SERI/TP-254-2020
UC Category: 59c
DE83011986

Measured Performance of 50 Passive Solar Residences in the United States

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July 1983

To be presented at the ASES
PASSIVE 83 Conference
Glorieta, New Mexico
7-9 September 1983

Prepared under Task No. 1583.48
WPA No. 439

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
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Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $4.50
Printed Copy $7.00

NOTICE

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ABSTRACT

This paper summarizes the thermal performance of 50 passive solar residences in a variety of U.S. locations. These buildings were monitored as part of the Solar Energy Research Institute (SERI) Residential Class B Passive Solar Performance Monitoring Program.

The paper describes the monitoring and performance evaluation methods and presents the overall heating season performance of the buildings in graphical form. We draw some general conclusions from these results and discuss the validity of extrapolating such conclusions to passive solar buildings in general.

1. INTRODUCTION

The SERI Residential Class B Passive Solar Performance Monitoring Program is a low-cost program that evaluates the thermal performance of selected residential buildings throughout the country (1). The goal of this program is to provide a consistent measure of the thermal performance of different types of passive buildings in different climates. Instrumentation is limited to that needed to calculate the monthly building energy balance, separating passive solar heating from the other building energy flows. Thermal storage and other individual components are not monitored, and no attempt is made to determine a building's thermal processes in detail.

Instrumentation began in 1981. At that time, SERI was to coordinate the national program, and the Regional Solar Energy Centers (RSECs) were to oversee the operation of the monitored sites in their regions. More than 60 buildings were instrumented to some degree. However, the regional centers closed at the end of 1981, and SERI assumed the supervision of as many of the sites as possible. We assembled sufficient 1981-1982 data to summarize the performance of 40 buildings (2). In addition, we plan to provide the research community with more detailed monthly performance calculations, hourly raw measurement values, and complete site handbooks that describe the buildings and measurements in more detail.

Also, we instrumented 40 buildings for the 1982-1983 heating and cooling seasons, ten of which are included in this paper. The complete results from these buildings will be available in late 1983, along with comparisons between measured performance results and monthly design tool predictions.

2. PERFORMANCE EVALUATION APPROACH

The Class B program features on-site data processing using a standardized microprocessor data acquisition system (DAS). The DAS collects up to 22 continuous measurements every 15 seconds and processes these values in the microprocessor. The system is programmed to calculate daily and monthly performance factors in real time and print them on a daily basis. These real-time computations include the major building energy flows, weather variables, and the other basic monthly performance factors required in the Class B program. With proper DAS programming and operation, these factors, which are the basis of this paper, can be taken directly from the DAS, requiring off-site computation only for statistical data analysis.

The system also produces magnetic data storage tapes that contain hourly averages of the raw continuous measurements. The raw data tapes and the monthly performance factor summaries are transcribed into the SERI computer system for archiving and further analysis. If necessary, the monthly summaries are corrected for any programming errors. If this is impossible, the hourly data are used to calculate the summaries. The hourly data have many potential applications, such as graphic data presentations and statistical building characterization.

Building thermal performance calculations are based on a monthly building energy balance. The energy balance is calculated for a single control-volume that includes the air of the living zone, defined as conditioned space and space that always remains within 10°F (6°C) of conditioned space temperature. This usually excludes attics and garages and includes basements and sunspaces only when the space is conditioned.

The energy balance has four components: a heat-loss component and three gains—auxiliary heat, internal heat, and passive heat. The passive heat used by the building is found by subtracting the measured heat delivered to the building by auxiliary and internal sources from the building heat loss, calculated from measured temperature difference. The passive heat includes the effects of all passive heat gains and losses, not just the direct solar gain through the south-facing glazing. Other passive energy flows include solar gains through east and west windows, solar absorption by walls and roofs, thermal buffering by sunspaces, thermal storage mass effects, and additional infiltration and venting caused by the occupants. Direct measurement of all these energy flows would be difficult and is beyond the scope of the Class B program.

Living zone heat loss is the product of the living zone heat-loss coefficient and the measured indoor-outdoor temperature difference. The indoor temperature is the average of several living zone temperatures, measured at locations that represent the building's major heat loss areas. The heat loss coefficient is measured using electric coheating (3) and is adjusted for infiltration effects, based on pressurization and tracer-gas infiltration measurement (4,5). The building heat-loss coefficient, along with other building and heating system characteristics, is stored in the DAS computer software to be used during the real-time data reduction. Details of the coheating procedure and other measurement techniques are included in the installation manual for the Class B program (6).

3. SUMMARY OF RESULTS

Figure 1 shows the overall heating season performance for 50 buildings in the Class B program. Each bar represents the total building heating load divided into passive, auxiliary, and internal heating components. The energy quantities are normalized per unit floor area and degree-day (based on measured indoor-outdoor temperature difference). The buildings are ordered from left to right according to total purchased heating energy (auxiliary plus internal). We will use this value as a building performance index (BPI). At the top of each bar, the south glazing to floor area ratio and passive system types are indicated (DG = direct gain, SS = sunspace, TW = Trombe wall, WW = water wall). We refer to the ratio of the passive heating component to the total heating load as the passive heating ratio (PHR).

The buildings are identified by a three-letter site code. The first two letters denote the region of the country, and the third letter denotes the specific building in the region (DM=Denver, MA=Mid-America, NE=Northeast, SS=South, WS=California). An additional site code prefix, MB, identifies buildings in the SERI Passive Solar Manufactured Buildings Program (MBA is in Denver, MBB is in Wisconsin, and MBD is in North Dakota). Figure 2 shows the location of each building.

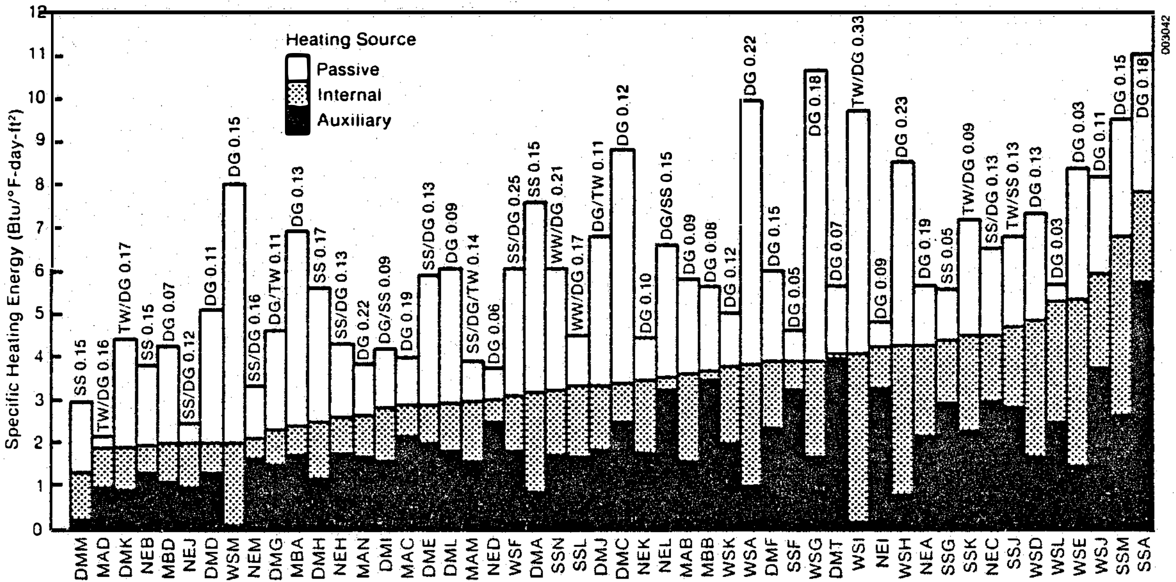

Fig. 1. Heating Season Energy Summaries for 50 Monitored Buildings

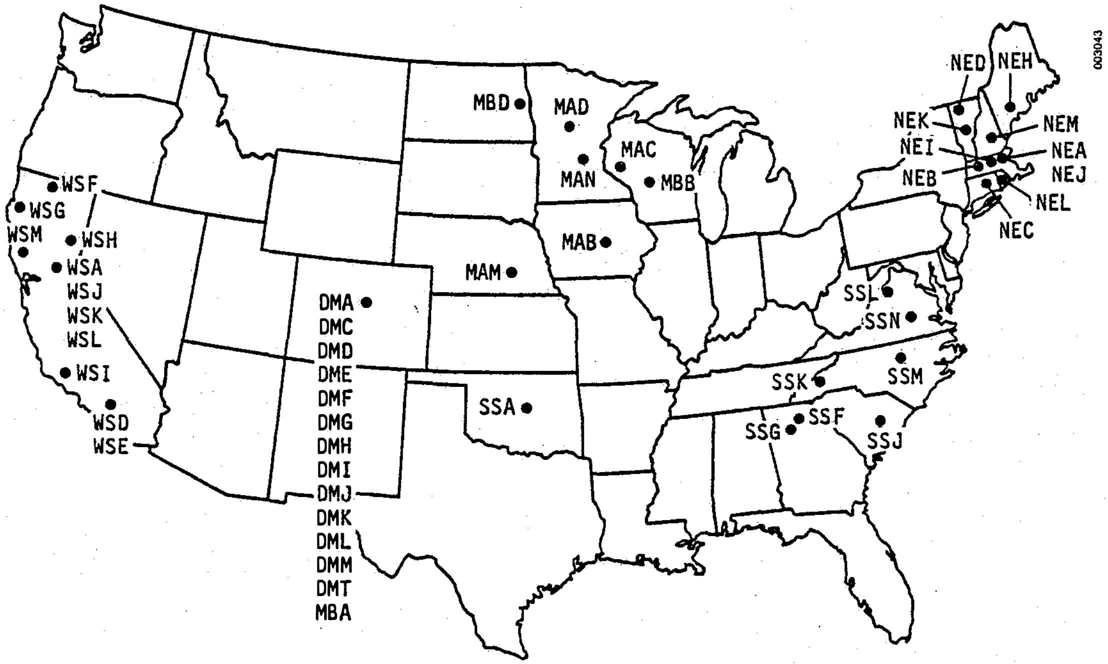

Fig. 2. Class B Site Locations

The 50 sites included in this report represent a wide variation in building and passive system size, configuration, and operation. The thermal performance of these buildings also varies a great deal. Much of the practical relevance of the results presented here lies in the study of the individual building summaries. However, some general observations can be made regarding the overall performance of the monitored buildings.

The following conclusions are based on interpretations of the results in Fig. 1 and a simple statistical analysis of the results. The statistical approach involves averaging the results and grouping them according to various categories, such as passive system type and geographical region. The statistical results are shown in Table 1 for 48 sites and in Table 2 for several categories of buildings. Sites WSE and WSL were eliminated from the sample because they were included in the program as nonsolar comparison buildings (7).

Table 1. Statistics of Key Variables

Variable	Mean	Standard Deviation
Inside temperature [°F(°C)]	67.56 (19.76)	3.09 (1.72)
Monitored days	127	31.5
Passive heating fraction	0.393	0.159
Building performance index [Btu/°F-day-ft^2 (kJ/°C-day-m^2)]	3.469 (70.86)	1.270 (25.94)

Note: Number of homes in sample: 48

First, these buildings have low auxiliary heating needs. Figure 1 shows that the auxiliary heating is generally less than 3 Btu/°F-day-ft^2 (60 kJ/°C-day-m^2) with an average of 1.9 Btu/°F-day-ft^2 (38 kJ/°C-day-m^2). Conventional buildings typically use from 6-12 Btu/°F-day-ft^2 (120-240 kJ/°C-day-m^2), and the proposed Building Energy Performance Standard would allow 4 Btu/°F-day-ft^2 (80 kJ/°C-day-m^2). We will not, however, attempt to calculate an energy savings comparison in relation to a standard nonsolar building. The basis of such comparisons is inherently arbitrary and the results are subject to one's assumptions of what is standard. Swisher and Cowing (2) present sufficient information to allow the reader to make any desired comparisons. The average BPI, which includes internal heat, was 3.5 Btu/°F-day-ft^2 (70 kJ/°C-day-m^2), indicating that internal heating was nearly equal to auxiliary heating on the average.

Second, the energy saving effects of insulation and weatherization are critical. Modest solar designs

Table 2. Thermal Performance Mean Estimates by Category

Category	Number in Sample	BPI Btu/°F-day-ft^2 (kJ/°C-day-m^2)	PHF	Incident Radiation Btu/day-ft^2 (kJ/day-m^2)
System type				
Direct gain	29	3.76 (76.8)	0.395	—
Sunspace	11	2.76 (56.4)	0.383	—
Mass wall	5	3.45 (70.5)	0.393	—
Water wall	2	3.38 (69.0)	0.335	—
Hybrid	1	3.17 (64.8)	0.587	—
Location				
Denver	14	2.85 (58.2)	0.501	1320 (14,980)
New England	10	3.19 (65.2)	0.287	875 (9,930)
Midwest	7	2.80 (57.2)	0.323	913 (10,360)
South	8	4.89 (99.9)	0.287	5611 (6,370)
California	9	4.00 (81.7)	0.493	891 (10,110)
Night Insulation				
Yes	20	3.48 (71.1)	0.406	—
No	28	3.46 (70.7)	0.385	—

on very tight buildings generally use less heat than more ambitious solar designs on very leaky buildings, and low heat losses will increase the fraction of the heating load met by the solar components. Figure 1 shows that the largest purchased energy users (right side of the graph) have relatively high total heating loads; and with the exception of a few very heavily solar-driven buildings in Denver, Colo., and Northern California, the buildings with higher heat-loss coefficients required more purchased heat. Some of the smallest purchased energy users (left side of the graph) were buildings in the Northeast that had moderate passive heating and very low heat-loss coefficients.

Third, the solar performance is variable. From the data collected so far from the largest sample yet of passive solar houses monitored in a consistent manner, we can say that the passive solar systems contribute a statistically significant portion (39%) of the total heating load, or 55% of the net heating load (total load minus internal heat). Figure 1 shows several buildings with large passive heating contributions, but this does not necessarily translate into energy savings. While many heavily glazed buildings perform well in terms of auxiliary heat (e.g., sites DMK, DMM, NEB, NEM, WSM), some are disappointing (e.g., sites NEA, SSA, SSM, WSJ).

Fourth, it appears that the habits of the building's occupants in using the building are critical to passive system performance. This especially applies to the use of operable components such as insulation, sunspace doors, and vents. There was no significant statistical difference in either the BPI or PHF for houses with night insulation and those without (see Table 2). In reviewing the operation of the individual buildings, we found that most of the buildings with disappointing performance had a problem with operable components or occupant participation. There are several reasons for this. In some cases, the occupants were simply inattentive. Some automatic components, such as thermostatically controlled fans, did not operate properly. Several occupants, however, ignored operable components because the components were not sufficiently simple or convenient to use. This indicates that designers should continue to improve the simplicity and convenience of manual components and emphasize reliability in selecting automatic components.

Fifth, none of the basic passive system types (direct gain, sunspace, and thermal storage wall) had significantly better or worse overall performance. It is interesting to note that several of the sunspace designs used very little purchased heat, but did not have an especially large passive heating contribution. This points out the advantage of using a sunspace for a thermal buffer, for reducing heat losses, as well as for a solar energy collection device.

Sixth, performance varied significantly by location. The PHF means for California and Denver were significantly different (at the 95% confidence level) from the means for the other regions. As expected, the solar contributions were larger in the West. The differences in measured incident radiation, shown in Table 2, accounted for some of this difference. The BPI means for California and the south were significantly higher than those for the colder regions. There are three reasons for this: (1) the buildings in the colder regions tend to be more heavily insulated; (2) there tends to be more venting of internal heat in the warmer regions; and (3) the degree-day normalization may introduce a slight bias in favor of the colder climates.

Seventh, the passive solar houses are comfortable, with an average indoor temperature of 67.6°F (19.8°C). The time-averaged temperature of each site ranged from 54°-73°F (12°-23°C).

4. CONCLUSION

The estimated mean BPI of 3.469 Btu/°F-day-ft^2 (70.86 kJ/°C-day-m^2) has a 95% confidence interval of ±0.363 Btu/°F-day-ft^2 (7.41 kJ/°C-day-m^2). Thus, given the assumptions that the monitored houses are representative of the population of passive solar houses and that the measured BPI values are not consistently biased, then with a 5% risk of error the true mean BPI is within ±10.5% of the estimated mean. Work is in process to determine the validity of the above two assumptions regarding the representativeness of the monitored houses and the extent of any bias in the individual BPI estimates. No obvious sources of bias in the BPI estimates have been uncovered as yet. Lack of information about the number, characteristics, and location of the general population of passive solar houses has made a test of representativeness of the monitored houses difficult.

The 50 buildings in this sample clearly show that passive solar design can achieve very low purchased energy usage in all regions of the country. These results also show that solar performance can be improved further, especially with regard to operable components such as movable insulation.

5. ACKNOWLEDGMENTS

We thank Blair Hamilton, Don Frey, Michael Holtz, Mark McKinstry, Ralph Beckman, Jim Boswell, Tom Cowing, George Yeagle, and all the other people who have contributed to the Class B Program. This work was sponsored by the U.S. Department of Energy, Division of Passive and Hybrid Solar Heat Technologies.

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