LESSONS LEARNED FROM THE BPA SOLAR HOMEBUILDERS PROGRAM

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ABSTRACT

From October 1982 through September 1983, 16 new, energy-efficient solar homes were monitored by BPA for thermal performance. The homes were located in Portland, Oregon, and Spokane, Washington. Use was made of the Class B passive solar monitoring methodology, as developed by the Solar Energy Research Institute. Results will be presented, including: (1) monthly energy balances for the homes (and system efficiencies derived from their balances); (2) comparison between measured and design tool predicted performance; and (3) design recommendations regarding thermal mass, air handling, etc., developed from analysis of the monthly and hourly data.

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INTRODUCTION

The Bonneville Power Administration (BPA), in compliance with the Pacific Northwest Electric Power Planning and Conservation Act of 1980 (PL 96-501), operated the Solar Homebuilders Program (SHBP) in Portland, Oregon, and Spokane, Washington, during 1982 and 1983 with assistance from the Western Solar Utilization Network (Western SUN, now defunct). The purpose of the program, which was modeled closely upon the Denver Metro Program of the Solar Energy Research Institute (SERI), was to demonstrate energy-efficient passive solar residential design to the building industry and public, and to study the thermal performance of the actual buildings. The SHBP was targeted to the medium priced, or tract housing, market in order to maximize its impact, but not all the designs were within the target price and size.

PROGRAM DESCRIPTION

The SHBP included design team selection, design review, home show, and thermal performance monitoring elements. Design teams, consisting of a builder, an architect, and a solar designer/engineer, were chosen competitively from a large number of applicants, based upon experience, market segment, and knowledge of energy conservation and passive solar design. The team submitted two conceptual designs and full construction documents for the chosen design to a design review committee, which consisted of BPA and Western SUN architects and engineers, and outside consultants. The designs were reviewed and critiqued in person for energy efficiency, practicality and ease of construction, market appropriateness, and, to a lesser degree, architectural merit. Certain energy analysis was required for both design optimization and technology transfer.

Energy conservation elements were heavily stressed throughout design review as typically more cost-effective than passive solar elements, and therefore necessary prerequisites. Glazing area was limited based upon conditioned floor area and effective thermal mass, using rules of thumb specified in (Mazria, 1979). These recommendations were generally adhered to by the design teams, although some of the designs were somewhat more mechanically complex and heavily glazed than desired. The design cost was reimbursed by BPA. The entire program cost to BPA was $5.2 million.

The SHBP homes were shown to the public in 2 home shows. The Portland homes were constructed in Hillsboro, a suburb located a 25 miles west of Portland. They were shown in a "Solar Parade of Homes", which was separate from the Homebuilders Association (HBA) home show for 1982. The homes were adjacent to each other, and only 6 of the original 12 designs were actually constructed, due to high interest rates. The Spokane homes were constructed in a southeast suburb, and were also adjacent to each other. They were shown in the major HBA home show for 1982, and received about the same number of visitors as the Portland homes, even though the Spokane area has a much smaller population. All 10 Spokane designs were constructed. Most of the Hillsboro homes and some of the Spokane homes were built speculatively.

DESCRIPTION OF THE HOUSES

Of the 17 homes constructed and shown, 16 were monitored for thermal performance. (One house in Spokane was not monitored, because no agreement could be reached with the homeowner). Characteristics of the monitored homes are summarized in Table I. They are all of wood frame construction, with relatively open floor plans. Average size was 1580 $ft.^2$, and average asking price was $85,000.

All the homes were insulated in excess of local building codes, some considerably, and were also more air-tight than average. The average total heat loss coefficient was 370.0 BTUh/°F, compared to approximately 500 BTUh/°F for local code compliance, as measured by electric coheating. The average seasonal infiltration rate was 0.29 ACH, or perhaps half of current practice, as estimated from a blower door test.

Two passive solar system sizing rules were used during review: south glazing area should be no more than 20 percent of floor area, and exposed thermal mass should not be less than twice the south glazing area. These rules were reasonably closely complied with in the designs. All designs utilized direct gain (south-facing glazing) and, additionally, 10 of the designs incorporated a sunspace, and 2 incorporated masonry storage walls.

Of the 16 houses, 8 were occupied for the entire monitoring period (October 1982 through September 1983), 4 were occupied for part of the period, and 4 were unoccupied for the entire period. Unoccupied houses were heated, with thermostats set generally at 65 °F, for most of the monitoring period. (A methodology is described below for estimating occupied performance for their unoccupied periods). Monitoring agreements were signed with all occupants, which included a $300 fee for access and compensation for not heating with wood. Almost no woodburning occurred.

MONITORING METHODOLOGY

Use was made of the Class B passive solar monitoring methodology, as specified in (Frey, 1982), with some minor modifications. Microprocessor-controlled data loggers sampled 10 to 20 channels of temperature (exterior, and 4 to 6 interior or buffer zone), solar radiation (horizontal and vertical), electric power (total, space heating, water heating, major appliances, and outside lighting and appliances), and on-time for vents, moveable insulation, etc.

The principal goals of Class B monitoring are to form a monthly, one-zone energy balance for the building (including delivered auxiliary, internal gains, and solar gains), and adequately characterize the internal and external environments. To this end, one-time tests are made of overall heat loss coefficients, overall furnace delivery efficiency (using the measured loss coefficient), and infiltration rate (from a blower door test). The overall heat loss coefficient is adjusted several times per month, based upon a linear wind speed correction estimated from (Sherman, 1980).

Class B monitoring has been performed for approximately 150 buildings nationwide, and results reported in (Swisher, 1983). Site data and standard format monthly and hourly performance data, the latter on 9-track magnetic tape, are available for these sites as well as the 16 sites discussed in this paper.

RESULTS

Results for three measures of thermal performance are summarized in this section, including both unoccupied and occupied houses. Purchased energy, space heating energy, and solar efficiency (utilized passive solar space heating compared with available vertical insolation) have been chosen as the primary figures of merit. Use has been made of the LASL Solar Load Ratio methodology (Balcomb, 1983) in order to interpret this efficiency, and in an attempt to account for non-standard weather and occupancy. As shown in Table II, the monitoring period was somewhat warmer and sunnier than average in both Portland and Spokane.

Purchased Energy

As shown in Table III, there was considerable variation in purchased energy, both in total and as disaggregated. This reflects the large variation in building use patterns, and illustrates the difficulty in using such data to evaluate the thermal performance of a particular design. (Natural gas consumption has been converted to equivalent kWh input, using actual heating values of fuel.)

For the occupied sites, the average total purchased energy was 24221 kWh/yr, or 14.7 ± 5.6 kWh/ft^2-yr; the average space heating purchased energy was 10416 kWh/yr, or 6.3 ± 2.3 kWh/ft^2-yr; the average purchased water heating energy was 5879 kWh/yr, or 2193 ± 820 kWh/capita-yr; and the average purchased lights and appliances energy was 7927 kWh/yr, or 3147 ± 1273 KWh/capita-yr. The occupied sites, on average, used 43 percent of their purchased energy for space heating, 24 percent for water heating, and 33 percent for lights and appliances. Purchased energy was, on average, not appreciably lower than for standard construction, due primarily to the higher than average appliance consumption in Spokane and low gas furnace efficiencies.

Delivered Space Heating Energy

Sources of space heating energy delivered to conditioned space for the period October to April are summarized in Table IV. These were derived using the Class B methodology: total heat loss estimated from a measured loss coefficient and average inside temperature, delivered auxiliary estimated from a measured delivery efficiency, utilized internal gains estimated from measured non-space heating consumption corrected for water heater, dryer, and other gains and losses, and utilized passive solar gains by subtraction.

For occupied sites, the average total heating load for the period was 44.4 MBTU, and average indoor temperature (estimated from 3 to 5 sensors as a heat loss coefficient weighted average) was 67±3°F. Average delivered space heating energy was 17.2 MBTU, and average utilized internal gains were 15.3 MBTU, or 72±36 KBTU/day, or 28±9 KBTU/capita-day. The observed internal gains are in good agreement with standard assumptions (Balcomb, 1983). Thus, space heating was provided on average as 39 percent from auxiliary systems, 34 percent from internal gains, and 27 percent from passive solar gains.

In an attempt to normalize these results for average conditions of weather and occupancy (and make better use of the unoccupied house data), space heating energy was calculated using the Volume III SLR methodology (Balcomb, 1983) for the period from November to March, using actual conditions for each site: degree days to variable base temperature, vertical insolation, utilized internal gains, and heating thermostat set point, taken as average indoor temperature. This substitution of indoor average temperature for thermostat setting is a source of error in use of the SLR methodology (although for the cloudy Pacific Northwest winter conditions the error should be minimized), and is the reason for only utilizing November to March for these calculations. Results are given in Table V.

The average November to March auxiliary space heating energy was 17.4 MBTU, and was estimated using the SLR methodology to be 12.5 MBTU, or 28 percent lower. Agreement for direct gain houses was perfect, on average: 12.6 MBTU in both cases, although the 2 lower heating load houses (10 and 11) used less energy than predicted, due probably to less venting of excess heat. Agreement for sunspaces was poor; 18.9 MBTU actual and 11.1 MBTU predicted, or 41 percent lower.

The calculated space heating energy for November to March was then "calibrated," by dividing it by the actual space heating energy used for the same period. This process attempts to account for deviations from the standard SLR methodology assumptions (particularly for sunspaces) which cannot be corrected for directly. This factor was then applied to the estimated yearly space energy which had been calculated using the SLR methodology with standard assumptions of weather and occupancy, to generate a final, "corrected" space heating energy estimate to be compared with various performance standards. This first order correction assumes that the variation between actual and SLR estimates is not a function of input assumptions (weather and occupancy). The validity of this assumption is uncertain.

As can be seen from Table V, there is considerable variation between the actual and corrected space heating energy for November through March, for some houses. As can also be seen, the corrected energy values are generally lower than the actual values for the unoccupied houses, the lower internal gains having been more than compensated for by the lower temperatures. (Unoccupied houses were actually kept at approximately 60°F for the monitoring period, due to undesired thermostat readjustment). Also, for houses which had large internal gains, the corrected space heating (which assumes 80,000 BTU/day) is considerably larger than the actual space heating.

In terms of normalized space heating energy, the average for these houses was actually 3.2 and 3.1 kWh/ft^2-yr for Portland and Spokane, respectively. It is estimated to be 3.3 and 5.8 KWh/ft^2-yr for Portland and Spokane, respectively, when standardized for weather and occupancy. These can be compared with the energy budgets for the Model Conservation Standards (MCS) as proposed by the Northwest Power Planning Council (NPPC, 1983); 2.0 and 2.6 kWh/ft^2-yr for Portland and Spokane, respectively, and with the assumed normalized consumption for current building code construction in Portland and Spokane; 5.8 and 8.9 kWh/ft^2-yr, respectively. These homes, then, would be expected to use 43 percent less space heating energy than for typical new construction, but 65 percent more than the MCS budgets in Portland on a long-term average basis. In Spokane they would be expected to use 35 percent less than typical, but 123 percent more than the MCS budget.

Solar Efficiency

Table VI summarizes a measure of efficiency of utilization of the available passive solar energy by these houses; the ratio of the (subtractively calculated) passive solar heating to the available vertical insolation on the south-facing glazing. This ratio would be expected to be less than one, due to glazing transmittance, venting of excess heat, and losses of heat from the passive system itself (especially sunspaces), and greater than one due to solar gains from non-south-facing glazing.

The average solar system efficiency for the period from November to March was observed to be 0.35, and predicted to be 0.50. For direct gain systems, the actual efficiency was actually greater than predicted: 0.62, compared to 0.55. This may have been due to less venting of excess solar heat, as several of the direct gain houses were observed to tolerate fall and spring temperature swings in excess of SLR assumptions. For sunspace systems, actual efficiency was considerably less than predicted: 0.23, compared to 0.48. This was very likely due, primarily, to inadequate transfer fan systems and controls.

DISCUSSION

A number of conclusions regarding monitoring, data processing methodology, and design implications, can be drawn from the SHBP data. Although the sample size is relatively small, we have attempted to correct for non-standard weather and occupancy conditions in order to separate the thermal performance of the design from the as-occupied thermal performance. Our experience in managing the considerable volume of data in the program has also suggested several related lessons.

Monitoring Lessons Learned

Filtering, or scanning of raw data for errors and problems, is a vital first step in data analysis, and impossible to completely automate. Use of several logic and consistency tests to flag possible problems for later scrutiny by the analyst, especially in graphic form, is somewhat time-consuming, but quite effective. Possible checks include data out of range, or conditionally out of range, and closure between main and submeter readings.

Redundancy, especially in metering, is highly recommended, and automatically integrated energy consumption should be regularly checked against manual meter readings. Also, meter failures are rare but do occur, especially gas meters.

Regarding use of the Class B methodology, calculation of derived parameters ("functions") using on-site data reduction was not convenient or practical, due to the frequently iterative nature of achieving good energy balances. Data should be quickly examined for closure of the basic energy balance, so problems can be detected and corrected.

Design Implications

A frequent problem with sunspace performance in these houses was transfer of solar heat into the conditioned space. In Table VI, we can see the average sunspace efficiency was much lower than predicted using the SLR methodology: 0.23, compared to 0.48. Errors included use of furnace fans to distribute sunspace heat, which caused unacceptable comfort problems, and overly complex fan controls, which were not adequately explained to occupants and installers. Fan noise was also a problem. A solution would be to use a separate, moderately sized (200 CFM) transfer fan controlled by one, single-stage thermostat sensing sunspace heat availability. The fan could be manually or automatically enabled, based upon living zone heat demand.

Most furnace systems were of quite low overall delivery efficiency: an average of 0.46 for gas, and 0.55 for electric. This was due to a number of factors. Ductwork was, in almost all cases, uninsulated, often to provide heat for unheated basements. A more efficient solution would be to insulate basement ceilings, and insulate and seal all ductwork outside of conditioned space. Furnaces were, in general, quite oversized, owing partly to limited size availability. The one crawlspace plenum system was of low efficiency, 0.55 with electric heat, due to leakage and ground coupling. The one underfloor mass storage system was also of very low efficiency, 0.36 with gas heat, due to ground coupling and inappropriate controls.

Very limited temperature stratification was observed, both in conditioned space and in sunspaces. Average floor to ceiling temperature differences in single-story vaulted spaces was seldom more than 1°F, on average. Ceiling fans were effective in reducing what little stratification existed, but were seldom used. Sunspace floor to ceiling temperature differences of less than 5°F were typical.

Considerable energy use was observed for hot water heaters and freezers which were located outside the conditioned space. This heat could be better utilized if the appliances were located in conditioned space (summer overheat considerations permitting, or if a method for venting the heat during the cooling season were provided).

Unreasonable overheating (in excess of 85°F) was observed only in the few south-facing rooms totally without thermal mass, and not at all in spaces which provided the recommended mass-to-glass ratio. Daily temperature swings of 15°F were not uncommon in direct-gain houses for sunny days in fall and spring.

REFERENCES

J. Douglas Balcomb, et al., "Passive Solar Design Handbook," Volume 3, Los Alamos, New Mexico, 1983.

Donald Frey, et al., "Installation Manual for the SERI Class B Passive Solar Data Acquisition System," SERI/TR-254-1671, Golden, Colorado, 1982.

Edward Mazria, "The Passive Solar Energy Book," Emmaus, Pennsylvania, 1979.

Northwest Power Planning Council, "Northwest Conservation and Electric Power Plan," Volume 1, Portland, Oregon, 1983.

M. H. Sherman and D. T. Grimsrud, "Measurement of Infiltration Using Fan Pressurization and Weather Data," LBL-10852, Berkeley, California, 1980.

Joel Swisher and T. Cowing, "Passive Solar Performance," SERI/SP-281-1847, Golden, Colorado, 1983.

Table I: House characteristics.

Site	Floor Area (ft^2)	Solar Glazing Area (ft^2)	Seasonal* Ave.Infil. (ACh)	Passive System Types Type**	Furnace Delivery Efficiency***
1	1860	286	0.31	DG/SS	0.45
2	1200	294	0.10	DG/TW	0.51
3	1900	181	0.44	DG/SS	0.62
4	1540	258	0.27	DG/SS	0.36+
5	1470	290	0.34	DG	0.49
6	1880	186	0.28	DG/SS	0.61
7	1890	273	0.29	DG/SS	0.49
8	1750	295	0.15	DG/SS	0.34
9	1460	260	0.21	DG/SS	0.40
10	1270	95	0.11	DG	1
11	1320	34	0.36	DG	0.47
12	1380	145	0.43	DG	0.49
13	1360	109	0.41	DG/TW	1
14	1740	275	0.33	DG/SS	1
15	1700	350	0.43	SS	0.55
16	1610	199	0.15	DG/SS	1

* Estimated from blower door tests using methodology of (Sherman, 1980).
** DG = direct gain; SS = sunspace; TW = trombe wall.
*** Measured using the methodology in (Frey, 1982).
\+ Averaged for October to April; modified monthly due to thermal mass storage floor effects.

Table II: Weather summary.

Site	65°F Degree Days (DD/yr) Monitoring Period	Average	Horizontal Insolation (BTU/month) Monitoring Period	Average
Hillsboro*	4733	4792	1284	1075
Spokane	6538	6835	1356	1224

* Average conditions for Portland, Oregon.

Table III: Purchased energy summary.

Site	Flr Area (ft^2)	Number Occpts	Months Unoccupied	Purchased Energy (KWh/yr)* Total	Space Htg	Water Htg	Lght/Appl
1	1860	4	0	40515	15224 (G)	12878 (G)	12413 (E)
2	1200	2	0	19013	7218 (G)	5479 (G)	6316 (G)
3	1900	5	0	39187	17926 (E)	9089 (E)	12171 (E)
4	1540	1	4	14988	7057 (G)	2621 (G)	5319 (E)
5	1470	2	5	21544	12828 (G)	5338 (G)	3378 (E)
6	1880	3	0	30976	13246 (G)	10376 (G)	7355 (E)
7	1890	4	0	43170	15978 (G)	7023 (G)	20168 (E/G)
8	1750	2	0	21297	10965 (G)	5304 (G)	5028 (E)
9	1460	4	4	25906	12680 (G)	5515 (G)	7717 (E)
10	1270	2	0	7300	1198 (E)	1888 (E)	4214 (E)
11	1320	2	0	14197	4201 (E)	3943 (E)	6053 (E)
12	1380	0	12	15137	14018 (G)	147 (G)	972 (E)
13	1360	0	12	9659	8374 (E)	766 (E)	519 (E)
14	1740	0	12	11192	9945 (E)	217 (E)	1030 (E)
15	1700	1	4	12555	6474 (E)	1089 (E)	4992 (E)
16	1610	0	12	7177	6776 (E)	169 (E)	232 (E)

* E = electric, G = gas; equivalent kWh input from actual fuel heating value.

Table IV: Heating season* delivered space heating energy.

Site	Delivered (MBTU) Total	Auxiliary	Internal	Passive
1	61.47	22.1	22.92	9.45
2***				
3	64.56	35.14	26.58	2.84
4	29.41	8.28	9.62	11.48
5	50.75	21.1	5.25	24.4
6	60.8	26.4	17.3	17.2
7	69.8	26.5	27.6	15.7
8	38.6	11.1	12.4	15.1
9	39.29	16.96	12.97	9.38
10	27.89	4.1	11.44	12.66
11	27.73	5.93	16.05	5.75
12**	39.9	23.48	3.43	13.02
13**	36.5	26.94	1.38	8.88
14**	51.83	33.57	2.97	15.31
15	24.16	11.48	5.94	6.75
16**	34.34	22.79	1.35	10.21

* October through April.
** Unoccupied all year.
*** Unavailable at this writing.

Table V: Standardized auxiliary space heating energy.

Site	Actual* (MBTU)	Estimated* (MBTU)	Standardized Estimate** (MBTU)	Corrected** (MBTU)	Normalized (kWh/ft^2-yr) Actual	Normalized (kWh/ft^2-yr) Corrected
1	18.7	8.09	20.2	46.7	2.95	7.36
2+						
3	30.7	24.9	35.6	43.9	4.73	6.77
4	7.0	1.81	5.11	19.8	1.33	3.77
5	19.4	17.7	29.48	32.2	3.86	6.41
6	23.3	21.2	27.2	29.9	3.63	4.66
7	22.9	12.2	26.4	49.6	3.55	7.69
8	10.0	3.84	8.53	22.2	1.67	3.72
9	16.1	4.7	8.17	28.06	3.23	5.63
10	3.6	7.12	11.3	5.7	0.95	1.32
11	5.5	6.5	7.46	6.51	1.22	1.45
12***	21.7	19.0	17.8	20.3	4.61	4.31
13***	22.8	22.8	17.8	17.8	4.91	3.83
14***	28.8	16.6	15.9	27.6	4.85	4.65
15	10.8	2.27	3.94	18.8	1.86	3.24
16***	20.2	13.7	14.9	22.0	3.68	4.00

* November through March.
** Yearly.
*** Unoccupied all year.
+ Unavailable at this writing.

Table VI: Passive solar efficiencies.

Site	System Type	Vertical Insolation (MBTU)	Utilized Passive Solar Actual (MBTU)	Utilized Passive Solar Estimated (MBTU)	Efficiency Actual (MBTU)	Efficiency Estimated (MBTU)
1	DG/SS	34.8	6.01	61.6	0.17	0.48
2**	DG/TW					
3	DG/SS	22.0	0.03	5.83	0.001	0.27
4	DG/SS	31.4	7.51	17.5	0.24	0.40
5	DG	35.3	15.8	17.5	0.45	0.50
6	DG/SS	22.6	11.0	12.1	0.49	0.54
7	DG/SS	33.2	9.76	19.9	0.29	0.60
8	DG/SS	35.9	10.5	16.6	0.29	0.46
9	DG/SS	31.6	3.77	15.2	0.12	0.48
10	DG	10.4	8.05	4.67	0.77	0.45
11	DG	5.54	4.35	3.36	0.79	0.61
12	DG	15.9	7.33	10.0	0.46	0.63
13	DG/TW	11.9	5.37	5.37	0.45	0.45
14	DG/SS	30.2	8.37	20.6	0.28	0.68
15	SS	38.3	3.26	11.8	0.09	0.31
16	DG/SS	21.8	6.28	12.8	0.29	0.59

* November through March.
** Unavailable at this writing.