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PERFORMANCE EVALUATION OF THE BALCOMB SOLAR HOUSE*

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Summary

Additional instrumentation was added to the Balcomb solar house for a six-week period and up to 85 channels were recorded hourly. Some new findings based on an evaluation of these data are presented. 1) The thermal comfort characteristics of four rooms are documented. 2) Relative humidity in the living room varies from 30 to 50%; these data are used to infer an evaporation rate in the house of about 25 kg of water/day. The evaporation rate correlates reasonably well with greenhouse temperature. 3) Heat storage in the greenhouse floor is estimated at about 0.30 kWh/day-m^2 based on temperatures measured at four depths. 4) Several thermal characteristics of the rock bed are deduced but it is evident that the heat flow is not yet completely understood.

1. INTRODUCTION AND REVIEW

The Balcomb solar house is located in Santa Fe, New Mexico, at an elevation of 2200 m and a latitude of 35.8^{o}N. It is a two-story building with a total living area of 182 sq m plus an integral, attached two-story solar greenhouse with 32 sq m of floor area. The solar heating is primarily passive but also incorporates an active system for supplemental heat storage. Warm air is drawn through ducts from the top of the greenhouse and forced by two 250 W fans through rock beds located beneath the downstairs living area floors; distribution is passive by conduction up through the floor. The house is very well insulated with an overall measured heat loss coefficient of 314 W/^{o}C (counting the greenhouse as an unheated space). There is ample mass for heat storage in the masonry (adobe) wall which separates the greenhouse from the house, the rock-on-dirt floor of the greenhouse, the rock beds, and a partially bermed north wall. The house was designed and built by Susan and Wayne Nichols as the first unit in their first all-solar subdivision.

An overall energy balance and evaluation was reported in a previous paper (1) based on 176 days of data from the period 1 November 1978 through 24 April 1979. This evaluation showed excellent performance. The solar heating fraction was 89% and only 1833 kWh of auxiliary heat was required to maintain comfortable conditions throughout this

*Work performed under the auspices of the US Department of Energy, Office of Solar Applications for Buildings.

3344°C-day interval during which -24°C outside temperatures were observed occasionally.

This performance places the house among the lowest energy buildings in the world. One widely-used measure of performance is the utility energy use of the building per square meter of floor area per unit of temperature difference between the inside and the outside, averaged over the entire heating season. Here it is appropriate to cite two values, one in which only the auxiliary energy is counted and the second in which all non-solar heat in the building is counted, including heat from people, appliances, lights, and all other internal energy sources. For the Balcomb house these two values are as follows:

$0.12 \quad W/^{o}C - m^2$, auxiliary only

$0.57 \quad W/^{o}C - m^2$, all internal energy

Special Monitoring in 1980

During the period 26 February through 9 April, 1980, additional instrumentation channels were added to the house in order to obtain better insight into the energy flow inside the house. Up to 85 channels were recorded on an hourly basis. The primary purpose of this paper is to update Ref. (1) with some new findings. Not all of the data have yet been evaluated.

2. THERMAL COMFORT

Equally important to the reporting of auxiliary energy requirements in a monitored building is the reporting of the comfort conditions obtained. During the six-week detailed monitoring period, both shielded air temperature and globe temperature probes were placed in the dining room, living room, master bedroom (upstairs, west end) and central upstairs bedroom. A detailed study of the monitored results indicate that the globe temperature and air temperature measurements are virtually identical hour by hour throughout the entire period. This is not unexpected since the house is well insulated and reasonably airtight and thus both the air temperature and the mean radiant temperature would tend to equilibrate near the average of the surrounding surfaces temperatures. The only exception to this observation is during occasional periods when a fire was burning in the fireplace of the living room when the globe temperature is appreciably higher than air temperature. Thus it seems reasonable to use measured room air temperatures as a measure of the effective temperatures in this building.

Air temperature measurements were made in four rooms during the entire 176 days of the 1978-1979 heating season. These data were sorted to determine the number of hours of occurrence for each 0.55°C temperature band (1°F) according to whether the time was between 7 a.m. and 11 p.m. or between 11 p.m. and 7 a.m. These results are shown in Figs. 1 - 4.

As can be seen, the temperature range is smallest for the dining room. This downstairs room was thermostatically controlled to a minimum of 18.3°C. The living room temperature is very similar. The other three rooms shown were uncontrolled spaces; that is, no auxiliary heat was used. The master bedroom tends to be warmer than the central bedroom because of the large surface of mass wall common with the greenhouse.

BALCOMB RESIDENCE
1978-1979 HEATING SEASON

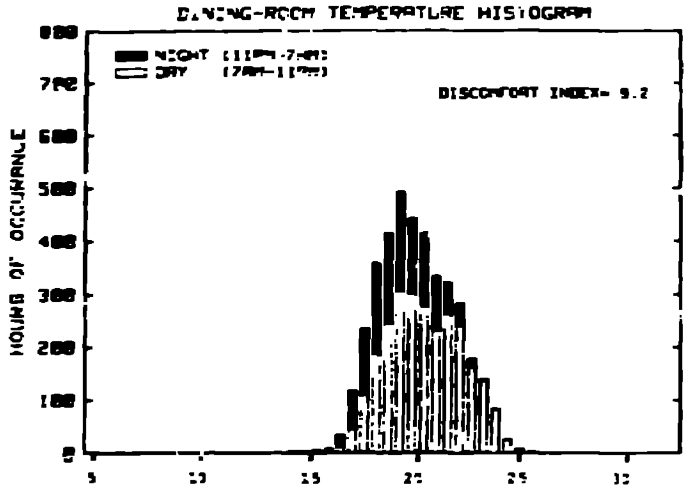


Fig. 1 ROOM TEMPERATURE, DEG C

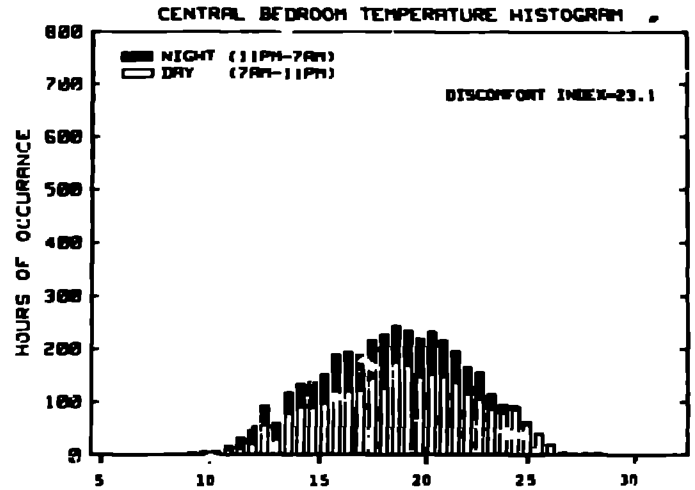


Fig. 3 ROOM TEMPERATURE, DEG C

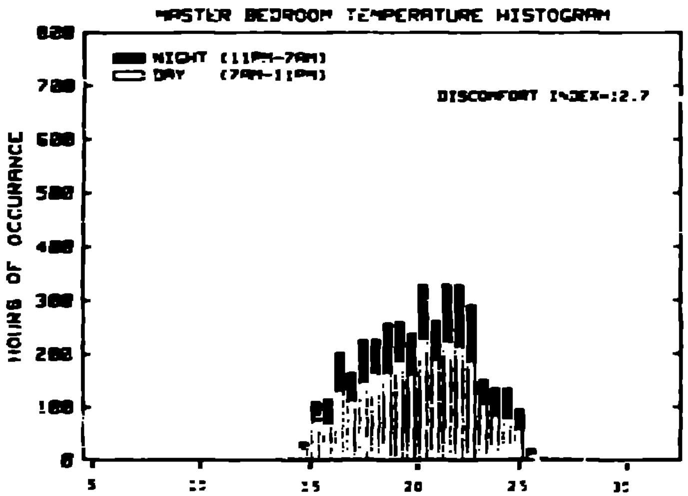


Fig. 2 ROOM TEMPERATURE, DEG C

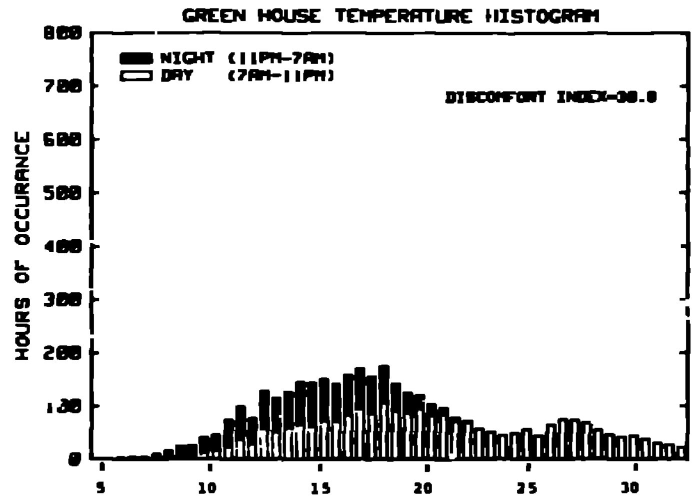


Fig. 4 ROOM TEMPERATURE, DEG C

The central bedroom upstairs is the coldest in the house, having no direct auxiliary heating and a very indirect connection to the greenhouse. Its main heating is by daytime convection through the doorway connecting to the greenhouse and conduction up through the floor from below. This leads to large temperature variations and occasional low temperatures. The greenhouse itself exhibits a wide range and bi-modal characteristic being, on average, much warmer in the day and cooler at night.

The "discomfort index" shown on the figures is the mean-square difference between the observed temperatures and Fanger's "preferred temperature." The units are degree C squared. In this calculation the 7 a.m.-11 p.m. hours were weighted twice as much as the 11 p.m.-7 a.m. hours. This method of calculating a discomfort index is recommended by Carroll (2). Thus, the square root of the discomfort index is a time-weighted variation from the preferred temperature, in ^{o}C.

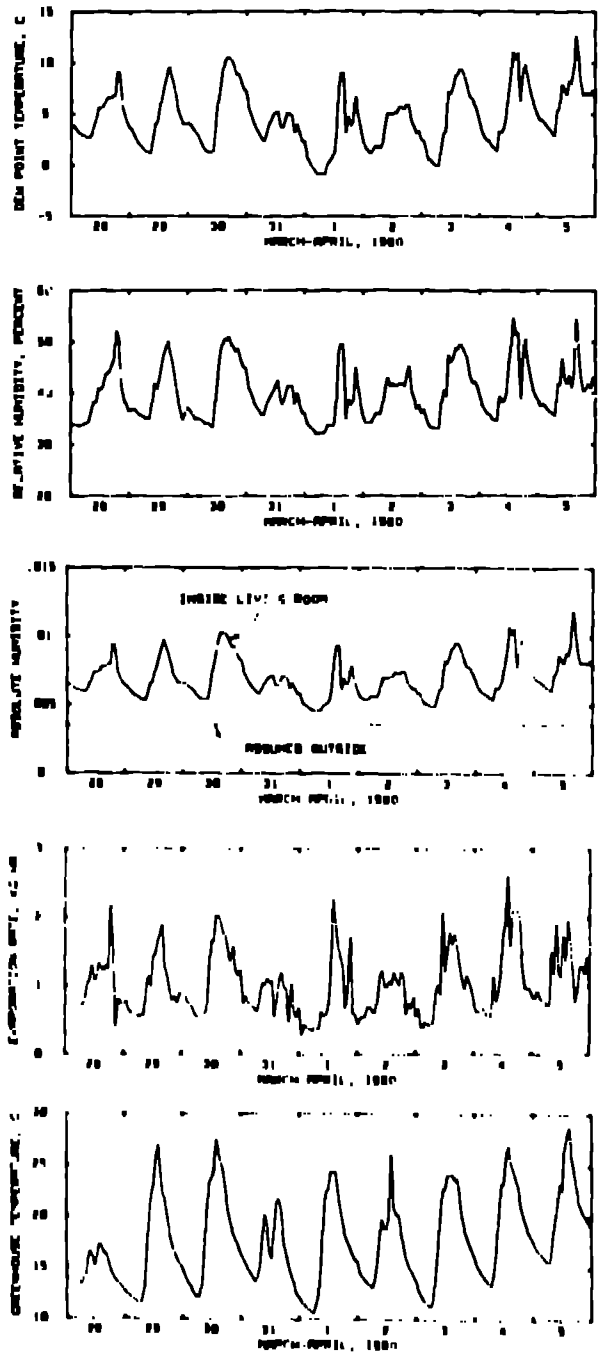
3. EVAPORATION OF WATER

Dewpoint temperatures were monitored continuously during the period 28 March-5 April, near the floor in the north corner of the living room. This measurement is shown in Fig. 5. The relative humidity and absolute humidity (in kg of water per kg of dry air) can be determined from the dewpoint and air temperature measurements in the living room using the psychometric relationships. These calculated values are shown on Figs. 6 and 7. Although absolute humidity was not measured outside, it was obviously very much lower than inside the house. An absolute humidity of approximately .003 kg water/kg dry air is fairly characteristic of New Mexico during this month and was used during the subsequent analysis. This corresponds to an outdoor relative humidity of 80% to 100% during the early morning hours of the coldest nights. It is evident that substantial water vapor must have been added to the air inside the house in order to maintain an absolute humidity more than two times higher. Sources for water within the house are evaporation from humans, cooking, clothes drying, and transpiration from plants within the greenhouse.

Air infiltration can be estimated from data taken during a blower-door test made by the Lawrence Berkeley Laboratory. The apparent total leakage area of the house inferred from these data is approximately 900 cm^2 corresponding to an air infiltration rate of 0.5 to 0.7 air changes per hour during normal conditions. Although this might vary somewhat due to wind velocity and stack effects, it is sufficiently accurate for the present analysis to assume a constant air infiltration rate of 0.6 ACH.

Using a simple mathematical model the evaporation rate required to sustain the observed absolute humidity in the house can be calculated, given the assumed outside absolute humidity and a house volume of 450 m^3. The result is shown in Fig. 8.

It is felt that the predominant source of water evaporation within the house is from the large number of plants in the greenhouse. Strong air mixing occurs between the house and the greenhouse during the day when the connecting doors are open. Following this reasoning, attempts were made to correlate the evaporation rates, shown in Fig. 8, against the corresponding greenhouse air temperature measurements, shown in Fig. 9, on an hour-by-hour basis. A surprisingly good correlation was obtained as shown in Fig. 10. A similar attempt was made to correlate against solar radiation but almost no correlation was observed.



Figs. 5-9

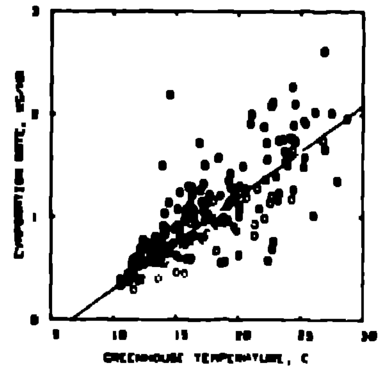


Fig. 10 Hourly correlation

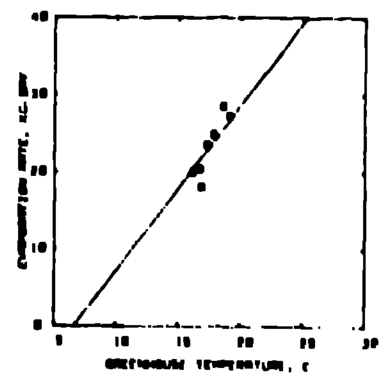


Fig. 11 Daily correlation using daily average greenhouse temperature.

The scatter in Fig. 10 is very understandable considering that the house was occupied during this period, the plants were watered intermittently, doors were opened and closed, and the wind was variable. Notwithstanding these variations, an unmistakable trend of increasing evaporation rate with increasing greenhouse air temperature is observed as might be expected by transpiration from the greenhouse plants. In order to develop an empirical model for subsequent energy analysis, it is assumed that the evaporation rate is linear with greenhouse temperature and approaches zero at the value of 6.7°C. The slope of the line can then be determined in order to yield the correct total daily evaporation corresponding to the average greenhouse temperature. This correspondence is shown on Fig. 10 and the same line is drawn also on Fig. 11. The inferred daily evaporation is given by the formula:

$$2.15 \times (Tg-6.7) \quad \text{kg/day; } Tg = \text{average greenhouse temperature}$$

The energy implications of this evaporation are undoubtedly negative. Nearly all of the water evaporated should leave the building with the exfiltration air. During the coldest weather a small amount may be condensed on window and other surfaces within the house but this is generally insignificant in the house itself. Condensation on the greenhouse glazing is noticeable at times which would have the effect of recycling some of this heat energy to the glazing surface. If one assumes that this effect is negligible, then the energy required for the evaporation would be given by the following formula:

$$1.35 \times (Tg-6.7) \quad \text{kWh/day}$$

This energy represents about 10% of the clear-day solar gains and is therefore significant. However, the main effect is on sunny days when the energy can easily be spared, and it may help alleviate greenhouse overheating. In the dry climate of New Mexico, water vapor added to the house in winter is considered a significant bonus maintaining the relative humidity in the 30-50% range instead of the 10-20% which would result from simply warming outside air.

4. HEAT STORAGE IN GREENHOUSE FLOOR

Temperature measurements were made in the greenhouse floor at depths of 1.25, 5, 15, and 30 cm. The floor is constructed of 5 cm of sandstone rock (flagstone) laid on ordinary earth. The temperature measurements were made near the center of the greenhouse at a location which would be unshaded during most of the day. Temperature traces for a representative days are shown in Fig. 12.

A technique has been developed for determining heat fluxes directly from temperature measurements made in massive wall and floor sections. The technique is described in Ref. 3 which presents all equations and a detailed example for a Trombe wall situation. The method also allows for an in-situ measurement of thermal diffusivity which is then used to determine thermal conductivity.

The method is based on the solution of the heat diffusion equation assuming one dimensional heat flow using two measured temperatures, in this case at 5 cm and 30 cm depth. A thermal conductivity value of 1.21 W/°C-m was found to yield a calculated temperature at the 15-cm depth which almost exactly matches the measured temperatures (assuming a volumetric heat capacity of 1.2 MJ/m^3°C). Heat fluxes at depths of 5 cm and 30 cm were thus inferred.

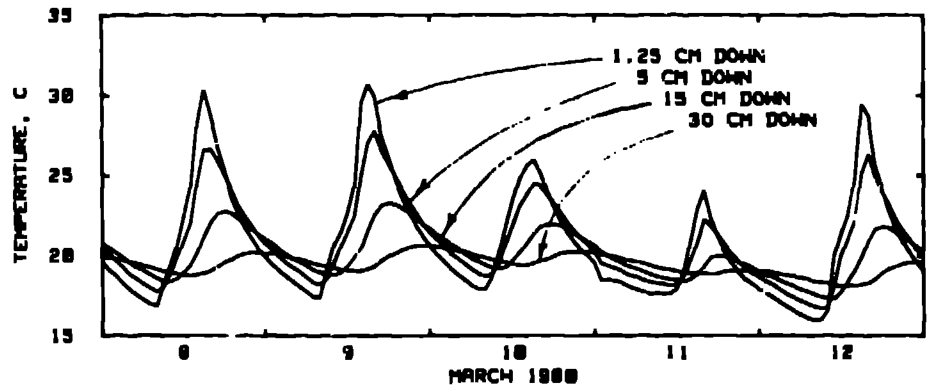


Fig. 12 Greenhouse floor temperatures.

Following this, the heat flux at the surface was inferred using the temperature measurement at a depth of 1.25 cm and the above information. Heat fluxes are given on Fig. 13. The surface heat flux can then be integrated to determine the amount of heat which is stored in the floor on a daily basis and returned to the greenhouse (diurnal heat storage) and the net heat flow into the ground.

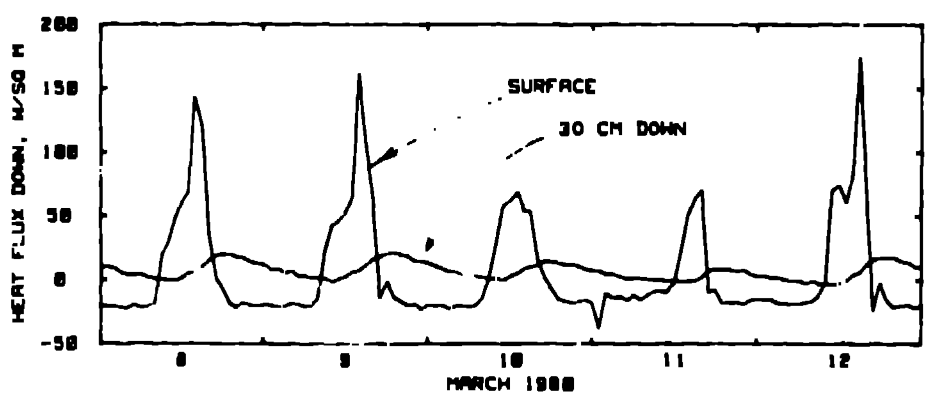


Fig. 13 Greenhouse floor heat fluxes.

There are 19 days of good continuous data taken between 1-18 March, 1980, including four partly cloudy days and rest sunny. For these days, the average heat conducted down into the floor is 0.46 kWh/m^2-day of which 0.30 kWh/m^2-day is returned to the greenhouse at night and 0.16 kWh/m^2-day continues downward. This represents a major part of the energy required to maintain the greenhouse always above 7°C without auxiliary heat.

5. ROCK BED OPERATION

Results based on a preliminary analysis of the 28 March - 5 April, 1980 rock bed data have already been published (4) and will only be summarized here. The key findings are:

a. Reverse thermosiphoning of warm air from the rock beds back to the greenhouse was confirmed and stopped by installation of temporary plastic-film backdraft dampers. The average daily energy loss due to reverse thermosiphoning from both rock beds is estimated roughly as 3.6 kWh/day or about 20% of the input. Stopping this leak increases the floor temperature by 4.4°C during sunny weather and about 2°C during cloudy weather.

b. Heat flows up through the floor above the rock beds were inferred from three sets of measurements taken at the top and bottom of the concrete slab which covers the rock be... These fluxes are lower than anticipated. For the 30-day data analyzed, the average heat flow up through the floor is only 47% of the rock bed energy loss inferred from rock bed temperature swings.

c. A rough, sunny-day energy "balance" attempted during periods when reverse thermosiphoning was stopped is as follows:

	kWh/day	%
Average sunny day input	17.4	100
Measured heat flow up through floor	5.2	30
Estimated side conduction up through floor	1.3	7
Estimated conduction loss to ambient	3.8	22
Unaccounted for	7.1	41

The input is calculated from the integral of (flow rate) x (T inlet-T exit) and the two conduction flows are calculated using UA values estimated for the flow paths. It is evident that the rock bed behavior is not completely understood. Some of the unaccounted for heat may be lost to the earth and not useful to the house.

d. Rock bed exit temperature profiles can be predicted reasonably well using a mathematical model driven by measured inlet temperatures. Based on this, it is concluded that bypass of air above or around the rock bed, if it exists, is less than 15%.

e. Boroscope examination of each rock bed showed the rocks to be clean and free of organic growth.

f. It is now evident that the rock bed energy flows reported in Ref. (1) are too large and should be revised; this should have little or no effect on the overall energy balance of the house but will affect the balance between house and greenhouse.

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4. J. E. Perry, "Rock Bed Behavior and Reverse Thermosiphon Effects," The Fifth National Passive Conference, Amherst, MA, October 19-26, 1980.