MEASURED PASSIVE SOLAR PERFORMANCE FROM NEW RESIDENCES IN DENVER, COLORADO

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ABSTRACT

This paper discusses the thermal performance of twelve passive solar residences in the Denver, Colo., metropolitan area. These buildings were monitored during the 1981-1982 heating season as part of the Residential Class B Passive Solar Performance Monitoring Program. A low-cost approach to building thermal monitoring is explained, including the instrumentation hardware, the real-time data reduction program, and the performance evaluation methodology. The buildings are described in detail, with monthly and seasonal summaries of weather data and the basic building energy flows. Future detailed analysis efforts, using hourly data, are discussed briefly.

1. INTRODUCTION

The Residential Class B Passive Solar Performance Monitoring Program is a low-cost program that evaluates the thermal performance of a large number of residential buildings throughout the country (1). The goal of Class B performance monitoring is to support passive solar building research by determining consistently the thermal performance of passive buildings of several different types and in different climates. Instrumentation is limited to that needed to calculate the monthly building energy balance, the solar fraction, and solar savings. Thermal storage and other individual components are not instrumented, and no attempt is made to determine a building's thermal processes in detail.

A central feature of Class B monitoring is that it uses on-site data processing and displays performance results using a standardized microprocessor data acquisition system (DAS). Off-site processing of the monitoring results only includes such elements as regression analysis (for statistically determining building loss coefficients, etc.) and comparative analysis of data from different sites. This data processing arrangement improves the reliability and credibility of the monitoring data and facilitates debugging and maintenance of the on-site DAS by providing real-time checks on both sensor output and performance factors.

Data are received on up to 22 channels every 15 seconds, and channel averages are stored on cassette tape every hour. These data are later transcribed to the SERI mainframe computer system. In addition, daily and monthly performance factors are calculated in real time and then printed and stored on a daily basis. Physical and thermal characteristics of the building, such as furnace efficiency and solar aperture area, are measured at the beginning of the monitoring period and stored in the microprocessor software.

2. ENERGY BALANCE METHODOLOGY

Building thermal performance is calculated for a one-zone energy balance. The balance is calculated for the air of the living zone, defined as conditioned space and space that always remains within $6^{o}C$ ($10^{o}F$) of conditioned space temperature. The living zone may not include the entire building floor area and may or may not include sunspaces. The passive solar heat actually used by the building is calculated by subtracting the measured heat delivered to the building by auxiliary and internal sources from the building heat loss, calculated from measured temperature differential. This method is simpler to implement than using an additive calculation to determine passive heating because the quantities that are difficult to measure, such as venting of overheated air and transfer of heat to and from mass walls, are not needed.

Living-zone heat loss Q_{loss} is calculated using a single living zone temperature (averaged from multiple sensors) and a living zone loss coefficient. The loss coefficient is measured using electric coheating (1,2). Infiltration measurements are used to correct the loss coefficient for wind speed and other effects (3,4). Details of these measurement techniques are included in the installation manual for the Class B Program (5).

Delivered auxiliary heating Q_{auxh} is continuously monitored using furnace burner on-time, with a single measurement of delivery efficiency, for gas- or oil-fired systems, or measured power for electric systems. The fuel delivery efficiency is measured during the coheating experiment and may be corrected periodically for part load effects. No wood stoves or fireplaces are allowed, and heat pumps must be operated only in a resistance heating mode.

Delivered internal heat gains Q_{int} include the space heating effects of domestic hot water, water heater tank losses, and miscellaneous electric appliances. Heat gains from domestic hot water and tank losses are estimated based on continuous measurement of domestic water heater burner on-time for gas- or oil-fired systems or measured power for electric water heaters. Heat from other electric appliances and lights is included in the measurement of total electrical power delivered to the building.

From these values the passive heating used by the living zone Q_{pash} is calculated as:

$$Q_{pash} = Q_{loss} - Q_{auxh} - Q_{int}. \qquad (1)$$

The heating can be divided among three sources:

PHR = passive heating ratio = Q_{pash}/Q_{loss}
AHR = auxiliary heating ratio = Q_{auxh}/Q_{loss}
IHR = internal heating ratio = Q_{int}/Q_{loss}.

PHR calculated in this manner is not the same as the Solar Savings Fraction (SSF) used in the Solar Load Ratio monthly analysis technique (6). SSF is based on a building load that excludes the contribution of internal gains, that maintains the building at a uniform temperature, and that excludes the steady-state thermal losses through the solar glazing. The building load in the Class B methodology includes internal gains and solar aperture losses and allows the building temperature to float above the thermostat set point.

3. CONTINUOUS MEASUREMENTS

The continuous measurements include horizontal and vertical solar radiation, outdoor temperature, indoor temperatures in five different zones (including sunspace and unconditioned buffer area), status of insulating shutters, and all purchased energy quantities including space heating, hot water, air conditioning, fans, lights, and appliances.

Gas- or oil-fired furnaces and water heaters are monitored by detecting the on-time of the appliance using a relay or a thermal switch. The on-time is multiplied by the fuel flow rate and heating value to obtain the energy use. Power consumption in electric furnaces, water heaters, etc., is obtained by monitoring line voltage and current to the appliance. Total electric consumption is measured using a utility-installed, watt-hour meter. Miscellaneous light and appliance electricity use is determined by subtracting the individually-monitored appliances from the total.

4. REAL-TIME DATA REDUCTION

Real-time calculations include the major energy flows in the building: heating load, purchased space heating, water heating, internal heating, and solar heating. Long-term averages of several channel inputs, including weather parameters, are continually updated. Also, the time in which the interior temperature falls into a given 3°C (5°F) bin is accumulated. This is a measure of interior thermal comfort and stability.

The data reduction program (written in BASIC) is executed every 15 seconds when the data channels are scanned. Using the data channel values, the program updates over 50 daily and monthly performance factors. The data reduction program can be modified to include other factors, such as maximum and minimum temperatures and wind-corrected building thermal loads.

At midnight, the daily totals and accumulated monthly totals are printed out on a thermal printer. In addition to summarizing the building thermal performance, these printouts are useful in checking system and sensor operation and in isolating particularly interesting days to examine in more detail (e.g., extremely cold and sunny days).

5. DENVER RESULTS

Sixty-one buildings throughout the country were monitored during the 1981-1982 heating season, 12 in the Denver, Colo., metropolitan area. These 12 residences were built by first-time solar home builders participating in the Denver Metro Solar Homebuilder's Program (7).

Table 1 describes each of the buildings, its basic thermal properties, and its solar and auxiliary heating components. All of the buildings are wood-frame, low-mass designs, and they generally use exposed concrete slabs or brick veneered interior walls for thermal mass. All of the buildings are well insulated (R19 walls, R30 ceilings are typical) and use double-glazed windows.

A pressurization test determined the infiltration rates in typical winter weather and under a 4-Pa design pressure. These rates were used to extrapolate the coheating results to give the building heat loss coefficient at wind speeds of zero and 3-m/s

(7 mph). The loss coefficient at 3-m/s was used for the energy balance calculations.

Monthly summaries of the basic building energy flows are presented along with monthly weather data. The seasonal totals are estimated using daily averages for each month, including those with incomplete data. Thus, for those months, the daily averages are extrapolated over the time when data were unavailable.

5.1 Alpert House

The Alpert house is a multi-level design with south windows, skylights, and a clerestory. The top level contains the family room, with a vaulted ceiling for the clerestory and a brick veneered north wall. The living room and kitchen are at grade level and contain the remaining solar glazing. Two bedrooms on the north side are partially below grade level with a half basement.

Table 2 summarizes the Alpert house thermal performance. Although the solar aperture area is relatively small (only 11% that of the floor area), it was effective in meeting about half the heating load through the winter. The solar gain had little effect on the north bedrooms, which typically remained as much as 11°C (20°F) cooler than the family room on sunny winter days.

5.2 Arnold House

The Arnold house uses direct gain from south windows and a clerestory. The central living room has a vaulted ceiling to accomodate the clerestory, which charges a 20-cm (8-in.) thick brick partition wall. The south glazing includes a small internal sunspace with skylights and a tile floor.

Table 3 summarizes the Arnold house's thermal performance. Although it is a large house, it is relatively tight, with infiltration at only 0.32 air changes per hour under typical winter conditions. The building heat loss coefficient per unit of floor area is the lowest of the houses monitored in Denver.

The solar aperture area is only 10% that of the floor area, and, consequently, the passive heating ratio was as low as 15% in December. Because of the efficienty of the building envelope, however, the auxiliary heating energy needs were small for this size house.

5.3 Ferguson House

The Ferguson house is a large, two-story building with the north side bermed so that the lower level is below grade level. A large direct-gain component charges a two-story solarium, which is open to nearly every interior room. The solarium has a tile floor and is backed by a 20-cm (8-in.) thick concrete wall with brick veneer. The south windows are fitted with manually-operated insulating shutters; however, the shutters are usually left open.

Table 4 summarizes the Ferguson house thermal performance. The building heat loss coefficient is relatively high, but is low for such a large building. The solar component provided nearly 60% of the winter heating load before the building was occupied, and about 50% thereafter (when the indoor temperature was kept 2°C higher).

5.4 Heritage House

This is a two-story building with a large solar aperture area (17% that of the floor area) divided between an attached sunspace and a site-built, south-wall air heater. The air heater charges a 8.5-m^3 (300-ft^3) rock bin located under the northern half of the house. The sunspace has both vertical and sloped glazing and a tile floor. It is separated from the living area by a concrete wall and four 1700-L (450-gal) water-filled tubes. The sunspace also contains a hot tub, providing additional mass and, because it's used frequently, a significant internal heating source.

Table 5 summarizes the Heritage house's thermal performance. The solar components were effective, contributing 67% of the heating load during a cold February. This high passive heating ratio was partly because of relatively low indoor temperatures, averaging 18.5°C (65°F). Individually controlled electric room heaters allowed the occupants to heat a small area of the building, resulting in low overall building temperatures and efficient use of solar and electric energy.

5.5 Klaus Townhouse

This is a townhouse unit with common east and west walls. A two-story attached sunspace, with both vertical and sloped glazing, forms the south end of the unit. The sunspace is separated from the main living space by a brick wall, which has sliding glass doors to both levels, allowing some direct solar gain. A thermostatically-controlled fan draws warm air from the sunspace to charge a rock bin under the north rooms.

The thermal performance is summarized in Table 6. With little exposed surface area, the building heat loss coefficient is quite low, such that internal heat generation suppled over 20% of the heating load through the winter. The sunspace also performed well, contributing over 50% of the load every month. Despite large sunspace temperature variations, the interior temperatures were always 16°-24°C (60°-75°F) throughout the winter, showing no tendency to overheat.

5.6 Walden House

The Walden house receives direct solar gain at the basement level, the main level, and through the clerestory. The living room, which is the primary southern zone, has a vaulted ceiling above the clerestory and contains a brick veneer window seat and brick veneer interior walls. A thermostatically-controlled fan draws warm air from the high point to a 2.1-m^3 (74-ft^3) rock bin in the basement.

The thermal performance is summarized in Table 7. Despite a relatively large solar aperture area (15% that of the floor area), the solar performance was disappointing, with less than 40% of the mid-winter heating load met by the passive system. The most likely explanation is that the rock-bin energy storage system did not function adequately, causing the heavily-glazed living room area to overheat and lose much of the collected energy. On sunny winter days, with the outdoor temperature below freezing, the living room was often above 30°C (86°F).

5.7 Acorn House

This is a manufactured panelized house with a two-story solarium. The solarium has a tile floor that is charged by a large direct gain component. Solarium air is open to the interior living space and can be vented into the attic. The solarium glazing is fitted with an R5 insulating curtain that is mechanically drawn at night. The house is being used as a sales model, so it is only occupied during the day.

The thermal performance is summarized in Table 8. Because the building was unoccupied at night, the internal gains were small and the night-time thermostat setting was about 13°C (55°F), resulting in low average indoor temperatures. The solar component supplied about 60% of the mid-winter heating load.

5.8 Friis House

The Friis house is a small split-level design with a partial basement and a crawl space. The south glazing is backed by a 1-m (3-ft) high brick veneered concrete wall. The main living area is at grade level, with bedrooms at the half-levels above and below.

Table 9 summarizes the Friis house thermal performance. The auxiliary heating energy is relatively uncertain because the occupants insisted on using their woodstove throughout the heating season. They allowed the interior temperature to remain cool, averaging 18°C (64°F). This reduced the purchased energy needs and allowed the solar component to meet about half the heating load.

5.9 Kurowski House

The Kurowski house is a large two-story design with a basement. One-third of the solar glazing is backed by a brick-veneered concrete wall with draw-bridge exterior insulating panels (which were rarely closed). The remaining glazing charges a two-story solarium, which is open to the interior living space. The solarium has a tile floor and is backed by a brick-veneered wall.

Table 10 summarizes the Kurowski house thermal performance. The building heat loss coefficient was not measured, so the heat loss quantities are based on a loss coefficient that was calculated using the infiltration test results and the building plans. The solar component supplied about 40% of the winter heating load. This low figure is probably due to the mass-wall insulating panels being neglected.

5.10 Tradition House

This small two-story house receives direct gain through most of the southern exposure. It is built on a below-grade slab with some floor area tiled and some carpeted. The south zone is backed by a 20-cm (8-in.) thick brick wall.

The thermal performance is summarized in Table 11. The building heat loss coefficient is high for such a small building. This is partly due to the sliding-glass doors that were used for solar glazing. These door units are especially susceptible to conduction and infiltration losses. The purchased energy requirements were not excessive, with the solar component providing 79% and 56% of the heating load in December and January, respectively. With the building unoccupied, however, some rooms were not heated fully. In January, for example, the average north bedroom temperature was 16°C (61°F).

5.11 Unique House

The Unique house is a large two-story design with an attached sunspace and a basement. Most of the main level is an open great room that receives direct gain through the sunspace, from skylights, and from additional south windows. The great room is also open to a loft above. The upper level and the basement also have south windows.

The sunspace has a tile floor and both vertical and sloped glazing. The design includes a thermostically-controlled fan to dump warm sunspace air into the basement. Apparently this was not used, however, as the sunspace performance depended on the presence of the homeowners. During the week, the house was usually empty, with the sunspace doors left closed (because the sunspace was quite cold in the morning). On sunny winter days, the sunspace temperature would exceed 30°C (86°F); but with the doors closed, the interior would remain cool and the back-up furnace would be needed early in the evening. On the weekends, the homeowners were usually home and opened the sunspace doors on sunny days. This would result in a cooler sunspace, a warmer interior, and less furnace use in the evening.

The thermal performance is summarized in Table 12. The building heat loss coefficient was extremely large, due to infiltration. It was not possible to adequately pressurize the building for an infiltration test. The builders were informed of this and have had better results with their more recent buildings based on this design. The solar component performed well, meeting over 40% of the large heating load. Tighter construction and more homeowner involvement could make this figure considerably larger.

5.12 U.S. Home House

This is a two-story house with a large 30-cm (12-in.) thick concrete mass wall with a selective surface. The mass wall glazing extends from the middle of the basement level, through the entire ground level, and, for half of the glazing width, through the upper level. There is also a small amount of direct gain. To reduce summer overheating, there is a mechanical ventilator at the top of the mass wall cavity, and the inside of the mass wall is fitted with reflective curtains to block sunlight and radiant heating from the wall.

Table 13 summarizes the thermal performance. Although the auxiliary heating requirements were not particularly large, the solar performance was disappointing. Despite a large aperture area (19% that of the floor area), the solar component supplied only about half the heating load in January and February. It is probable that the mass wall ventilator was not closed tightly during the winter, causing unnecessary heat losses from the wall.

6. SUMMARY

The 12 Denver buildings represent a range of designs built by first-time solar home builders. They vary in passive system type and sizing, building size and heating load, heat storage and distribution, and occupant involvement.

The buildings' performance also varied considerably, and some general observations can be made. First, those buildings with relatively low heat loss coefficients used less auxiliary heat and made more efficient use of solar gains than those with large glazing areas and high losses. The excellent performance of the Klaus townhouse is an example. Large infiltration losses were especially detrimental to the performanceof otherwise well-designed houses, such as the Tradition and Unique houses.

Operable solar components, such as thermostatically-controlled fan systems and moveable insulation, were critical to building performance, especially in houses with large glazing areas. For example, the insulating panels on the Kurowski house were not used, and the rockbed system in the Walden house did not operate properly. These problems caused excessive heat losses from the heavily-glazed areas of these houses, nearly negating the solar gains. The solar component provided 39% of the heating load in the Kurowski house and 36% in the Walden house. However, the solar glazing also caused approximately 28% and 30% of the buildings' heating loads, respectively. Thus, the net energy saving compared to an adiabatic south wall was only 11% of the total heating load in the Kurowski house and 6% in the Walden house. Other component operation problems occurred in the Ferguson, Unique, and U.S. Home buildings. This strongly indicates that designers should further emphasize simplicity and convenience in manual components and reliability in automatic components.

7. FUTURE WORK

The results presented here are based on the performance factors computed during real-time data reduction. In addition to these basic performance factors, one can use the raw hourly data, which are now stored on the SERI computer, for more detailed analysis. One can examine the interior zone temperatures to determine thermal comfort and the effectiveness of sunspace-to-interior coupling, thermal storage, night insulation, and other components. Also, statistical techniques can be used to calculate a building's thermal characteristics based on hourly Class B data (8). These analysis efforts are just starting, and more detailed results will be available in the future.

8. REFERENCES

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TABLE 1. BUILDING SUMMARY

Measurement Areas	Alpert	Arnold	Ferguson	Heritage	Klaus	Walden
Living Zone Floor Area						
(m^2)	142	241	262	157	128	174
(ft^2)	1527	2590	2820	1684	1376	1873
Ground Coupling	basement	basement	berming	--	--	basement
Auxiliary Heating	gas forced air	gas forced air	gas forced air	electric resistance	gas forced air	gas forced air
Primary Passive System	direct gain	direct gain	direct gain	sunspace	sunspace	direct gain
Solar Aperture						
(m^2)	15.0	24.5	33.9	25.9	13.8	26.6
(ft^2)	161	264	365	279	149	286
Loss Coefficient						
(W/°C)						
no wind	158	157	243	217	83	190
3 m/s wind	232	253	369	309	137	248
(Btu/h-°F)						
no wind	299	298	461	411	157	361
7 mph wind	439	480	700	586	260	471
Infiltration Rate						
(ACH/h)						
design-4-Pa pres.	2.65	1.50	2.77	2.17	3.53	2.53
typical-5°C, 3 m/s	0.64	0.32	0.70	0.58	0.72	0.70

TABLE 1. BUILDING SUMMARY (concluded)

Measurement Areas	Acorn	Friis	Kurowski	Tradition	Unique	U.S. Home
Living Zone Floor Area						
(m^2)	221	121	235	126	301	166
(ft^2)	2375	1298	2531	1360	3236	1784
Ground Coupling	--	basement	basement	--	basement	basement
Auxiliary Heating	electric forced air	gas forced air	gas forced air	gas forced air	gas forced air	gas forced air
Primary Passive System	direct gain	direct gain	direct gain	direct gain	sunspace	mass wall
Solar Aperture						
(m^2)	26.4	13.0	28.5	15.5	40.5	31.5
(ft^2)	284	140	307	167	436	339
Loss Coefficient						
(W/°C)						
no wind	235	134	242*	229	305	160
3 m/s wind	327	195	290*	303	423	197
(Btu/h-°F)	446	255	460*	434	578	303
7 mph wind	620	370	550*	574	802	373
Infiltration Rate						
(ACH/h)						
design-4-Pa pres.	2.77	4.04	2.67	3.60	>4*	2.13
typical-5°C, 3 m/s	0.65	0.76	0.45	0.83	>1*	0.45

*Estimates

TABLE 2. PERFORMANCE SUMMARY: ALPERT HOUSE

Measured Quantity	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.*	Total
Days of Complete Data	11/30	23/31	19/31	28/28	31/31	--	112/151
Horizontal Radiation (MJ/m^2-day)	9.3	7.1	9.0	11.8	15.7	--	10.6
Vertical Radiation (MJ/m^2-day)	18.1	16.1	17.4	17.8	14.9	--	16.8
Average Outdoor Temperature (^{o}C)	5.9	0.9	0.7	-1.0	4.4	--	2.2
Average Indoor Temperature (^{o}C)	21.1	19.4	19.8	19.4	20.3	--	20.0
Living-Zone Heat Loss (MJ/day)	301	370	381	407	315	--	354
Passive Heating (MJ/day)	183(61%)	171(46%)	181(48%)	214(53%)	164(52%)	--	181(51%)
Auxiliary Heating (MJ/day)	46(15%)	110(30%)	142(37%)	142(35%)	103(33%)	--	108(31%)
Internal Heating (MJ/day)	72(24%)	88(24%)	58(15%)	51(12%)	48(15%)	--	64(18%)
Specific Auxiliary Heating ($KJ/^{o}C$-day-m^2)	26	44	57	52	52	--	46

*Data not yet available.

TABLE 3. PERFORMANCE SUMMARY: ARNOLD HOUSE

Measured Quantity	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Days of Complete Data	27/30	31/31	31/31	28/28	29/31	30/30	176/181
Horizontal Radiation (MJ/m^2-day)	8.5	6.3	7.1	9.4	13.7	18.3	10.5
Vertical Radiation (MJ/m^2-day)	17.3	16.4	16.7	16.6	13.7	11.5	15.4
Average Outdoor Temperature (^{o}C)	5.6	0.6	-1.1	-0.4	5.8	8.9	3.2
Average Indoor Temperature (^{o}C)	21.7	20.8	20.5	20.3	20.4	20.6	20.7
Living-Zone Heat Loss (MJ/day)	352	440	469	451	319	255	381
Passive Heating (MJ/day)	137(39%)	66(15%)	118(25%)	131(29%)	127(40%)	101(40%)	113(30%)
Auxiliary Heating (MJ/day)	103(29%)	224(51%)	202(43%)	172(38%)	86(27%)	68(27%)	143(37%)
Internal Heating (MJ/day)	112(32%)	150(34%)	149(32%)	148(33%)	106(33%)	86(33%)	125(33%)
Specific Auxiliary Heating ($KJ/^{o}C$-day-m^2)	34	52	43	38	28	30	38

TABLE 4. PERFORMANCE SUMMARY: FERGUSON HOUSE

Measured Quantity	Nov.*	Dec.*	Jan.*	Feb.	Mar.	Apr.	Total
Days of Complete Data	30/30	25/31	23/31	28/28	31/31	30/30	167/181
Horizontal Radiation (MJ/m^2-day)	10.2	7.7	8.7	12.1	16.0	19.4	12.3
Vertical Radiation (MJ/m^2-day)	18.3	17.2	16.0	18.4	15.0	7.2	15.3
Average Outdoor Temperature (^{o}C)	6.2	1.2	-0.6	-0.6	3.9	7.2	2.9
Average Indoor Temperature (^{o}C)	20.1	19.2	18.0	20.6	20.8	20.4	19.8
Living-Zone Heat Loss (MJ/day)	439	573	591	674	538	411	537
Passive Heating (MJ/day)	415(94%)	354(62%)	391(66%)	347(52%)	256(48%)	203(49%)	326(61%)
Auxiliary Heating (MJ/day)	0	191(33%)	173(29%)	263(39%)	122(22%)	86(21%)	138(26%)
Internal Heating (MJ/day)	24(6%)	28(5%)	27(5%)	64(9%)	160(30%)	122(30%)	71(13%)
Specific Auxiliary Heating (KJ/^{o}C-day-m^2)	0	43	35	53	32	29	32

*Building unoccupied

TABLE 5. PERFORMANCE SUMMARY: HERITAGE HOUSE

Measured Quantity	Nov.*	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Days of Complete Data	26/30	22/31	16/31	26/28	31/31	30/30	151/181
Horizontal Radiation (MJ/m^2-day)	8.3	6.2	7.1	10.0	14.3	18.8	10.8
Vertical Radiation (MJ/m^2-day)	15.2	12.7	12.7	15.5	13.0	11.4	13.4
Average Outdoor Temperature (^{o}C)	5.7	3.3	1.4	0.9	5.5	9.3	4.4
Average Indoor Temperature (^{o}C)	19.1	19.7	17.3	18.1	18.1	18.8	18.5
Living-Zone Heat Loss (MJ/day)	356	434	423	458	334	252	376
Passive Heating (MJ/day)	232(65%)	171(39%)	271(64%)	305(67%)	192(58%)	161(64%)	221(59%)
Auxiliary Heating (MJ/day)	16(5%)	96(22%)	47(11%)	76(16%)	11(3%)	5(2%)	42(11%)
Internal Heating (MJ/day)	108(30%)	168(39%)	105(25%)	77(17%)	131(39%)	86(34%)	113(30%)
Specific Auxiliary Heating (KJ/^{o}C-day-m^2)	8	41	18	28	6	4	17

*Building unoccupied

TABLE 6. PERFORMANCE SUMMARY: KLAUS TOWNHOUSE

Measured Quantity	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Days of Complete Data	17/30	28/31	31/31	28/28	31/31	30/30	164/181
Horizontal Radiation (MJ/m^2-day)	8.5	5.8	8.1	11.0	15.1	19.6	11.3
Vertical Radiation (MJ/m^2-day)	15.8	14.8	16.6	17.6	15.2	13.2	15.5
Average Outdoor Temperature (°C)	7.8	-0.3	-1.1	-0.3	5.1	8.7	3.3
Average Indoor Temperature (°C)	21.6	19.8	18.4	18.4	19.2	20.4	19.6
Living-Zone Heat Loss (MJ/day)	162	237	230	221	167	138	192
Passive Heating (MJ/day)	122(76%)	138(58%)	130(57%)	119(54%)	96(57%)	80(58%)	113(59%)
Auxiliary Heating (MJ/day)	4(2%)	61(26%)	53(23%)	56(25%)	31(19%)	22(16%)	39(20%)
Internal Heating (MJ/day)	36(22%)	38(16%)	47(20%)	46(21%)	40(24%)	36(26%)	40(21%)
Specific Auxiliary Heating (KJ/°C-day-m^2)	3	26	21	23	18	18	18

TABLE 7. PERFORMANCE SUMMARY: WALDEN HOUSE

Measured Quantity	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Days of Complete Data	25/30	6/31	13/31	24/28	20/31	18/30	114/181
Horizontal Radiation (MJ/m^2-day)	7.9	7.5	7.1	11.3	13.3	16.9	10.6
Vertical Radiation (MJ/m^2-day)	14.4	14.5	11.6	17.7	13.5	10.2	13.6
Average Outdoor Temperature (°C)	5.7	5.6	1.1	1.7	4.8	9.0	4.7
Average Indoor Temperature (°C)	22.1	21.4	18.8	20.2	20.5	20.4	20.6
Living-Zone Heat Loss (MJ/day)	350	340	377	397	336	245	340
Passive Heating (MJ/day)	146(42%)	52(16%)	124(33%)	157(39%)	148(44%)	100(41%)	121(36%)
Auxiliary Heating (MJ/day)	115(33%)	201(59%)	161(43%)	133(34%)	95(28%)	68(28%)	129(38%)
Internal Heating (MJ/day)	89(25%)	86(25%)	92(24%)	107(27%)	93(28%)	77(31%)	90(26%)
Specific Auxiliary Heating (KJ/°C-day-m^2)	52	91	54	46	40	42	54

TABLE 8. PERFORMANCE SUMMARY: ACORN HOUSE*

Measured Quantity	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Days of Complete Data	22/30	15/31	17/31	18/28	23/31	9/30	114/181
Horizontal Radiation (MJ/m^2-day)	9.7	5.1	6.1	11.0	14.4	16.1	10.4
Vertical Radiation (MJ/m^2-day)	17.6	13.3	11.6	17.8	15.0	8.8	14.0
Average Outdoor Temperature (°C)	7.6	-0.9	-2.8	0.3	6.4	9.2	3.3
Average Indoor Temperature (°C)	19.8	17.5	16.1	17.9	19.6	19.2	18.3
Living-Zone Heat Loss (MJ/day)	332	504	520	481	442	278	426
Passive Heating (MJ/day)	268(80%)	325(64%)	309(59%)	279(58%)	319(72%)	191(69%)	281(66%)
Auxiliary Heating (MJ/day)	25(8%)	144(29%)	165(32%)	163(34%)	81(18%)	58(21%)	106(25%)
Internal Heating (MJ/day)	39(12%)	35(7%)	46(9%)	39(8%)	42(10%)	29(10%)	39(9%)
Specific Auxiliary Heating (KJ/°C-day-m^2)	11	34	35	41	31	29	30

*Building unoccupied at night.

TABLE 9. PERFORMANCE SUMMARY: FRIIS HOUSE

Measured Quantity	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Days of Complete Data	19/30	28/31	20/31	28/28	31/31	30/30	156/181
Horizontal Radiation (MJ/m^2-day)	8.8	7.7	8.3	12.4	16.0	20.3	12.2
Vertical Radiation (MJ/m^2-day)	14.2	13.8	12.3	15.6	14.8	13.6	14.0
Average Outdoor Temperature (°C)	4.8	0.6	0.1	-1.1	4.4	8.1	2.8
Average Indoor Temperature (°C)	18.2	17.2	18.2	18.8	17.8	18.0	18.0
Living-Zone Heat Loss (MJ/day)	219	272	297	322	219	160	248
Passive Heating (MJ/day)	117(53%)	129(47%)	167(56%)	152(47%)	110(50%)	67(42%)	124(50%)
Auxiliary Heating* (MJ/day)	56(26%)	89(33%)	79(27%)	112(35%)	55(25%)	41(26%)	72(29%)
Internal Heating (MJ/day)	46(21%)	54(20%)	51(17%)	58(18%)	54(25%)	52(32%)	52(21%)
Specific Auxiliary Heating* (KJ/°C-day-m^2)	34	41	36	48	33	33	37

*Auxiliary heating included estimated stove use.

TABLE 10. PERFORMANCE SUMMARY: KUROWSKI HOUSE

Measured Quantity	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Days of Complete Data	25/30	31/31	24/31	28/28	31/31	30/30	169/181
Horizontal Radiation (MJ/m^2-day)	8.3	7.2	8.2	11.5	14.9	19.3	11.5
Vertical Radiation (MJ/m^2-day)	14.8	15.0	14.2	15.8	6.5	4.7	11.8
Average Outdoor Temperature (°C)	6.4	1.4	-0.1	1.1	5.5	9.0	3.9
Average Indoor Temperature (°C)	22.3	21.7	22.2	21.7	21.8	21.7	21.9
Living-Zone Heat Loss* (MJ/day)	396	507	556	514	406	316	449
Passive Heating (MJ/day)	139(35%)	209(41%)	241(44%)	247(48%)	134(33%)	82(26%)	175(39%)
Auxiliary Heating (MJ/day)	171(43%)	207(41%)	219(39%)	192(37%)	176(43%)	145(46%)	185(41%)
Internal Heating (MJ/day)	86(22%)	91(18%)	96(17%)	75(15%)	96(24%)	89(28%)	89(20%)
Specific Auxiliary Heating (KJ/°C-day-m^2)	61	52	51	47	58	66	56

*Based on estimated loss coefficient.

TABLE 11. PERFORMANCE SUMMARY: TRADITION HOUSE

Measured Quantity	Nov.*	Dec.*	Jan.*	Feb.*	Mar.**	Apr.	Total
Days of Complete Data	30/30	27/31	31/31	11/28	--	11/30	110/151
Horizontal Radiation (MJ/m^2-day)	7.6	6.8	7.8	10.2	--	17.0	9.8
Vertical Radiation (MJ/m^2-day)	14.7	15.2	14.8	15.1	--	8.4	13.5
Average Outdoor Temperature (°C)	6.1	0.4	-0.7	6.9	--	8.7	4.2
Average Indoor Temperature (°C)	18.4	19.1	17.9	21.0	--	19.7	19.1
Living-Zone Heat Loss (MJ/day)	323	487	485	366	--	286	388
Passive Heating (MJ/day)	289(90%)	384(79%)	270(56%)	231(63%)	--	168(59%)	268(69%)
Auxiliary Heating (MJ/day)	17(5%)	75(15%)	189(39%)	111(30%)	--	51(18%)	88(23%)
Internal Heating (MJ/day)	17(5%)	28(6%)	25(5%)	24(7%)	--	67(23%)	32(8%)
Specific Auxiliary Heating (KJ/°C-day-m^2)	11	33	79	77	--	42	48

*Building unoccupied.
**Data acquisition system inoperative.

TABLE 12. PERFORMANCE SUMMARY: UNIQUE HOUSE

Measured Quantity	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Days of Complete Data	17/30	18/31	12/31	28/28	31/31	30/30	136/181
Horizontal Radiation (MJ/m^2-day)	8.9	7.6	7.4	11.4	15.5	19.7	11.7
Vertical Radiation (MJ/m^2-day)	16.0	16.8	14.3	16.5	15.1	13.1	15.3
Average Outdoor Temperature (°C)	5.2	-2.3	-1.9	0.4	5.0	8.7	2.5
Average Indoor Temperature (°C)	21.0	20.1	20.6	20.8	20.9	21.0	20.7
Living-Zone Heat Loss (MJ/day)	574	816	829	744	580	449	666
Passive Heating (MJ/day)	372(65%)	357(44%)	399(48%)	342(46%)	342(59%)	287(64%)	351(53%)
Auxiliary Heating (MJ/day)	116(20%)	357(44%)	323(39%)	279(38%)	142(24%)	88(20%)	218(33%)
Internal Heating (MJ/day)	85(15%)	102(12%)	106(13%)	122(16%)	96(17%)	74(16%)	97(14%)
Specific Auxiliary Heating (KJ/°C-day-m^2)	29	57	53	52	35	30	43

TABLE 13. PERFORMANCE SUMMARY: U.S. HOME

Measured Quantity	Nov.	Dec.*	Jan.	Feb.	Mar.	Apr.**	Total
Days of Complete Data	11/30	--	28/31	25/28	28/31	--	92/120
Horizontal Radiation (MJ/m^2-day)	9.3	--	8.4	11.9	14.7	--	11.1
Vertical Radiation (MJ/m^2-day)	17.2	--	17.5	18.4	13.7	--	16.7
Average Outdoor Temperature (°C)	8.4	--	-2.2	0	4.1	--	2.6
Average Indoor Temperature (°C)	22.4	--	19.8	20.5	20.6	--	20.8
Living-Zone Heat Loss (MJ/day)	237	--	374	347	280	--	309
Passive Heating (MJ/day)	218(92%)	--	172(46%)	182(53%)	184(66%)	--	189(61%)
Auxiliary Heating (MJ/day)	2(1%)	--	105(28%)	84(24%)	32(11%)	--	55(18%)
Internal Heating (MJ/day)	17(7%)	--	97(26%)	81(23%)	64(23%)	--	65(21%)
Specific Auxiliary Heating (KJ/°C-day-m^2)	1	--	31	28	14	--	18

*Data acquisition system inoperative.
**Data not yet available.