMETERS

A basic notion underlying performance analysis for the house is that energy losses can be characterized by a building loss coefficient. The rate of heat loss is equal to the product of this coefficient times the indoor-outdoor temperature difference. Building losses may be categorized into losses by conduction through the materials of the structure and losses by convection (termed infiltration) through openings and cracks in the structure. In evaluating passive solar buildings, it is useful to break the losses down into a portion due to the passive solar features of the structure and a portion due to the rest of the structure. Analytic estimation yields a net loss coefficient (excluding losses through the passive solar components) of 108 W/°C (4900 Btu/°F*day) and a total building loss coefficient of 255 W/°C (11600 Btu/°F *day). However, since the building loss coefficient is such a key parameter in subsequent analyses, an experimental estimate is desirable.

Regression analysis was done to obtain an estimate of the total building loss coefficient during the heating season based on measurements taken under conditions of actual house use. Daily measurements of temperature, insolation, and electrical consumption were fit to a single-node energy balance equation, which includes a one-day thermal storage term. The basic form of the equation is

$$L*(Ti-To) = Qa + F*Qs + C*(Ti-Tp) \quad (1)$$

where L is the total building loss coefficient, C is the effective thermal capacitance of the building, and F is the fraction of solar energy available outside the glazing which contributes to heating the house. Ti and To are the average daily indoor and outdoor temperatures, Tp is the indoor temperature of the previous day, Qs is the daily measured insolation striking the vertical south facing glazing area, and Qa is the daily electrical consumption. The parameters L, C, and F were to be estimated by regression (least squares fit) to the measured temperature and energy data.

Several forms of eqtn 1 were used for parameter estimation with data from monitoring periods in January and February. The result for L yielding the smallest standard error, 0.43°C (0.77°F), was 255 W/°C (11600 Btu/°F*day), which matches the analytic prediction given earlier. The resulting value for effective thermal capacitance (C), 19 kWh/°C (35900 Btu/°F), was higher than the design thermal mass of 14 kWh/°C (26700 Btu/°F). The estimate for F was 26%.

Another result of the regression analysis was a value for an intercept of 1.2°C (2.1°F) with a standard error of 0.43°C (0.78°F). This value, being positive, can account for energy gains (such as those from occupants and the solar domestic hot water system) which were left out of the energy balance equation.

4. HEATING SEASON PERFORMANCE

A performance breakdown in terms of solar versus auxiliary heat was determined from the metered electrical consumption, daily average outdoor temperatures, and the estimated building loss coefficient. Monthly heating loads were computed by multiplying an indoor-outdoor temperature difference integral, expressed as degree days per month, times the building loss coefficient. So that the results would be independent of internal gains due to lighting, appliances, and occupants, a reference heating load was used in the analysis rather than the actual building heat loss.

4.1 Energy Balance Analysis

The heating season performance analysis was based on a house energy balance of the form

$$L*(Tset-To) = Qint + Qaux + Qsun \quad (2)$$

where Tset is the desired indoor temperature (thermostat set point), Qint is internal gains, Qaux is auxiliary heat supplied, and Qsun is the balance, attributed to solar gains. The thermostat set point, 20°C (68°F), was used rather than the actual indoor temperature so that solar gains causing the house to rise above the set point were not counted as useful gains.

Internal gains were computed from the metered total electrical consumption by subtracting the heat pump usage and adding estimated gains from occupants. Occupant gains were estimated from log book and visitor's register records using a value of 132 Watts (450 Btuh) per occupant.

A reference (balance point) temperature was defined for the time periods under consideration by the relation

$$Tref = Tset - Qint/L \quad (3)$$

in which Qint was taken as the daily average internal gains over the time period. Physically, Tref represents the outside temperature below which internal gains are not sufficient to maintain a minimum indoor temperature of Tset. The reference heating load for the time period was then defined as

$$Qref = L * DDref \qquad (4)$$

where DDref are degree days computed to the base Tref. The total building loss coefficient used was the empirically estimated value of L equal to 255 W/°C (11600 Btu/°F*day). Reference temperature was not found to vary greatly from month to month around the seasonal average of 16.7°C (62°F), so this value was used for the analysis.

The solar contribution for space heating was then evaluated by subtracting the measured auxiliary heat used from the reference heating load. A solar heating fraction was calculated as

$$Fsun = 1 - Qaux/Qref \qquad (5)$$

Tables 1 and 2 contain the results of these calculations for the 1981-1982 and 1982-1983 heating seasons.

4.2 Observations and Discussion

No auxiliary heat was needed in October and November even though there were significant heating requirements for these months. Their heating load was met entirely by the passive solar heating system. Note that heating load as used here refers to the space heating requirements over and above that met by internal gains. February was an exception for the 1982-1983 season because of the monitoring period from February 6 through February 22, during which time the house was closed to the public and the heat pump turned off. Consequently, the 91% solar heating fraction shown for February 1983 is certainly not representative of performance when a comfortable set point temperature is being maintained.

Performance for the first season (1981-1982) looks somewhat better than for the second season, particularly since the winter was colder on a degree day basis. However, the house was occupied by a different student that year, and operated in a more electricity-conserving manner. The heat pump was turned off during periods when the house was not occupied and the wood stove and fireplace were occasionally used. During most of the 1982-1983 heating season, the heat pump was left running with the thermostat set at 20°C (68°F) and neither the wood stove nor fireplace were used. Aside from the 17 days in February previously mentioned, the only extended time the heat pump was off was during the holiday break from December 21 through 31, 1982. One can therefore conclude that overall performance was quite consistant for the two seasons.

The values for solar gains depend on the value of the building loss coefficient, since they were inferred by subtraction from an estimated heating load rather than measured directly. Calculations were done to assess the sensitivity of the computed solar gains to uncertainties in the building loss coefficient. The above analysis was repeated for building loss coefficients higher and lower than the estimated value of 255 W/°C (11600 Btu/°F*day). For an uncertainty in the building loss coefficient of 25%, the range of solar fractions was 68% to 84%, indicating that overall performance was quite good for likely values of the building loss coefficient.

4.3 Normalized Results

A useful way of summarizing the heating season performance of a passive solar house is suggested in reference (4). The total building heat loss for the season and its breakdown into internal gains, auxiliary heat, and solar gains were normalized by dividing by the heating degree days for the season and the floor area of the house. Table 3 presents the data in this manner. In this table, total heat loss was computed as the product of the building loss coefficient times the number of heating degree days for the season. Internal gains were subtracted from the total loss, leaving the heating load to be met by the passive solar heating system and the auxiliary heating system (heat pump). Subtracting the measured auxiliary heat leaves the inferred solar gains. It should be noted that the total heat loss includes losses through the passive solar components of the building, so that the bottom lines in Table 3 are solar gains, including those needed to make up losses through the passive components.

Normalized performance was quite consistent over the two seasons, and the values shown here compare well with those reported in a survey of 38 monitored passive solar buildings (4). The ratio of glazing area for the house to floor area is 0.25, which is in line with the ratios reported there. The normalized total heat loss for the house was 1.6 $W/m^2*°C$ (6.8 $Btu/ft^2*°F*day$). This value, which is a measure of how well energy conservation is implemented in the structure, is somewhat higher than the median value (6.5 $Btu/ft^2*°F*day$) reported in the survey. The NCSU Solar House ranks among those buildings having the lowest normalized auxiliary heat requirements. It is higher than average in internal gains due to the high electric light usage when the house is open for visitors on weekdays.

A seasonal solar collection efficiency for the passive components can be computed using normal insolation values for the locale. The insolation received on a vertical south-facing surface from October through April is 675 kWh/m^2 (214,000 Btu/ft^2). For the 39m^2 (417ft^2) aperture of the NCSU Solar House, this yields 26000 kWh (89 million Btu) per season. Using this as a base resulted in seasonal collection efficiencies of 23% for 1981-1982 and 20% for 1982-1983. The difference in efficiency may not be meaningful because actual insolation was certainly not the same for both years. It is worth noting that the 20% to 23% efficiency calculated here is close to the value for F of 26% obtained with the regression analysis discussed earlier.

4.4 Temperature Stability

Indoor temperatures were quite stable during the periods of observation. On sunny winter days, the temperature in the living room on the upper level of the house generally fluctuated from the thermostat set point of 20°C (68°F) up to around 24°C (75°F). The highest temperature recorded was 26°C (78°F), which occurred at 2:00 PM on February 1, 1983. This day was bright and sunny with the outdoor temperature reaching a high of 14°C (58°F), and it followed two previous sunny days with highs over 16°C (60°F). Indoor temperature swings were more moderate later in the season, when outdoor temperatures were warmer on the average but the sun was higher in the sky.

Sunspace temperature was also quite stable. The daily fluctuation was typically in a range of about 3°C (5°F) below to 5°C (8°F) above the average daily temperature in the sunspace. The maximum daily fluctuation observed was from a low of 13°C (55°F) to a high of 23°C (73°F) on February 7. The maximum sunspace temperature recorded during the winter was 28°C (82°F) on both January 31 and February 1, 1983, which were unusally warm sunny days for that time of year. The minimum observed sunspace temperature was 9°C (48°F) at 7:00 AM on February 15. This was during the February monitoring period when auxiliary heat in the house had been off for a week. The outdoor temperature was 1°C (33°F) at the time and the two previous days had been cold and cloudy.

5. CONCLUSIONS

The results presented here affirm the excellent heating season performance of the NCSU Solar House reported earlier (3) on the basis of the low auxiliary energy requirements for its first year of operation. The good performance can be attributed to the good passive solar design, particularly the energy conservation features and the sunspace. The enclosed sunspace is aesthetically pleasing as well as thermally efficient with three sides adjoining the living space and ample window and door openings to permit exchange of heat to the living space. That sufficient thermal mass is included in the design is evidenced by the good temperature stability of both the living space and the sunspace. Energy conservation was emphasized; this is important in the southeastern region of the United States to minimize summer cooling as well as winter heating needs. The effectiveness of sufficient insulation, high quality components and construction technique, with special attention paid to caulking and weatherstripping needed to reduce infiltration losses, has been demonstrated.

The results given here apply to heating season performance. That summer performance is also good, as has been shown by the low electrical consumption for cooling (3). Evaluation is needed, however, of the cooling load liabilities (particularly in early autumn) that might be imposed by the Trombe walls and sunspace. Further research on the NCSU Solar House is needed to detail the component-by-component performance, both winter and summer, of the passive solar features.

6. REFERENCES

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TABLE 1. 1981-1982 Heating Season Monthly Performance

Month	Avg Temp °C	Avg Temp °F	Degree-days (18°C)	Degree-days (65°F)	Avg Hrs of Sun	Int. Gains	Ref. Load	Aux. Heat	Solar Gains	Solar Fract.	Heat Bill	Total Bill
OCT	14	57	131	253	6.9	459	591	0	591	100%	$ 0	$ 24.60
NOV	11	51	226	425	5.9	586	1152	0	1152	100%	0	31.38
DEC	4	40	421	776	4.8	585	2321	311	2011	87%	6.66	37.98
JAN	2	36	494	907	4.4	602	2766	700	2067	75%	15.00	47.22
FEB	8	46	290	538	4.8	718	1550	543	1007	65%	11.64	50.10
MAR	11	52	219	411	6.1	643	1108	258	851	77%	5.52	39.96
APR	14	57	128	244	7.2	513	598	36	562	94%	0.78	28.26
Season	9	48	1907	3554	5.7	4105	10088	1848	8240	82%	$39.60	$259.50

Energy values are reported in kWh and bills are based on an electricity cost of $0.06/kWh

TABLE 2. 1982-1983 Heating Season Monthly Performance

Month	Avg Temp °C	Avg Temp °F	Degree-days (18°C)	Degree-days (65°F)	Avg Hrs of Sun	Int. Gains	Ref. Load	Aux. Heat	Solar Gains	Solar Fract.	Heat Bill	Total Bill
OCT	16	61	95	182	5.5	592	438	0	438	100%	0	$31.70
NOV	11	52	209	392	4.1	605	1071	0	1071	100%	0	32.40
DEC	9	48	292	542	2.8	503	1560	219	1341	86%	4.70	31.63
JAN	3	38	452	828	4.6	628	2498	946	1552	62%	20.28	53.92
FEB *	5	41	366	675	5.1	467	2009	186	1823	91%	3.98	29.02
MAR	11	51	233	438	6.2	633	1183	452	730	62%	9.69	43.57
APR	12	54	161	305	7.1	632	788	249	540	68%	5.33	39.20
Season	9	49	1805	3362	5.1	4059	9547	2052	7495	79%	$43.98	$261.46

Energy values are reported in kWh and bills are based on an electricity cost of $0.06/kWh

* The heat pump was off for 17 days in February 1983, so performance for that month is atypical.

TABLE 3. Normalized Heating Season Performance of the NCSU Solar House

	October 1981-April 1982			October 1982-April 1983		
	10^3kWh	W / m^2*°C	Btu / ft^2*°F*day	10^3kWh	W / m^2*°C	Btu / ft^2*°F*day
Total building heat loss:	12.1	1.6	6.8	11.5	1.6	6.8
Internal gains:	4.1	0.5	2.3	4.1	0.6	2.4
Heating load:	8.0	1.1	4.5	7.4	1.0	4.4
Auxiliary heat used:	1.8	0.3	1.1	2.1	0.3	1.2
Solar gains	6.2	0.8	3.4	5.3	0.7	3.2

Normalization is based on the living space floor area of 158 m^2 (1700 ft^2) and total building loss coefficient of 255 W/°C (11600 Btu/°F*day).

Solar Glazing area of the house is 39 m^2 (417 ft^2); ratio to floor area is 0.25.