Toward Net Energy Buildings Case Studies

Design, Construction, and Performance of the Grand Canyon House

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A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute, Battelle, and Bechtel
for the U.S. Department of Energy
under Contract No. DE-AC36-98-GO10337

DOE/GO-10099-795

June 1999 • NREL/TP-550-24767

Toward Net Energy Buildings

The U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) collaborates with building owners and developers to advocate cutting-edge, energy-efficient buildings through research on advanced passive solar/whole-building design. This design approach examines the integration of all building components from design through commissioning that influence energy performance, and optimizes their interactive roles to reduce energy use without increasing construction costs. These buildings encourage use of passive solar technologies, including daylighting, passive solar heat, and natural cooling combined with efficiency measures and other appropriate renewable energy strategies.

The whole-building design process begins during the conceptual design phase and continues until the building is commissioned. NREL researchers work with building owners and their team of architects, engineers, contractors, and building managers to draft the initial building design, minimizing the building's predicted energy consumption using energy simulation tools. The energy-saving features are then refined during the design phase. After construction and commissioning, the building is monitored to evaluate its performance and to validate simulations performed during the design. Monitoring data are then published in technical reports, case studies, and conference papers and used to direct needed research.

The primary objectives of these collaborative research activities are: (1) to investigate methods of creating very-low-energy buildings; (2) to create verified design and analysis tools for solar building design; (3) to test and analyze design concepts and technologies in residential and non-residential buildings; (4) to measure and test performance of these buildings to further develop and enhance the design, construction, and commissioning of buildings and tools needed to design them; and (5) to identify future research areas.

The design team, which includes the building owner and tenants (if applicable), must be committed to using passive solar/very-low-energy building techniques to supply 75% of the building's heating, cooling, and lighting energy. That saves approximately 70% in energy costs relative to an established base-case building. For renovated buildings, energy cost savings should be 30% relative to an established base case. Buildings must also be in the pre-design stage or earlier. Buildings already planned are too far into the process for substantial, effective energy choices to be made. Finally, occupied buildings must be available for at least one year for performance testing by NREL researchers. As part of the research effort, DOE is also working with industry partners to define achievable energy reduction goals for modular construction and national accounts, such as restaurant and retail chains, based on their unique requirements and corporate environments.

As part of the collaborative agreement, the building owner funds all normal design, construction, and commissioning costs. DOE, under the direction of Mary-Margaret Jenior, funds the low-energy building research, design analysis, monitoring, and reporting. Paul Torcellini, National Renewable Energy Laboratory, is the technical task leader.

Executive Summary

The house built on the south rim of the Grand Canyon is a joint project of the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) and the U.S. National Park Service. The house is also part of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 13 (*Advanced Solar Low-Energy Buildings)*. NREL provided design advice, performed detailed analysis, and monitors the building performance. The project architect was OZ Architecture of Denver, Colorado.

NREL used pairs of ENERGY-10 (a software that simulates designs for low-energy buildings) calculations to compare the house as monitored with a reference house built in accordance with the Council of American Building Officials Model Energy Code and the Home Energy Rating System criteria, using standard occupancy assumptions for both houses. Energy consumption of the Grand Canyon house for non-internal gains was reduced by 75%.

The principal reason for this good performance is the house's exceptional thermal envelope. The overall building loss coefficient (BLC) is only 149 Btu/h•ºF; the smallest BLC NREL has ever measured in a short-term energy monitoring (STEM) test. This BLC includes natural infiltration but excludes floor and Trombe-wall heat flows, which were measured separately.

Although internal gains are about equal to those assumed, passive solar performance from the Trombe wall and direct gain is not as good as expected, providing less than one-half the anticipated solar contribution. The integrated mechanical system (IMS) fulfills its water-heating function properly; however, the IMS performance as a space heater cannot be determined from the measured data.

A mathematical model of the house was developed in which heat flows were either measured, calculated based on measured quantities, or determined by regression. Based on this model, researchers estimated the total energy balance for the winter months, October through March. This period was used for comparing the actual measurements with the preconstruction estimates. These results are given in Table 1, in which the columns labeled “measured” are based on the calibrated model and the column labeled “predicted” refers to the estimate published in the IEA SHC Programme reports prior to construction. Measured data from Table I are displayed as an energy balance diagram in Figure 1.

Table I. Energy Balance for October through March

	Measured	Measured	Predicted	Comments
Heat Required	**kBtu**	**kWh**	**kWh**	
Envelope heat loss	19,722	5681	9893	$U \times (T_h - T_a)$
Floor heat loss	2332	683	2418	
Q_{air} (DHW)	2130	624		Domestic hot water
Q_{air} (space heat)	2638	773	1002	Infiltration
Venting	1601	469	548	Open windows
Total heat required	28,423	8330	13,861	
Heat Supplied	**kBtu**	**kWh**	**KWh**	
Internal gains	8050	2359	2472	
Baseboard electric	5691	1668	1654	
IMS space heat	1435	421	NA	
Trombe wall net	4296	1259	2845	
Direct gain (gross)	8951	2623	6890	
Total heat supplied	28,423	8330	13,861	
Direct gain net	3318	972	2435	
Total back-up heat	7126	2089	1654	

DHW = Domestic hot water
kBtu = Thousand British thermal units
kWh = Thousand kilowatt-hours
U = Building loss coefficient
T_h = House temperature
T_a = Ambient temperature
Q_{air} = Energy needed to heat exhaust air

The fact that the predicted and measured back-up heat values are nearly the same, 2089 kilowatt-hours (kWh) versus 1668 kWh, is probably coincidental—the result of many compensating effects. Note that the predicted total energy flows are much greater than the measured heat flows—primarily a result of the predicted BLC being much higher than the measured BLC. This compensates for the solar performance being less than predicted. The difference between the predicted and measured back-up heat is within the uncertainties inherent in both the simulation and the evaluations based on the measured data.

A post-test evaluation was done using the ENERGY-10 program. The weather data from the site were used to adjust the Flagstaff TMY2 (typical meteorological year) weather. The house model was adjusted to agree with the measured BLC, and the daily internal gains from lights, hot water, and appliances were adjusted to correspond to the average daily value of 16.08 kWh per day measured during the three summer months. The thermostat was set to 66.3ºF, the measured house temperature averaged over the October-through-March time period. The back-up heat predicted using the ENERGY-10 model is 2673 kWh, which compares to the 2089 kWh inferred from the measured data. Both values are derived using the assumption that the predicted internal gains are constant throughout the year. Again, the difference between this prediction and the measured back-up heat, 584 kWh (7% of the total building energy flow), is within the uncertainties in both numbers.

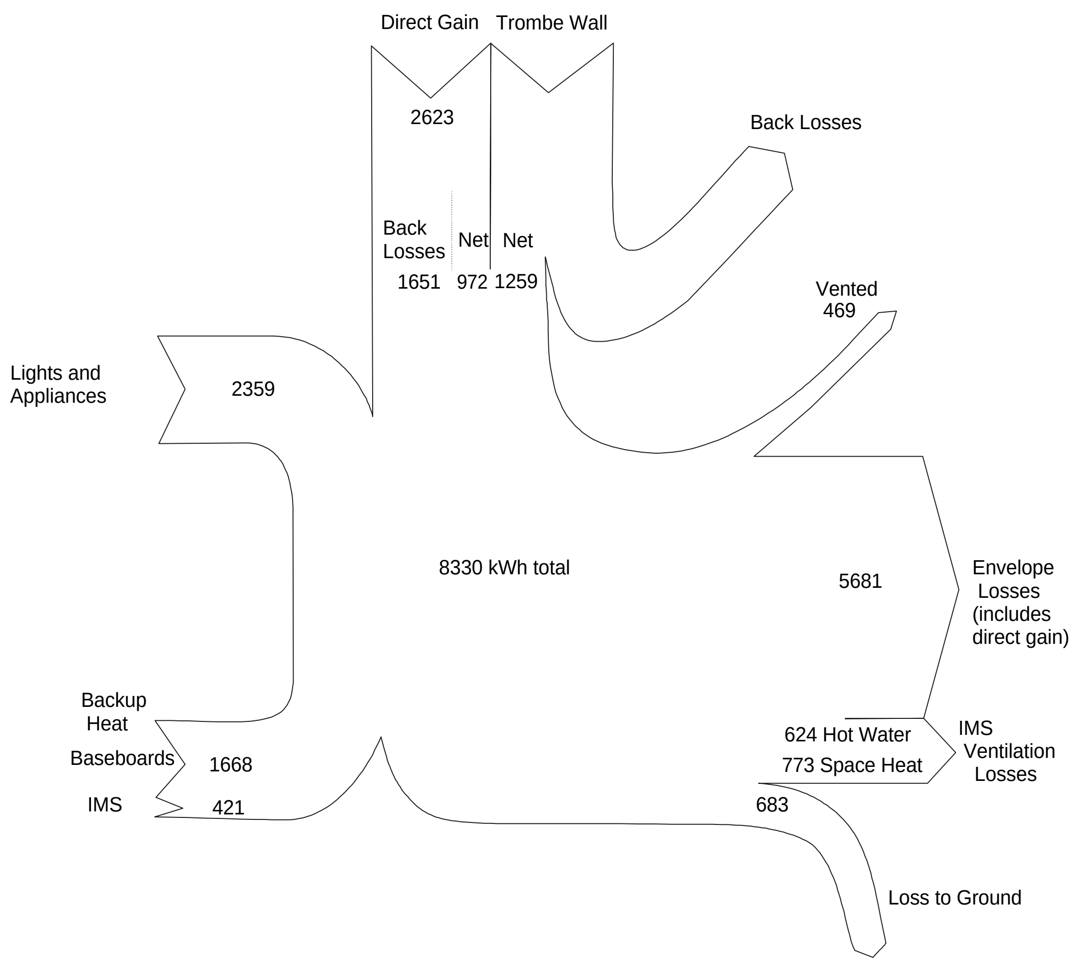

Figure I. Energy-balance diagram for October through March.

Time and financial constraints did not permit NREL to conduct a complete comfort evaluation, and only the indoor temperatures were measured (see Appendix C). An interview with one of the residents indicates that despite the fact that the home is typically within the comfort level, the residents did not agree about the comfort in winter. The residents used very little auxiliary heating. While one resident found the temperature to be acceptable, the other was not comfortable at the lower temperatures. Both residents said that bedroom temperatures were too warm in the summer. However, the authors do not believe air-conditioning is necessary in this home and recommend that ceiling fans be installed.

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Introduction

The U.S. Department of Energy (DOE) conducts low-energy buildings research activities at the National Renewable Energy Laboratory (NREL). These advanced, low-energy buildings activities encourage architects and engineers to work with NREL researchers to maximize a building’s potential energy savings through whole-building design. The whole-building design process begins during the building’s conceptual design and continues until the building is commissioned.

Both residential and non-residential buildings may participate in the research activities, but to do so, the buildings must meet at least one of the following criteria:

- Solar technologies satisfy at least 75% or more of the building’s energy demand.
- Energy consumption is 70% less than an equivalent building built that meets the Home Energy Rating System (HERS) reference building.
- Solar technologies reduce energy consumption by at least 30% for retrofit and renovation projects.

NREL's advanced, low-energy building research began with DOE's involvement with Task 13 of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Program. Task 13, also called *Advanced Solar Low-Energy Buildings,* was an international effort aimed at evaluating technologies and design approaches in an effort to produce low-energy buildings. These research activities began with projects at Grand Canyon National Park, in Arizona, and near Yosemite National Park, in California. This paper focuses on the research project at the Grand Canyon.

NREL provided design advice, performed detailed analysis, and monitors this single-family house located on the south rim of the Grand Canyon. The house was designed in collaboration with the U.S. National Park Service (NPS) as a rental unit for NPS employees working in the park. Built in 1995–96, the house has been occupied by an NPS employee since its completion. Its design, which incorporates new and innovative building systems and equipment, demonstrates the benefits of designing with the climate to achieve major savings.

IEA SHC Task 13

IEA SHC Task 13, *Advanced Solar Low-Energy Buildings,* involved 13 countries that collaborated on the design of 14 houses over a period of 7 years. The purpose of the task was to evaluate technologies and design approaches that would lead to very-low-energy housing. As part of the effort, each country designed, built, and monitored one or two houses.

The Task's final report (Hestnes, Hastings, and Saxhof 1997) shows that despite wide variations in climate and housing types, overall savings of about 75% could be achieved (compared with contemporary construction practices). The report also shows that each country employed similar strategies—high levels of insulation and air-tightening, passive solar heating, heat recovery, and efficient back-up equipment. All countries addressed issues such as reduced hot-water energy use (many used solar water heaters), summer overheating, and efficient lights and appliances.

Predictions indicate that the houses will consume, on average, 16,400 British thermal units (Btu) per gross square foot of floor area (44 kilowatt hours per net square meter [kWh/m^2]), which is 25% of typical contemporary houses in the same locations. Most notably, the predicted energy for space heating, on average, is 5200 Btu per gross square foot of floor area (14 kWh /m^2), which is 15% of typical contemporary houses (Hestnes, Hastings, and Saxhof 1997) in the same locations (most of the houses are in cold climates). The strategies that made this possible were:

- Designing compact, well-insulated, tight envelopes to reduce transmission losses
- Recovering heat from exhaust air
- Using passive solar gains
- Producing and using auxiliary heat efficiently to satisfy the remaining heating requirements.

Although all the houses were or are being monitored, the Grand Canyon project did not fall within the timeframe of Task 13. The monitoring results therefore are not included in the final report. An IEA SHC Working Group has been formed to track and summarize the Task 13 monitoring results. Although the United States is not a formal partner in the working group, NREL shares monitoring results with this entity.

House Description

The single-family residence located on the south rim of the Grand Canyon serves as rental housing for Grand Canyon National Park employees. It has two stories 1582 ft^2 of floor area, three bedrooms, and abuts an established housing area where 59 new housing units were planned for construction. The plan for the house, Model A1, was chosen by NREL from among several plans proposed by the project architect, OZ Architecture of Denver, Colorado.

Site

Solar access was a major criterion in selecting the site for the house, because most houses in the subdivision are overshadowed by large pines. NREL researchers were assured that the site would have no shading from the south.

The site lies at an elevation of 6930 ft, 36°1′ north latitude, 112° west longitude. The terrain is generally flat and wooded predominantly with ponderosa pine, piñon pine, and juniper. The rim of the mile-deep Grand Canyon lies 3600 ft to the north. The existing housing area lies immediately to the north of the site. The Park Headquarters, the Mather Business Center, and the Mather Campground are located about 2300 ft to the east.

Climate

The climate is cold and snowy in the winter and mild in the summer. Winter snows typically occur in 3-day storm cycles interspersed with abundant sunshine. Based on 1997 data recorded at the site, annual average temperature is 48ºF, and there are 6448 heating degree-days (HDDs) (65ºF base). The fraction of solar radiation that penetrates the atmosphere during the winter months is about 64%. During the heating season, October 1 through March 31, there are 5253 HDDs, and the daily solar radiation incident on an unshaded south-facing vertical surface averages 1450 Btu/ft^2. These measurements are reasonably consistent with long-term data recorded at Flagstaff, Arizona, 70 miles to the south (see Table 2 on page 18).

Design Concept

Design concept information presented in this report is based on material published prior to construction. The house plan is shown in Figure 1 and the north-south section is shown in Figure 2. Differences that would affect performance between the house as designed and as built are noted later in this report.

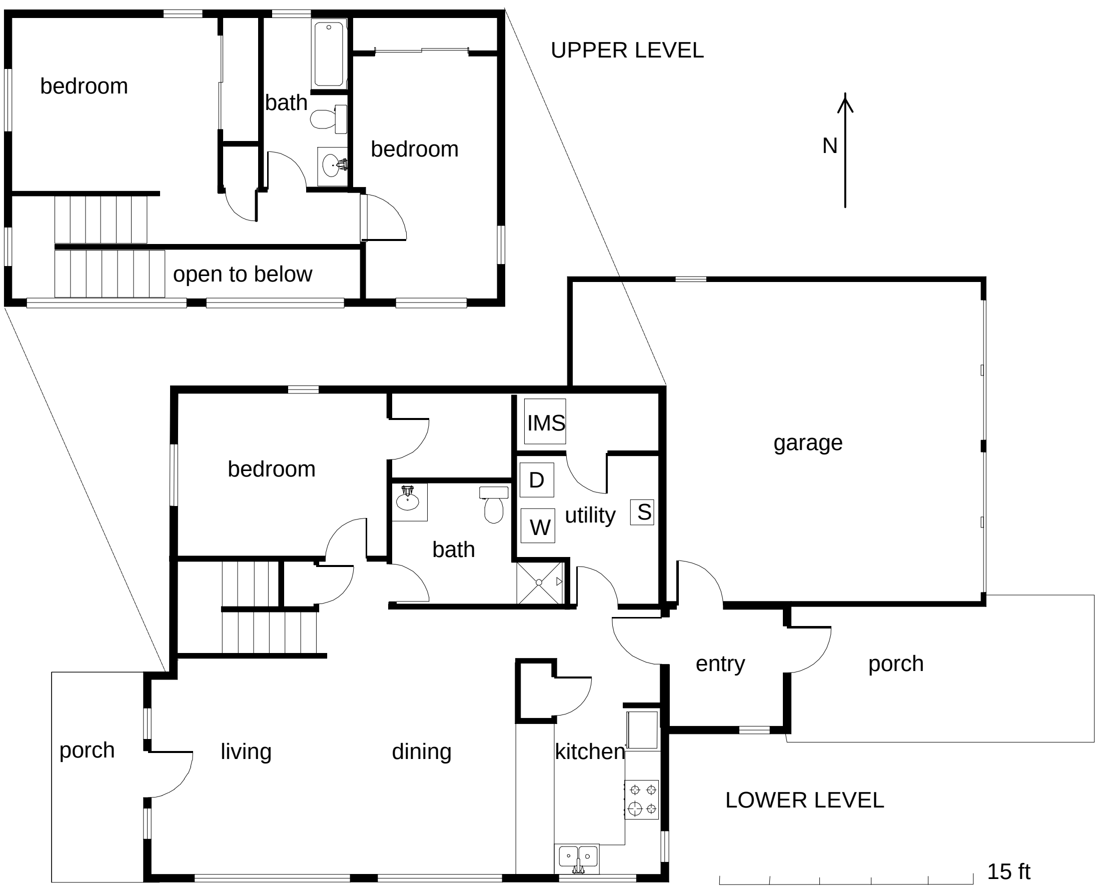

Figure 1. Grand Canyon house plan.

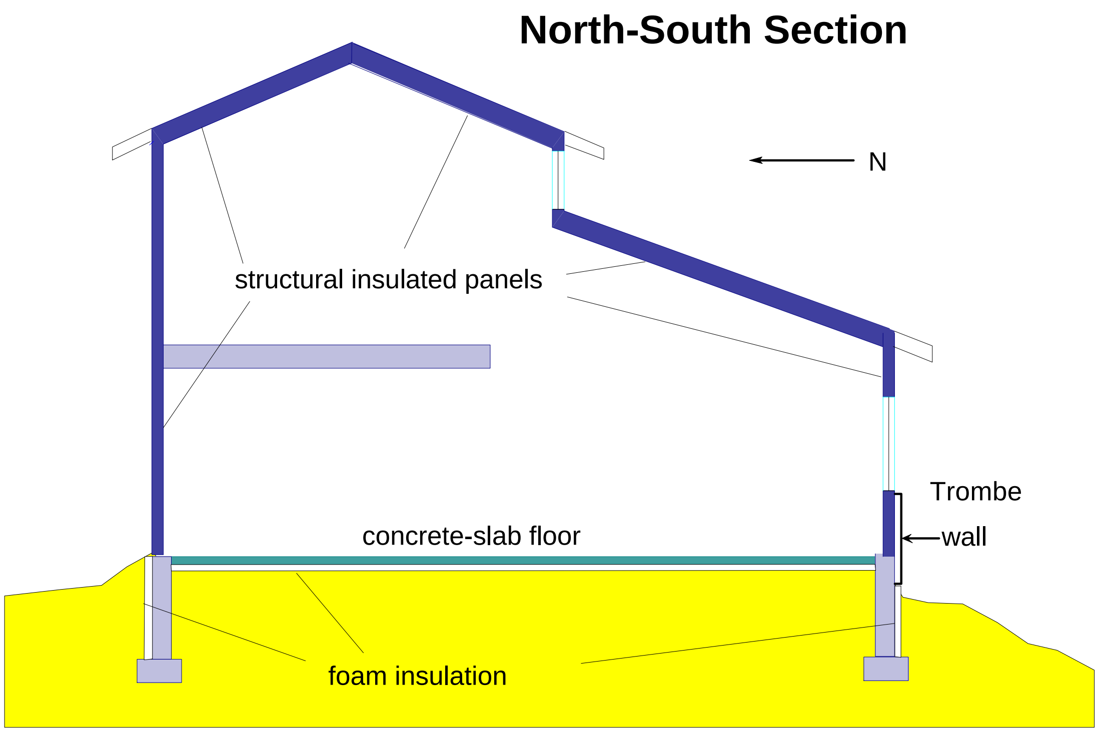

Figure 2. North-south section of the house.

<u>Design Team</u>

Architectural design	Joe Levy OZ Architecture 1580 Lincoln Street, Suite 200 Denver, CO 80203 303-861-5704
Energy design	J. Douglas Balcomb National Renewable Energy Laboratory 1617 Cole Boulevard Golden, CO 80401-3393 303-384-7507
NPS oversight	Janet Youngberg Denver Support Office National Park Service Lakewood, CO 80225

<u>Key features:</u>

- Structural insulated panels, which provide good insulation and airtightness
- Direct-gain passive solar heating
- Trombe wall passive solar heating

- Integrated mechanical system (IMS), which provides exhaust-air heat recovery
- Energy-efficient lights and appliances.

Energy-Efficient and Environmental Conservation Design and Construction

The house's floor plan is relatively compact, maximizing the living space within a small surface area while achieving ample southern exposure for passive solar heat collection.

The walls and roof are constructed of stress-skin panels made of expanded polystyrene foam sandwiched between strand-board made to size in the factory and trucked to the site. Trucking the panels to site results in minimum site disturbance, an important factor within a national park. These precut panels are an engineered system. Splines, pinned and glued, join the panels without the need for wood studs. Thermal bridges through wood members occur only at the top and bottom plates, at each corner, and around openings. Electrical service is run through precut holes along the centerline of the panels. The foam insulation is an expanded polystyrene made with fire retardants but without chlorofluorocarbons. According to the industry, this structure is four times stronger than conventional frame construction and very rigid because all joints are glued together.

Wall panels have 7.5 in. of foam, providing a nominal overall R-value of 34.2. Windows are located in cutouts in the panels and framed with wood. The roof panels have 10 in. of foam, providing an overall R-value = 45.1 Btu/h•ºF•ft^2. Component tests of small structures made with structural insulated panels have confirmed that the predicted overall building loss coefficient is realized in practice (Judkoff et al. 1997).

The house is of slab-on-grade construction. Two in. of foam perimeter insulation is added to the exterior of the foundation walls. There is an additional 2 in. of foam insulation under the entire area of the 4-in. concrete floor slab.

Infiltration was minimized by carefully sealing remaining cracks until the effective leakage area was within the specified range from 50 in^2 to 70 in^2, as measured in a blower-door test. (The final value was 31 in^2.) Good air quality is maintained by controlled ventilation provided by the IMS (described on page 7).

Passive Solar

Passive solar heating is provided by direct solar gain and a Trombe wall. Each system provides about the same net annual heating energy benefit.

Direct-gain solar heating is achieved simply by locating most of the windows on the south side. The rough frame opening of the south-facing windows is 98 ft^2. Glazing is double-pane with one low-emittance (low-e) coating to reduce radiation heat transfer and filled with argon gas to reduce convection. The window frames are wood. The nominal overall glazing U-value is 0.35 Btu/ft^2. The nominal solar heat-gain coefficient (SHGC) is 56% at normal incidence. Researchers predicted that there would be little advantage in using windows with a lower U-value in this sunny climate because the reduced solar transmittance would cancel the benefit of reduced heat losses.

The Trombe wall's delayed heat provides a balance to the direct-gain daytime heating. The Trombe wall's heat is delayed because of the time it takes for the heat to diffuse from the outer surface of the wall where the solar radiation is absorbed to the inner surface. From there, the heat is transferred to the house space by radiation and convection, primarily at night. A cross section of the Trombe wall is shown in Figure 3.

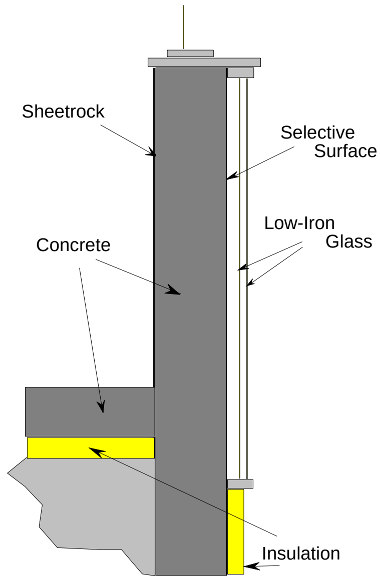

Figure 3. Cross section of the Trombe wall.

The Trombe wall, located below the south windows, extends across the entire south side of the house. The net glass surface area is 80 ft^2. From the exterior, it appears that the windows extend to the ground. From the interior, the Trombe wall is unnoticed, because it is covered on the inside of the house with drywall. The wall is nominally 8-in.-thick concrete, poured as an upward extension of the perimeter foundation. Its exterior surface is covered with a black, selective-surface foil, glued directly to the surface, that has an estimated solar absorptance of 0.93 and an infrared emittance of 0.07 (manufacturer's values). This greatly reduces thermal radiation heat flow from the wall to the glazing. To maximize transmittance, the glazing is clear, water-white double glass, without coatings. This combination was expected to yield a seasonal efficiency of 56%, which is about double that of a typical Trombe wall. The wall is neither vented to the house nor to the outside. (Vents would be counterproductive in this application because they provide hot air during the daytime on phase with direct gain, whereas the advantage of the Trombe wall is to provide heat out of phase with the direct gain.) Direct gain is used to heat the house during the day; the Trombe wall is designed to keep the house warm during the night.

Back-up Heating Equipment

Much of the heat required to maintain comfort is provided by solar gains and by the heat from people, lights, and appliances called "internal gains." The site has no natural gas supply, so the only alternatives are electric heat or bottled gas—both are expensive. The primary back-up heating system is baseboard electric-resistance convectors. Two advantages of electric baseboard heat are that installation is inexpensive and there is good temperature control in individual rooms. The latter is a particular advantage in a high-performance passive solar house because solar gains contribute very differently to each room. Some rooms may never require heat while others may account for most back-up heat.

The Integrated Mechanical System

The house also incorporates an IMS that combines the functions of auxiliary space heating, controlled ventilation, heat recovery, water heating, and auxiliary cooling in one unit. The unit is an Envirovent® Model HPVAC-120 manufactured by the Therma-Stor Products group of DEC. It consists of a 120-gallon insulated hot-water tank with the IMS. This unit contains ducting, dampers, a 690-watt compressor, two blowers, controls, and two heat exchangers that serve as the heat-pump evaporator and condenser. The manufacturer's coefficient of performance (COP) rating for the heat pump is 3.1. A schematic of the IMS is shown in Figure 4.

The unit can operate in several modes.

1. Water heating (priority mode). Heat is pumped from exhaust air if space cooling is not required, or pumped from the house if space cooling is required.
2. Space heating. If space heating is desired at a time when water heating is not required, heat is pumped from exhaust air into the recirculated house air.
3. Ventilation only. Air is exhausted from the house. The heat pump is off.
4. Space cooling. Heat is pumped from the recirculated house air to the hot-water tank or to exhaust air. (This function was not needed in this house.)
5. Off.

Indoor air quality is enhanced by a particulate-arresting filter on the recirculated indoor air that removes 98% of airborne particles 6 microns or larger.

Because the system incorporates a heat pump, researchers felt the IMS would be more efficient than the electric-resistance heat system; however, it cannot meet peak requirements. The IMS heat is delivered to the house at a central location, thus eliminating the need for a distribution system.

When the IMS system is on, it blows about 115 cubic feet per minute (cfm) of air out of the house. This depressurizes the house, causing an equivalent inflow of air through miscellaneous cracks, which overpowers the natural infiltration, increasing the energy required to heat the incoming air.

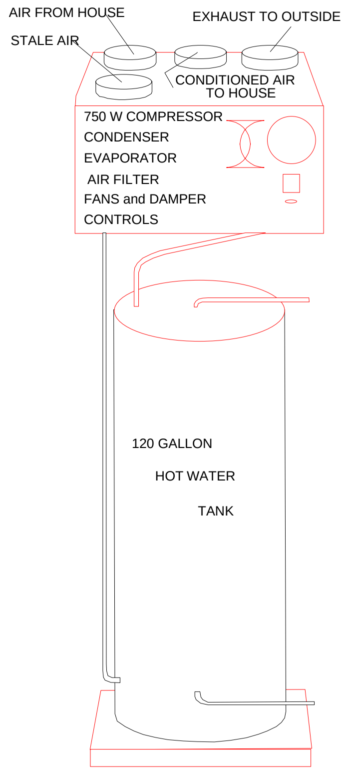

Figure 4. Schematic of the IMS.

Thermal Analysis

The first performance evaluations for this building were done using the *BuilderGuide* computer program. *BuilderGuide* uses the simplified solar-load ratio method in conjunction with a modified degree-day approach to calculate energy consumption. Subsequently, a custom hourly simulation computer model was developed based on a thermal-network approach. The results from these two models are reasonably consistent; however, the hourly model gives good insight regarding many aspects that cannot be studied using the *BuilderGuide* model.

Occupancy Assumptions

Performance predictions are sensitive to assumptions regarding the lifestyle of the residents. The following values were chosen to be consistent with calculations being made by most other participants in IEA SHC 13. It was assumed that:

- The thermostat would be maintained at 68ºF.
- The heat from lights and appliances would be 8.77 kWh/day (29,939 Btu/day, 3201 kWh/year), based on the use of efficient fluorescent lights and low-e appliances (especially the refrigerator). According to IEA, this level of internal gains is about 54% of that in a typical U.S. household (Balcomb et al. 1994).

Weather Data

The weather data used are representative of long-term average patterns at the site. An hourly weather file was prepared by starting with a typical meteorological year (TMY) weather file for Bryce Canyon (in southern Utah, north of the national park). Bryce Canyon is 590 ft higher than the South Rim, and the weather is quite sunny (winter clearness index [K_T], is about 0.64). Temperatures were adjusted downward by the difference in monthly average temperatures in Bryce Canyon and Flagstaff, Arizona, the closest monthly station,[*] which is about 70 miles to the south but at the same elevation.

Thermal Simulation Model

The thermal simulation model used during the design phase was a custom computer program written in the Hewlett Packard (better known as HP) Basic language. Using this language allows the user to easily and quickly make changes to the model. The simulation model employed, shown schematically in Figure 5, is custom programmed. All parameters and equations can be modified.

Figure 5 shows how heat flows within the building. Resistors represent heat-flow paths, between places where temperatures are calculated. The numbers next to the resistors represent the thermal conductance between these locations (Btu/h-°F). The other numbers, shown next to the temperature locations, are thermal capacitances in Btu/ºF. Thus, the diagram is a schematic of the 14 differential equations that describe the thermal behavior of the house. All the numbers shown in Figure 5 were calculated based on take-offs from the house plans. As implemented in this study, the model utilized the concept of a combined convection and radiation heat-transfer coefficient. The modeling algorithms used are similar to those used in both the SERI-RES program and in ENERGY-10.

The solar gain calculation was done in two steps. First, the hourly solar gain transmitted through the window glazings was calculated in a preprocessor program for each of five orientation planes (north, south, east, west, and horizontal). This calculation accounted for the angle-dependent transmittance of the glazing assembly. These solar gains were subsequently multiplied by the solar-gain coefficients shown in the table (lower-right corner, Figure 5) to obtain the hourly solar input to each temperature node. Solar gains were allocated to the air and to surfaces within the space as shown by the values on the arrows in Figure 5.

Heat flow from the bottom of the floor slab was modeled as a split path, one to the deep ground, and the second to the house perimeter.

The Trombe wall was modeled as one inner and one outer slice of concrete. Normally, more mathematical slices are required to obtain accuracy; however, by adjusting the resistance and capacitance values appropriately, the true thermal admittance properties of the wall were achieved. This method for modeling the Trombe wall, as well as the other modeling techniques used, had been previously validated.

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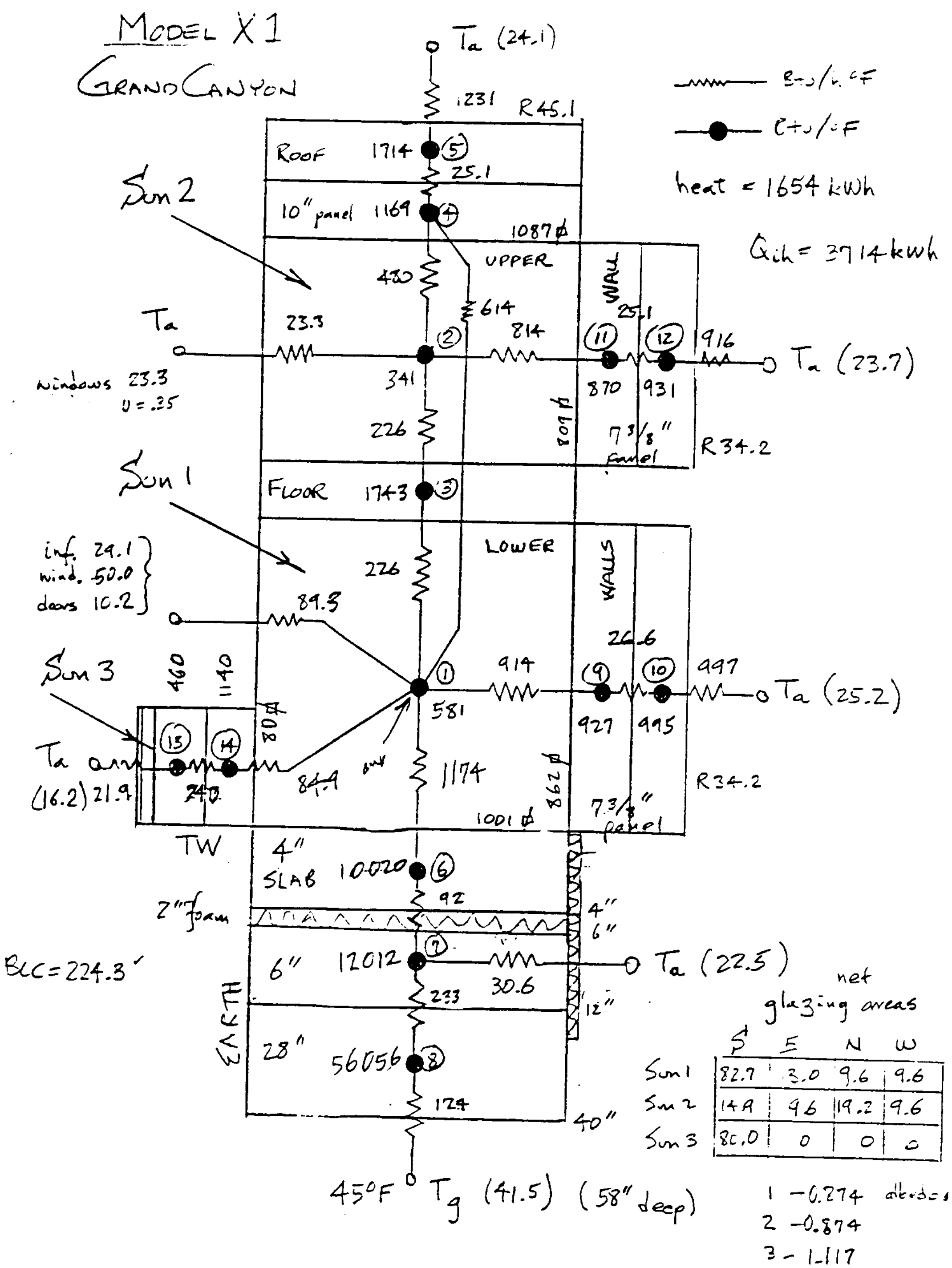
[*] Hourly TMY data for Flagstaff are included in the TMY2 weather set, but Flagstaff is not in the TMY version 1 dataset.



	S	E	N	W
Sun 1	82.7	3.0	9.6	9.6
Sun 2	14.9	9.6	119.2	9.6
Sun 3	80.0	0	0	0

Figure 5. Schematic of the simulation equations for the Grand Canyon house.

The program solves the ensemble of differential equations using an hourly time step within an implicit solution method using an exact energy-balance algorithm.

Winter Heating Performance

For uniformity in reporting results, it was agreed within IEA SHC 13 that all houses would be evaluated over a 6-month winter heating period from October 1 through March 31. This procedure was followed, even though about 18% of the heating degree-days occur outside these months. It was anticipated that solar gains would offset nearly all of the heating requirements in these months, so the estimates of auxiliary heat should not have been underestimated by much. (The monitored data confirm this.) Figure 6 shows the predicted energy balance for the house for the 6 winter months. (This figure can be compared directly with the measured energy-balance diagram (Figure I in the Executive Summary on p. iv.)

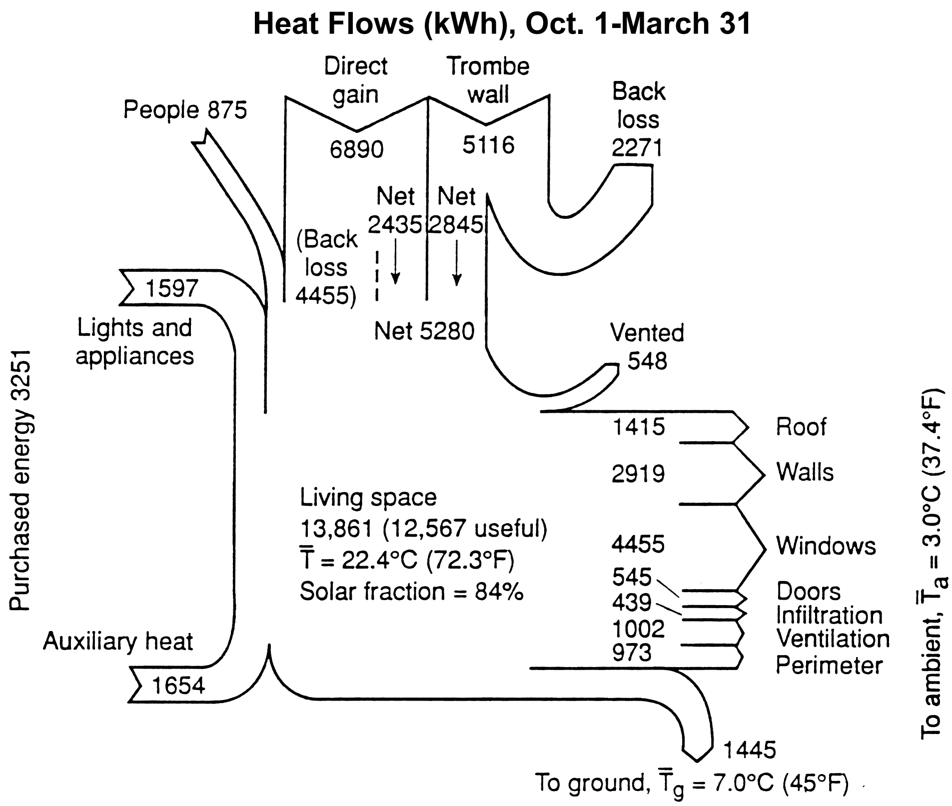


Figure 6. Predicted house energy balance for the winter.

Figure 7 shows predicted temperatures in the Trombe wall on a sunny, winter day. Note the outer-surface temperature peaks at 170ºF. (The measured outside-surface temperatures are *much* lower—see Appendix B.)

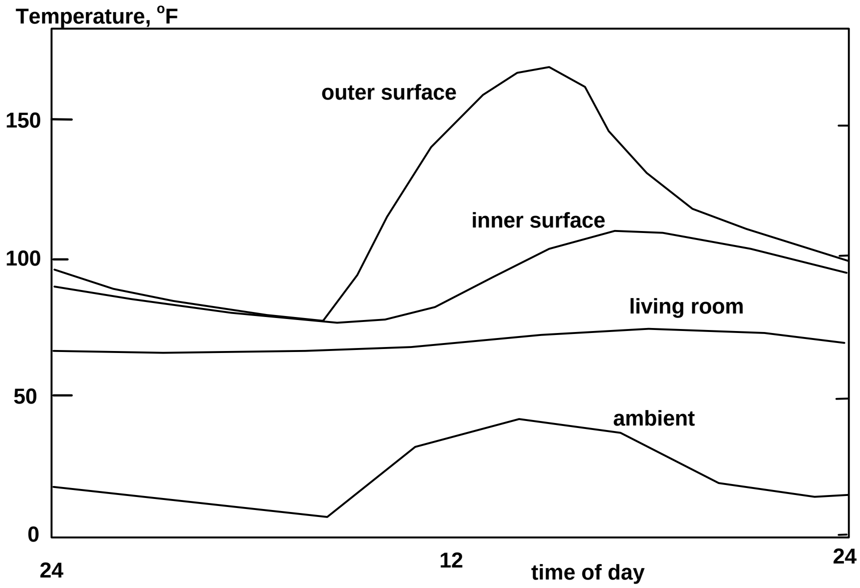


Figure 7. Predicted Trombe wall temperatures on a sunny winter day.

Thermal Stability

The home's high level of thermal integrity makes it nearly independent of the grid. With no back-up heat during a storm on the night of January 25, the home maintained the predicted minimum inside temperature of 51ºF.

Researchers found it interesting to speculate the consequences of a total power outage. In the worst-case scenario, there would be no internal gains, and the temperatures would be considerably more severe than those on the TMY weather file. To study this scenario, researchers looked at the long-term National Oceanic and Atmospheric Administration weather record, which showed a -22ºF minimum reported at Flagstaff. To get an idea of the resilience of the house, the simulated TMY temperatures were decreased by 16ºF, the difference between the TMY minimum and -22ºF . When this was done, the calculated minimum inside temperature was 34ºF, indicating that the house would not freeze.

Electric Heat Time of Use

An additional benefit of the design is that the back-up heat comes on mainly during the electric utility's off-peak demand period. The solar heat during the day carries through into the evening, the house gradually discharges, and the back-up heat, if needed, comes on about midnight, increasing until sunrise. This profile is out of phase with the utility-load profile, which typically peaks in the late afternoon. Thus, the back-up heat fills the valleys in the utility demand curve, tending to level it. This characteristic is obvious from the results of the simulation analysis. Figure 8 is a plot of time of day of the predicted back-up heat aggregated over the winter (October through March).

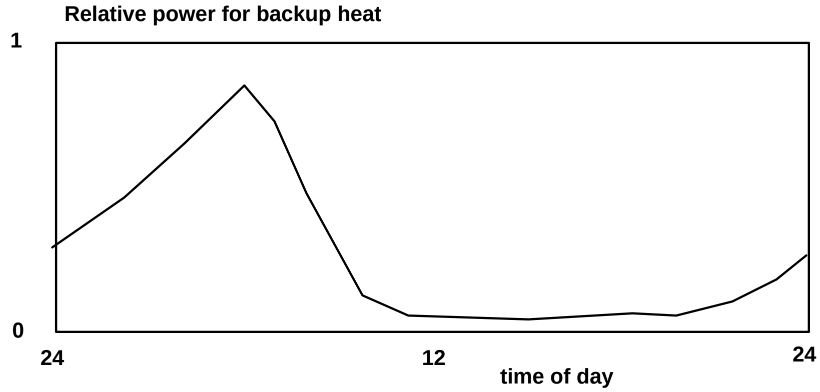


Figure 8. Predicted time of use of the back-up heat as a percentage of total capacity.

<u>Conclusion of the Design Analysis Predictions</u>

Good heating performance is achieved by keeping the design simple, paying attention to energy analysis results, and learning from practical experience. The thermal advantage of the Trombe wall is in the delayed, comfortable, slow heat it provides, which balances the daytime solar heat gain. The small resulting residual heating, ventilation, and air-conditioning (HVAC) requirements are met with a compact, inexpensive, integrated, multi-functional unit. Overall, annual auxiliary heating energy is only 1654 kWh (13.2 kWh/m^2, based on *net* floor area, or 3570 Btu/ft^2 based on *gross* area).

As-built House

The house was built largely according to design, with two exceptions. The walls were built with 10" SIP (structural insulated panels) panels rather than the 8" panels specified, and the perimeter foundation footings were omitted except on the south side under the Trombe wall. Figures 9 and 10 show two views of the house.

The Shading Issue

The area where the house is located is wooded with conifers of all sizes. Nearly all the other houses in the area are completely surrounded by large pines. Although researchers were assured by NPS that the site for this house would be clear of all shading from the south, this did not prove to be the case. Several large pine trees were left standing to the southeast of the house. These trees shade the house in the mid-winter months. This became evident during the initial monitoring of the house in late November 1996. Figure 11 shows a photograph of the house in early December, taken at 10:00 A.M. The shading is pronounced.

Figure 9. View of the house from the southeast.

Figure 10. View of the house from the southwest, showing the Trombe wall beneath the windows.

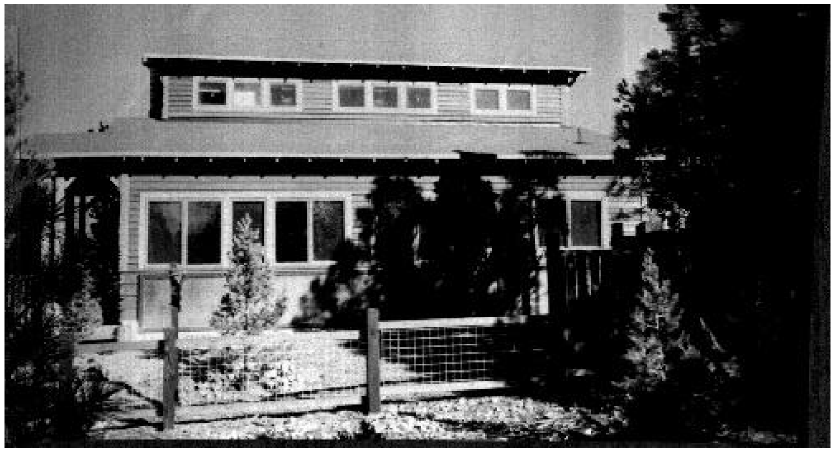


Figure 11. Photo of the house at 10:00 a.m. in early December showing the shading (prior to when one tree was cut).

Early review of the data indicated much lower temperature differences across the Trombe wall on the east end of the wall as compared to the west end. The initial conclusion was that this was because of the shading. Subsequent evaluations indicate that the cabinets in the kitchen are the *primary* reason for the lower temperatures, because they impede heat transfer into the room. The outside surface temperatures were also lower on the east end than on the west end, which was correctly attributed to the shading. (Otherwise, the temperatures would be higher as a result of the cabinets.)

After much discussion with NPS, all parties agreed to remove the trees causing the shading problem. The monitored data played a significant role in this discussion. In fact, only the largest tree was removed. The remaining trees still cause some shading (see plots in the section on Trombe wall evaluations in Appendix B).

Data taken just before and just after the trees were removed indicate that the shading effect was reduced but not eliminated. Although the shading is a contributor to the poorer-than-expected solar performance of the house, it is not possible to totally separate this effect from other possible explanations. (The shading effect shows up best in the Trombe wall evaluations summarized in Appendix B.)

Data Monitoring Setup

A data monitoring system was installed in December 1996, soon after the house was completed. As of March 1998 this system was still recording data, and it will be left in place for future studies (see Recommendations, p. 50).

During construction, a few sensors were installed in locations that would be inaccessible later.

- Sensors under the concrete floor slab—There are two sensors, one just below the two-inch insulation slab and one just above it, at each of two locations: (1) in the center of the living room and (2) near the outside wall in the northwest back bedroom. The temperature difference across the insulation provides a measure of the heat flow into the ground.
- Sensors located within the Trombe wall—There are three sensors—one near the outside surface, one at the center, and one near the inside surface—at the end of the wall. According to the NPS employee that installed the sensors, the sensors near the surface are located within ½ in. of the surface. During the pouring of the Trombe wall, the concrete forms failed near the west end of the wall, causing some confusion during the quick repair. Because of this, there is some ambiguity about the exact location of the center sensor at the west end. The trio of sensors at the east end is within the portion of the Trombe wall that backs onto the kitchen cabinets—this is expected to impede heat transfer from the inner surface of the wall to the room. These arrays of sensors provide a way to determine the heat fluxes at the inner- and outer-wall surfaces; thus, the wall itself becomes a dynamic heat-flux meter.

The first data were taken during a short-term energy monitoring (STEM) test. This was a standard STEM setup with data taken as required for the evaluation protocol. The STEM test was conducted from November 28 through December 1, 1996.

After the STEM test, installation of the long-term data acquisition system was completed, which includes a Campbell Scientific CR-10™ data recorder and a telephone modem for remote downloading of accumulated data. The installation includes the following instrumentation systems:

1) AD590 semiconductor sensors that measure temperatures with an accuracy of 1.0°F.
2) A hall-effect watt-transducer that measures electric power with an accuracy of 1%.
3) An amp clamp that measures current with an accuracy of 5%. The IMS is wired to 240 volts, and power is roughly 240 × amps, not accounting for the phase shift.
4) Li-Cor® PV pyranometers that measure solar irradiance with an accuracy of 8%.

Table 1 is a listing of the data in the CR-10™ record, which is a comma-delimited file with a one-line header. The data are recorded hourly using local standard time. Solar radiation and electrical power values are averages taken over the previous hour. Temperatures are measured on the hour. All temperatures are multiplied by 10. Channels 27, 28, and 29 were not processed. Channels 28 and 29 were recorded for diagnosing problems. According to the data values received, there were no data acquisition concerns.

Table 1. Monitored Data Channels

Channel	Designation	Units	Comment	Average (8760 hr in 1997)
1	117	--	Site designator—117 for this house	--
2	Year	Years		--
3	Day	Days	“Julian” day, starting with 1, going to 365	--
4	Hour	Hours	0 to 2300	--
5	Tground1	F	Center of house, below insulation	61.5
6	Tground2	F	Center of house, above insulation	67.5
7	Tground3	F	Master bedroom, below insulation	54.5
8	Tground4	F	Master bedroom, above insulation	61.5
9	TTromb1	F	East end, inside surface	78.7
10	TTromb2	F	East end, center	79.7
11	TTromb3	F	East end, outside surface	81.3
12	TTromb4	F	West end, outside surface	84.6
13	TTromb5	F	West end, center (actually offset)	82.4
14	TTromb6	F	West end, inside surface	78.5
15	TLR	F	Living room air	68.9
16	TMBR	F	Master bedroom air, downstairs	66.7
17	TEBR	F	East bedroom, upstairs	69.7
18	TWBR	F	West bedroom air, upstairs	70.3
19	Tamb1	F	Outside ambient air #1	48.2
20	Tamb2	F	Outside ambient air #2	48.2
21	Ihoriz	W/m^2	Global horizontal solar radiation, on roof	212.6
22	Ivert	W/m^2	Vertical south solar radiation, on upper eave	152.5
23	TotPower	W	Total house power	977.6
24	IMS-Amps	amp	Current transformer, IMS amps	0.9308
27	Wind		Wind velocity (not processed)	--
28	Tref	F	Reference temperature	--
29	Batt Volts	V	CR-10™ battery voltage	--

Monitored Data

The monitored data set is very clean. Of the 236,520 data points in 1997, only 15 points are missing. The monitored data were read into a special program developed for analyzing the results. This program is written in HP Basic. The data were first converted from text format to a packed, binary file with one record for each day. For convenience, this file was confined to the 1997 calendar year.

Weather Data

The weather data summary is shown in Table 2. For comparison, the long-term data for Flagstaff, Arizona, are shown on a line at the bottom.

Table 2. Weather Data Recorded at the Grand Canyon, 1997

Month	TAA	TMXA	TMNA	TMX	TMN	HS	VS	HDD	CDD
1	30.9	37.4	23.6	53.0	5.0	724	1,217	1070	0
2	32.0	40.8	23.3	54.0	11.7	1,294	1,567	923	0
3	42.4	55.3	28.8	67.5	1.9	1,970	1,629	712	0
4	43.7	54.5	31.4	71.9	21.2	1,906	955	662	0
5	59.1	73.2	43.1	88.6	31.2	2,217	736	223	10
6	63.2	78.0	46.4	86.3	36.0	2,407	591	117	33
7	68.5	82.9	52.6	91.4	43.0	2,237	631	12	97
8	66.1	78.7	54.3	85.1	46.8	1,741	756	12	57
9	58.8	70.0	49.1	80.6	34.5	1,533	1,058	168	5
10	44.6	55.3	33.1	71.3	20.3	1,516	1,706	645	0
11	39.2	49.1	28.7	62.6	21.0	995	1,544	782	0
12	29.2	37.9	19.7	49.4	1.3	863	1,562	1,121	0
Year average	48.2	59.5	36.2	91.4	1.3	1,618	1,161	6,448	202
Flagstaff	45.8	61.0	30.5	97.0	-2.3	1,630	1,219	7,131	145

TAA = Average temperature, ºF
TMXA = Average daily maximum temperature, ºF
TMNA = Average daily minimum temperature, ºF
TMX = Maximum temperature, ºF
TMN = Minimum temperature, ºF
HS = Average daily horizontal solar radiation, Btu/ft^2
VS = Average daily vertical solar radiation, Btu/ft^2
HDD = Heating degree-days, base 65ºF
CDD = Cooling degree-days, base 65ºF

A comparison shows that:

1. Temperatures at Flagstaff and at the Grand Canyon are very similar, with those at the Grand Canyon about 3ºF warmer. However, the average daily temperature range is much smaller at the Grand Canyon—23.3ºF compared with 30.5ºF in Flagstaff. Daily minima are 5.7ºF higher at the Grand Canyon whereas daily maxima are actually 1.5ºF less. These pronounced differences may be caused by the proximity of the site to the immense canyon, which might temper variations. Additional evidence of this effect is noted in the flattened nature of the typical daily cycles, especially in the winter months, as can be noted in the plots in Appendix C.
2. The solar radiation values from the two locations, 1618 versus 1630, have a less than 1% difference; a variable that can be measured to ± 9%.

The Grand Canyon data are for 1997, whereas the Flagstaff data are based on a 30-year average. This could explain some differences, such as the maximum and minimum values, but not the large observed differences in daily temperature range.

Individual Data Channels

Monthly and annual statistics for each channel were tabulated and plotted to observe overall trends. These tables and plots are shown in Appendix C. The tables show, by month, average, average daily high, average daily low, and maximum and minimum of the variable.

There are two sets of plots in Appendix C. The first set contains monthly average daily plots showing the typical variation over a 24-hour period for each month. The second shows the daily average value plotted for each day of the year. Together, they give a good picture of the 236,520 ($24 \times 365 \times 27$) data points.

In addition to the individual data, there are five aggregate variables shown.

- The "ambient temperature" is calculated by averaging the two outside temperatures, which are very similar—generally within 1ºF.
- The "house temperature" was calculated by averaging the four room temperatures.
- The "delta T" is the difference between the house temperature and ambient temperature.
- The temperature differences between the bottom and top of the under-floor insulation were calculated. These are "DTFLC" at the center of the house and "DTFLE" at the edge (in the master bedroom, near the perimeter). Note that there is surprisingly little difference between these—6ºF average in the center versus 7ºF average at the edge. This uniformity means that the choice of areas used to calculate the total floor heat loss is not a major issue. Note, however, that the average values of the edge temperatures are lower than in the center, as expected.

Total Power Consumed

The total house electric consumption and the electricity used by the IMS are shown in Table 4. The IMS power is included in the total power. The columns labeled "watts" (W) show the average consumption for the month. The kWh values are the watts times the number of hours in the month.

Table 4. Power Consumption by Month

Month	Total watts	Total kWh	IMS Watts	IMS kWh
1	1786.3	1329	453.5	337
2	1278.6	859	317.0	213
3	1095.3	815	321.1	239
4	1063.3	766	238.9	172
5	694.5	517	180.2	134
6	666.0	480	145.1	104
7	667.1	496	122.1	91
8	676.5	503	122.0	91
9	702.8	506	136.6	98
10	707.1	526	163.2	121
11	930.3	670	232.4	167
12	1463.8	1089	253.5	189
year		8556		1957

Observations/Conclusions

1. The overall power consumption of 8556 kWh is remarkably low for an all-electric house in this climate.*
2. The monthly average total power is constant over the summer months of June, July, and August at 670±6 W. Six hundred and seventy watts is a reasonable value for average non-space-heating energy use—it is slightly less than the national average household electric use (excluding space conditioning and hot water) of 776 W (566 kWh per month, 6802 kWh per year [Balcomb et al. 1994]). If this remained constant over the entire year, it would total 5869 kWh, leaving 2687 kWh for space heating.

* The national average energy use is 15,973 kWh, yet the Grand Canyon has significantly higher heating degree-days than the national average of about 5000 [2].

3. The monthly average IMS electric use is constant over the summer months of June, July, and August at 130±13 W. If this use remained constant over the entire year, it would total 1136 kWh, leaving 821 kWh for non-water-heating IMS use (when the IMS system is in the space-heating mode).

   The IMS cannot be evaluated as a water heater because the water consumption was not measured. However, 1136 kWh is a credible value for household hot-water energy use—the national average household hot-water energy use is 1534 kWh (Balcomb et al. 1994). In this household, water-heating use might be less than the national average because only two people live in the house. (Although the exhaust fan uses part of the IMS energy, which would decrease its apparent COP, the IMS heats water using a heat pump that has a manufacturer's COP of 3.1.)

4. The daily profile of total and IMS electric use is shown in Figure 12. The hot-water energy use spikes in the morning, presumably because of morning showers and other hot-water use activities. The hot-water use increases slightly just after noon, and it spikes again at about 9:00 p.m. Following each peak, the use decreases because the IMS requires several hours to reheat the tank.

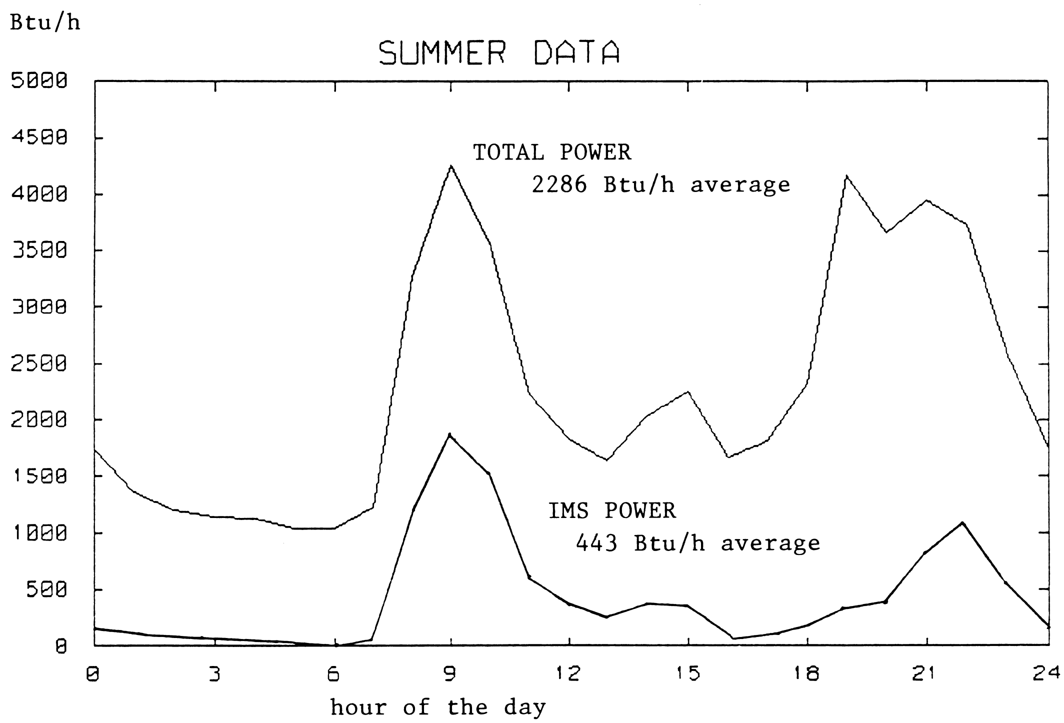


Figure 12. Daily schedule of total electric energy use and hot-water energy use (IMS power consumption) averaged over the 3 summer months. The non-hot-water energy use (the difference between the two curves) is fairly constant throughout the day, with a small peak at 9:00 a.m., and peaks strongly in the evening. Typical 4:00 a.m. energy use is about 1100 Btu/h (320 W).

It is evident from this preliminary look that the house performs very well. A back-up heat value of 2687 kWh (see item #2 above) corresponds to 5795 Btu/ft^2. The average annual heating energy use per household for the United States is about 28,800 Btu/ft^2 (Balcomb et al. 1994). However, the climate at the Grand Canyon is colder than the national average.

Data Analysis

The purpose of the data analysis was to go beyond the bottom-line result, shown in electric-use data (or the utility bills), to refine the numbers, and to estimate the energy performance of the home. The critical elements were:

- The tightness of the house, including the effectiveness of the insulation package and the air-tightening
- The effectiveness of the Trombe wall
- The effectiveness of the direct gain
- The effectiveness of the IMS.

The data analysis was divided into several steps. The overall approach was to develop an energy balance for the house. For the most important estimates, this heat balance was taken over 1-day periods. An energy balance was enforced for the mid-winter months of December, January, and February when it was reasonable to expect that the house was closed up (no open windows for extended periods).

To develop an energy balance, researchers needed estimates of as many of the main energy flows as possible deduced from the measured data. Three of the key heat flows were estimated independently:

1. *Heat loss from the house through the envelope by conduction and infiltration* is best estimated by calculating $BLC(T_{in} - T_{out})$, where BLC is the building loss coefficient measured by the STEM technique, T_{in} is the average inside temperature (average of the four measured room temperatures), and T_{out} is the outside ambient temperature (average of two measured temperatures). The BLC value determined in the STEM test—149 Btu/h•°F—is a solid number because (1) the method has been validated, and (2) the measurement is based on data taken when the house is unoccupied, miscellaneous internal gains are nearly zero, the IMS system is off, and other heat flows are small. This BLC estimate does not include the heat loss to the ground, but does include the effect of heating infiltration air.
2. *Heat loss from the house through the floor slab* is estimated from the temperature difference across the under-floor insulation measured in two locations.
3. *Heat gain to the house from the Trombe wall* is estimated from the temperatures measured in the Trombe wall—in effect using the wall as a dynamic calorimeter (see pp. 28 and 29).

The heat-flow terms remaining in the energy balance are:

1. *Electrical heat into the house.* Although the total electricity is measured, part of this goes to the IMS unit—its performance is not known.
2. *Heat loss induced by the IMS system while it is operating results from drawing cold air into the house.*
3. *Heat into the house through the direct-gain windows.* Although this heat gain is estimated during the STEM process, there was only one day of significant solar gain during the STEM-test period.
4. *Heat temporarily stored in the house materials.* This is very significant over a 1-hour period, can be important over a 1-day period, and is insignificant over a 1-month period.

Estimates of these terms were obtained during the evaluation (see pp. 27-33).

Before describing the evaluation, it is appropriate to describe the STEM test because the BLC result is crucial to the evaluation.

STEM Test

Short-term energy monitoring tests were performed on the Grand Canyon house. The test equipment, test procedure, and data analysis were done according to the STEM procedure developed at NREL (Burch et al. 1990). The test lasted for 5 days (November 27 through December 1, 1996) during which the building was unoccupied. Data from 11 measurement channels were used to re-normalize an audit-based simulation model of the house.

Occupied versus Unoccupied Testing

There are potential inaccuracies in judging the thermal quality of a house on the basis of data taken while the house is occupied. The biggest problem is that differences in the behavior of different residents can significantly affect the results, obscuring any estimate of the thermal-retention quality of the house. Occupancy issues fall in three major categories: thermostat settings, the amount of heat generated internally by lights and appliances, and window and door openings to the outside.

To help overcome these problems, NREL developed a method that combines measurement and theory. The method, called STEM, is based on a calibration of a building simulation model from data obtained during a short-term test conducted with the house unoccupied (Burch et al. 1990; Palmiter 1985; Subbarao 1998; Subbarao et al. 1988; Balcomb and Hedstrom 1980). The STEM method is described in Appendix A.

STEM starts with a simulation model. Because this model can be adjusted, it can be made fairly simple based on a quick audit. In the data analysis, adjustment factors are identified for each of three key building heat flows as follows: (1) heat flow per degree of inside-outside temperature difference under steady-state conditions, normally called the building loss coefficient; (2) heat stored in the building internal mass; and (3) heat from solar gains. Incorporating these factors into the mathematical model is called re-normalization. The re-normalized model can estimate long-term performance using typical weather data and occupancy patterns.

Test Procedure

A preliminary blower-door test is performed to determine the infiltration effective air-leakage area (ELA) of the house. Pairs of measurements are taken of the air flow into the house and the inside-outside pressure difference. The infiltration ELA is determined from a regression fit to a power-law relation between the two measurements.

To perform the test, the test procedure, or protocol, is programmed into the data acquisition computer. The objective is to obtain data near a steady-state condition during the first nights of testing and to do a cool-down test on the last night. Day-time data are used to determine the effect of solar gains. During the entire test, all house appliances and lights are turned off and all heating is from five portable baseboard electric heaters individually controlled by the data acquisition computer.

Data Analysis

Analysis of the test data is by the STEM 2.0 computer program, which incorporates the multi-zone PSTAR method (Palmiter 1985). This method is based on an hourly dynamic energy balance equation for the house. The audit description is converted to a SUNCODE™ computer model (a simulation program written by NREL under a subcontract to Ecotope [Subbarao 1988]) and is also used to derive a reduced PSTAR model, which is compact and fast running.

Heat flows are calculated for the whole house using the reduced model and measured temperatures. House air temperature is a weighted average of the four measured inside temperatures. The calculated primary heat-flow terms are the steady-state conduction from inside to outside; the heating of infiltration air; the internal mass storage effect caused by inside temperature changes; and all solar-gain effects, both prompt and delayed (calculated by SUNCODE). The other primary heat flow is the total measured electric heat. Secondary calculated heat flows include heat lost to the basement, extra heat loss caused by sky infrared temperature depression, and dynamic effects because of variations in outside air temperature.

The net of all these heat-flow terms normally does not yield an hourly energy balance because neither the model nor the audit description is exactly correct. The primary heat-flow terms are re-normalized using linear least squares to give a best fit to the observed heat input from the electric heaters. The re-normalization is done by determining adjustment factors for each of the three primary calculated heat flows, yielding a minimum least-square error over specially selected time periods.

Results

The leakage area was determined in the blower-door test to be 31 in.^{2}—less than the specified range.

1. The BLC is 149 Btu/h•°F. This should be compared to 131 Btu/h•°F for the audit description. These numbers both include 17 Btu/h•°F for the conductance caused by air infiltration. The BLC is the average value determined from measured conditions during the co-heating period. The calculated average infiltration rate during this time is 24 cfm, which corresponds to 0.11 air changes per hour, with a wind speed of 3 mph and an average inside-outside temperature difference of 30°F. This BLC does not include heat loss to the ground or from the Trombe wall because these terms were treated as known values during the analysis (see following sections).
2. The effective solar gain is 63% of the value predicted by the audit model.

The net heat-flow error term calculated after re-normalization is shown in Figure 13. The RMS deviation between the predicted and the measured value is 2338 Btu/h, which is a little higher than a typical STEM test result (about 1700 Btu/h).

In addition to the normal STEM test, researchers evaluated many early morning periods in the subsequent monitored period using the same methodology used in the STEM software. The results are consistent with the STEM test results and serve to enhance the credibility of the results.

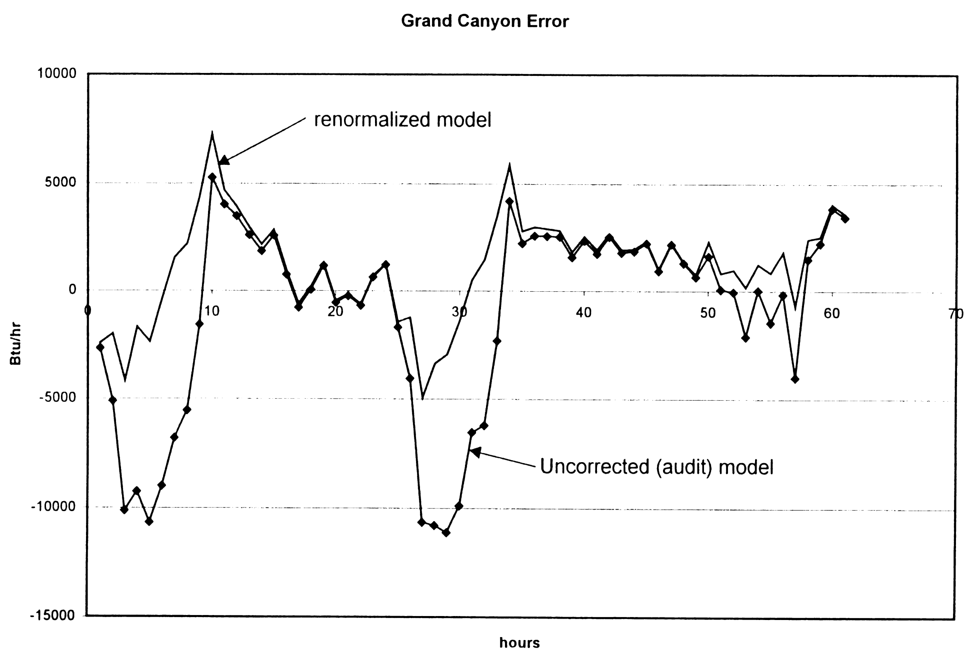


Figure 13. The energy-balance error term (Q_{net}) during the STEM test.

Conclusions of the STEM Test

The STEM procedure (Judkoff et al. 1998) provided an accurate determination of the BLC, which was the main goal. However, the solar-gain parameter was not determined as well. The building thermal mass could not be accurately determined, so the audit-model values were used because the standard error was comparable to the measured value.

Floor Heat Loss Estimate

The Grand Canyon house floor is well insulated against heat loss to the ground by 2 in. of rigid foam under the slab and 2-in. perimeter insulation on the exterior of the footings. As a convenient by-product of the under-slab insulation, researchers measure the heat flow to the ground by measuring the temperature difference (ΔT) across the insulation. The floor heat loss is calculated by assuming a conductance value for the 2 in. of rigid foam insulation of 0.1 Btu/h•ºF•ft^2, an area of 200 ft^2 for the perimeter floor area and 800 ft^2 for the center floor area (the area of the floor slab is roughly 1000 ft^2).

Tables of monthly average values of the temperatures and ΔTs are given in Appendix C along with plots showing daily variations by month, daily averages for each day of the year, and hourly data for the mid-winter months. Note that although there are large changes in the two ΔTs from month to month, the daily variation is very small. The total floor heat loss is highest in the summer at about 800 Btu/h and lowest in winter at about 400 Btu/h. The reason for this contradictory-sounding statement is that the inside temperature is higher in summer than in winter and the ground temperature does not change much.

The striking result is that the floor loss is small, averaging only 621 Btu/h over the year (182 W). The October-through-March average is 536 Btu/h for a total of 2.3 million Btu or 682 kWh. Researchers concluded that the floor insulation is very effective. The small value of 682 kWh is significant compared to the 2089 kWh of back-up heat required.

The measured winter ground heat loss of 536 kWh is 22% of the value of 2418 kWh predicted by the model. This is not surprising, in retrospect, because (1) the model accounted only for short-term dynamics,* (2) the model did not account for annual heat storage in the ground, and (3) it was assumed that the room temperature would be constant (i.e., within the range of thermostat settings) throughout the year. The first assumption is probably not too far from reality; however, the last two assumptions were not realistic.

The most important factor is the variation in inside temperature with seasonal changes. This is a lifestyle issue that would vary from resident to resident. The more complex models, including models that solve for ground heat flow, using finite-element calculations of two- or three-dimensional heat flow, would not be of much help because of the unpredictable variation in house temperature.

* In the model (see Figure 5) the BLC to the outside air was 22.5 Btu/h•ºF and the BLC to the deep ground temperature (which was assumed to be constant at 45ºF) was 41.5 Btu/

Trombe Wall Heat Flow and Other Performance Estimates

The Trombe wall performance is evaluated by solving the diffusion equation for one-dimensional heat flow through a solid, based on hourly temperatures measured on the wall's external and internal surfaces. By this process, it is possible to determine the heat fluxes at the surfaces. The heat flow to the room is one of the principal terms needed in the house energy balance.

It is also possible to infer other interesting information about the Trombe wall. Knowing the surface heat fluxes and the appropriate temperature differences, it is possible to estimate the U-values from the surface to the adjacent air space, which provides important insights.

The details of these results are in Appendix B. The conclusions are:

1. Peak Trombe wall outside-surface temperatures are much lower than expected, providing an early suggestion that the performance may be low. Peak sunny-day temperatures are 130ºF at the west end and only 110ºF at the east end. Other monitored Trombe walls have shown peak temperatures between 150ºF and 160ºF. A high of 170ºF was anticipated for this wall.

2. The performance of the Trombe wall is poor. The total heat delivered to the house over the 6 winter months is 1259 kWh, compared to 2845 kWh estimated when using the simulation model. The reasons for the poor performance are only partially understood. See item 6 below.

3. The U-value from the outside wall surface to the ambient air, estimated during the nighttime hours, is about 0.18 Btu/h•ºF•ft^2. This extremely low number is significantly less than the corresponding number of 0.28 Btu/h•ºF•ft^2 measured in a similar way in a Los Alamos test cell (both Trombe walls were double glazed and incorporated a selective-surface metal foil on the outside of the wall). The reason for this discrepancy is not known. However, this result rules out excessive heat loss as a possible explanation for the wall's poor performance. The inferred U-value is essentially the same for the west and east ends of the wall.

4. The U-value measured from the inside wall surface to the living room is 0.98 for the west end of the wall and 0.44 for the east end. The 0.98 value is credible for the combined effect of convection and radiation. The value is a bit low, which could be because of the drywall facing on the interior wall. The low value at the east end can be explained by the presence of kitchen cabinets that back up to the wall along the kitchen. Based on house drawings, researchers estimated an overall wall area of 56 ft^2 for the west end and 24 ft^2 for the east end. The cabinets account for some of the wall's poor performance.

5. The total heat flow from the wall to the room is 308 Btu/day•ft^2 for the west end of the wall and 123 Btu/day•ft^2 for the east end of the wall (averaged over December through February). The daily heat transferred to the room correlates very well with the daily incident solar radiation measured on the south vertical surface (for this purpose, the day is defined as the 24 hours starting at 6:00 a.m.). The efficiency of the Trombe wall (defined as the heat delivered to the room divided by the total solar

radiation incidence on the wall) is 20.4% for the west end of the wall and 8.3% for the east end of the wall. The low value of the latter is explained in part by the presence of the kitchen cabinets, but the west-end value is also poor. The wall efficiency was expected to be greater than 40%. This is explained partially by morning shade on the wall.

6. The solar energy absorbed on the outside of the wall surface is only about 44% of the incident solar energy. This implies that the transmittance of the glazing is much lower than the expected transmittance of about 85%. This could explain the wall's poor performance.

   There is no ready explanation for the low transmittance value. The wall was to be glazed as specified with two layers of clear water-white glass to obtain the highest possible transmittance. According to Tom Dressler, who oversaw the construction for NPS, the glazing installed was the type specified, although this was difficult to ascertain during site inspection.

Estimating Direct-Gain Solar Area and IMS Performance

With the heat flows determined in the previous three sections, the energy balance equations can be used to remove the remaining unknowns: (1) the effective solar-gain area and (2) the IMS system performance.

The IMS system operates more frequently at night when the solar gains are zero. The solar gain is largest during the day when the IMS system is likely to be off. These differences in timing help to separate the two effects. To take advantage of these timing differences, the data need to be evaluated hourly.

Correlation with the IMS power is important because it is a measured variable, and as much data scatter as possible should be removed to increase the accuracy of the solar area determination. This procedure proved to be effective in reducing the standard error in the solar area estimate. The result may be masking some unknown effects and may not be definitive about the IMS unit.

Simulation Model

The procedure uses a simple two-dimensional simulation model to solve the energy-balance equations each hour. There are two temperatures in this model, the house air temperature (T_h) and the temperature of a mass element (T_m), that represent all the mass in the space. Although a more complex model could have been used, this model was deemed suitable for the present purpose.

It is reasonable to assume that the daily solar gain into the house is proportional to the daily solar radiation incident on the south face of the house. The proportionality factor (A_s represented in square feet) is an effective solar area.

The actual south-facing, direct-gain glass area of the house is 97 ft^2. The effective solar area should be less than this because of glass absorption and reflections, site shading, and shading created by window recesses and mullions.

The behavior of the IMS unit is unknown. It pumps heat from exhaust air depositing heat in either the water or the room air. However, in doing so, it increases infiltration by depressurizing the house. The overall effect can be negative.

The two equations are:

$Q_{sim} = U (T_h - T_a) - F_1 (A_s Q_s + Q_{tw}) - U_m (T_m - T_h) + Q_{air}$ and

$M (dT_m/dt) = (1 - F_1) (A_s Q_s + Q_{tw}) - Q_{fl} + U_m (T_m - T_h)$,

where: Q_{sim} = heat required, Btu/h
$U = BLC = 149$ Btu/h•ºF
T_h = house temperature, measured
T_a = ambient temperature, measured
F_1 = fraction of solar and floor heat going into the air (assumed to be 20%)
A_s = effective solar gain area, ft^2, to be determined
Q_s = solar gain on the south vertical facade, measured, Btu/h
Q_{tw} = heat from Trombe wall, calculated in the last section, Btu/h
Q_{fl} = heat loss from the floor, calculated in a previous section, Btu/h
T_m = temperature of the massive element in the house, calculated
M = mass heat capacity of the massive element, assumed to be 4900 Btu/ºF
Q_{air} = heat required to condition air brought in by the IMS unit, Btu/h

$Q_{air} = (100) (1.08) (adr) (hours) (T_h - T_a)$
[assuming 100 cfm of air flow, a nominal value for the IMS unit]

hours = fraction of the hour that the IMS is on = IMS power/2300
[the IMS unit draws 2300 Btu/h (674 W) when on]

adr = air density ratio (compared to sea level) = 0.774.

A backward-difference solution of the second equation provides an algebraic equation for the mass temperature:

$T_m = (T_{mp} M + (1 - F_1) (A_s Q_s + Q_{tw}) - Q_{fl} + U_m T_h)/ (M + U_m)$,

where: $T_{mp} = T_m$ at the last hour.

Finally, the error in heat, Q_{err}, is given by:

$Q_{err} = Q_{total} – (1 - K_{IMS}) Q_{IMS} - Q_{sim}$,

where: Q_{err} = error in heat, the quantity to minimize, Btu/h
Q_{total} = total electric heat into the house, measured, Btu/h
Q_{IMS} = 3.412 (IMS watts – 130), Btu/h
K_{IMS} = fraction of the IMS electric energy that is deposited in the house.

It was assumed that all of the water heat is lost. The assumption is that 31% of the water heat remains in the house—a value that accounts for stand-by losses and heat transfer during use. If the assumption is incorrect, the effect will be absorbed in the resulting value of K_{IMS}.

The two unknowns in these equations are A_s and K_{IMS}.

The method of solution used was to individually correlate the daily error in house energy balance (leaving out the energy term being estimated) with daily Q_s and daily Q_{IMS} using the method of least-squares. Researchers iterated to find a consistent solution, because the two correlations are interdependent. (The correlations were done on a daily rather than an hourly basis for mathematical convenience. The plausibility of the result is demonstrated in Figure 15, showing no trend in the error when plotted against incident solar radiation.)

The values determined are:

A_s = 32 ft^2 and
K_{IMS} = 0.60 (see discussion below).

A_s is the Q_s multiplier required to explain the observed direct solar gain. The actual south-facing glazed area is 97 ft^2, implying that the fraction of incident solar energy transmitted into the house is 32/97 = 0.33 or 1/3. A transmittance of about 56% was expected from a high-transmittance, double, low-e glazing. This finding is consistent with the STEM test result, indicating relatively poor direct-gain solar performance.

K_{IMS} is the fraction of the electrical energy into the IMS unit that is deposited in the house as heat. Presumably, the heat is recovered from the exhaust air. The conclusion that this is less than unity *could be* an indicator that the IMS unit may not be effective in the space-heating mode. However, the error in the correlation is very large, with the result that the value of 0.60 is poorly determined.

This is not an effective way to test the IMS unit. Many unknown factors could be responsible for this result, including the unknown energy loss associated with clothes-drying air that is exhausted, or any other electrical energy included in the house total that is not deposited in the house, such as outside lights or any other outside appliance. The details of the two correlations are described below.

Estimating Solar Gain Area, A_s

The daily Q_s correlation graph is shown in Figure 14 with the least-square regression line plotted through the data. The value of A_s is 32 ft^2. To check this result, the *hourly* values of Q_{err} (calculated with A_s = 32 ft^2 and with K_{IMS} = 0.60) were plotted against the hourly Q_s in Figure 15. Note that there is no trend of errors with increasing solar gain.

There are 4368 points on the plot (24 hours x 182 days). The RMS error is 3189 Btu/h. This is a reasonable value, somewhat higher than the value of 1700 Btu/h found in a typical residential STEM test (Burch et al. 1990). This would be expected because the house is occupied and therefore has spurious large internal gains. Note that there are a few hours when the error is positive and very high. This is probably because of high-peak electric use that does not heat the room air directly, such as cooking and television. There are no points of high negative error, indicating that windows are probably not left open for extended times during this mid-winter period.

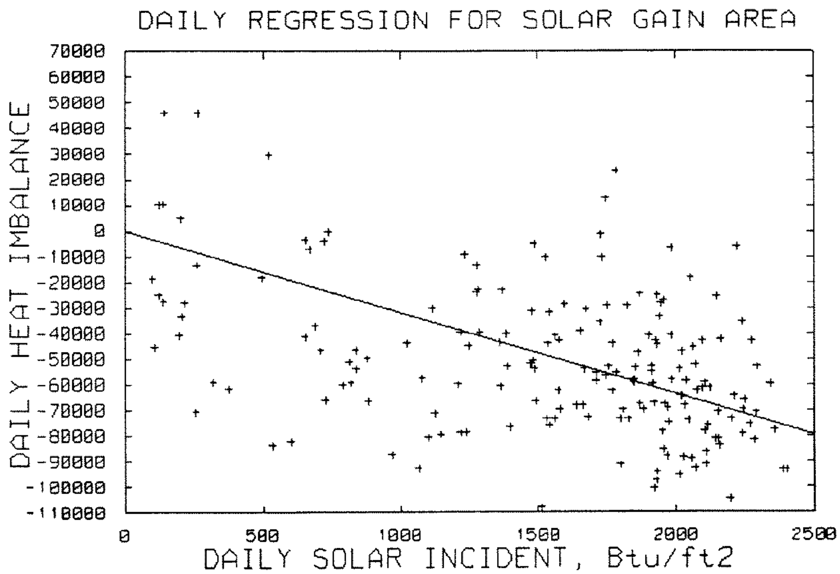


Figure 14. Correlation of daily energy-balance error, with daily solar gain on the south façade. The error calculation does not account for solar gain. The line is a regression fit to the data, assuming that the line intersects the vertical axis at zero. The slope of the line is 32 ft^2, indicating that this effective solar-gain area minimizes the squared error.

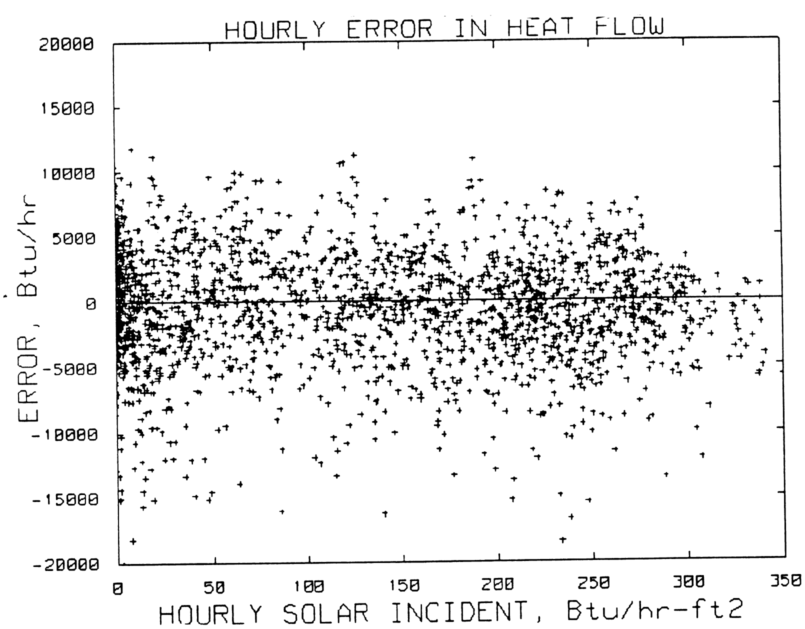


Figure 15. Plot of the hourly energy-balance error for the 6 months of winter versus the hourly solar gain on the south façade.

Estimating IMS Effectiveness

The daily Q_{IMS} correlation graph is shown in Figure 16, with the least-square regression line plotted through the data. The value of K_{IMS} is 0.60. Note that the trend of Q_{err} with Q_{IMS} is *not* very evident, resulting in the large relative error in the K_{IMS} estimate.

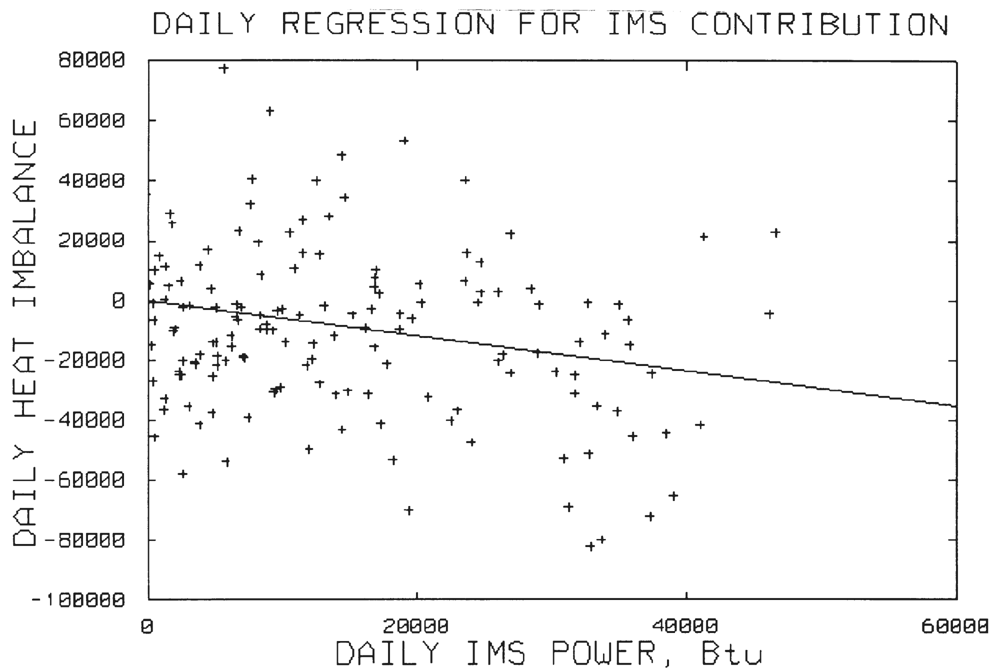


Figure 16. Correlation of daily energy-balance error with daily net IMS power (IMS power minus nominal water-heat power). The error calculation does not account for IMS heat. The line is a regression fit to the data, assuming that the line intersects the vertical axis at zero. The slope of the line is 0.60, indicating that this fraction of the IMS net power added to the house minimizes the squared error.

To check on this result, the *hourly* values of Q_{err} (calculated with $A_s = 32$ ft^2 and with $K_{IMS} = 0.60$) were plotted against the hourly Q_{IMS} in Figure 17. Note that there is a large clump of hours when the IMS is on, but there is no trend of errors with the IMS power.

Energy Balance for the Winter

A best estimate of the total energy balance for the winter months, October through March, can be made based on the model. This period is chosen for comparison with the preconstruction estimates. Results are given in Table 3.

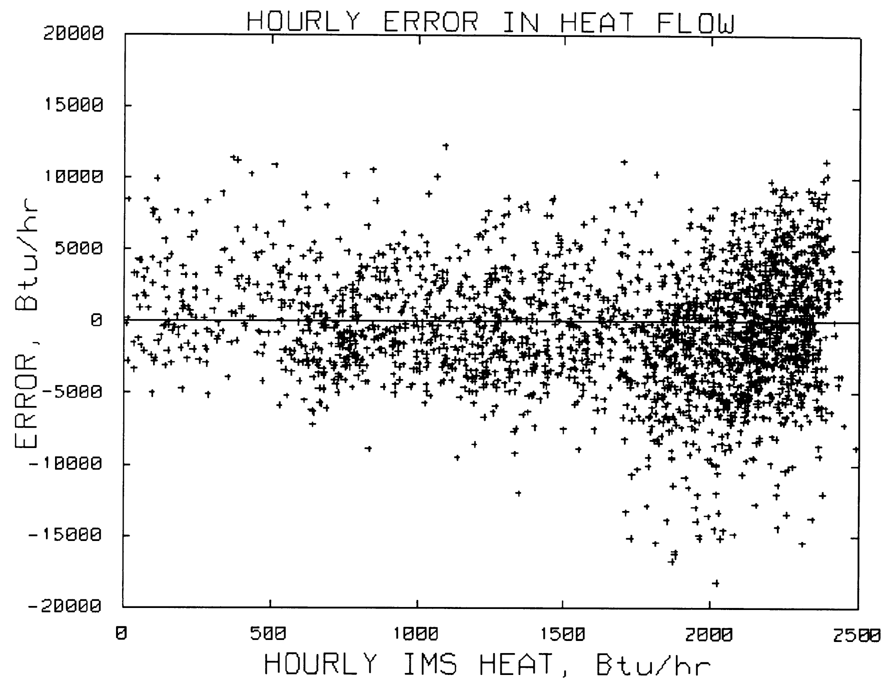


Figure 17. Plot of the hourly energy-balance error for the 6 months of winter versus the hourly IMS non-hot-water power.

Notes on Table 3.

1. The allocation of heat between “internal gains” and “back-up heat” is based on continuing internal gains at the summer levels throughout the year.
2. The calculation of Q_{air}, the heat required to warm the air drawn in by the IMS system, is based on the inside-outside temperature difference, the number of hours the IMS system is on, and the heat capacity of 100 cfm of air. The IMS operates 840 hours to heat water and 1040 hours for space heating.
3. Venting is the energy imbalance. The imbalance for the December through February time period is nearly zero. It is plausible that windows would not have been opened much, if at all, during this mid-winter period, but that windows would more likely be opened in October and March, when the temperatures are milder and the house might become uncomfortably warmer.
4. The “direct-gain net” value is the transmitted solar gain minus the calculated heat loss through the window (using the nominal window U-value of 0.35 Btu/h•°F•ft^2).

Table 3. Energy Balance for October through March

	Measured	Measured	Predicted	Comments
Heat Required	**kBtu**	**kWh**	**KWh**	
Envelope heat loss	19,722	5681	9893	U × (T_h - T_a)
Floor heat loss	2332	683	2418	
Q_{air} (DHW)	2130	624		Domestic hot water
Q_{air} (space heat)	2638	773	1002	Infiltration
Venting	1601	469	548	Open windows
Total heat required	28,423	8330	13,861	
Heat Supplied	**kbtu**	**kWh**	**KWh**	
Internal gains	8050	2359	2472	
Baseboard electric	5691	1668	1654	
IMS space heat	1435	421	NA	
Trombe wall net	4296	1259	2845	
Direct gain (gross)	8951	2623	6890	
Total heat supplied	28,423	8330	13,861	
Direct-gain net	3318	972	2435	
Total back-up heat	7126	2089	1654	

U = Building loss coefficient
T_h = House temperature
T_a = Ambient temperature
Q_{air} = Energy needed to heat exhaust air

Interview with the Residents of the Grand Canyon House

On August 8, 1998, Ed Hancock and Doug Balcomb of NREL conducted a telephone interview with one of the residents of the Grand Canyon house. They had intended to speak with both residents—a husband and wife who both work with NPS—but the wife was unavailable. The interviewers explained that they were interested in determining how satisfied the residents were with the house and in identifying any particular problems that might not have surfaced during the monitoring.

Initially, it was difficult to get the resident to discuss the energy aspects of the house. His primary concern was with the design of the building—room size, layout, traffic patterns, and so forth. It was apparent that he was not particularly happy with the design, as he continually voiced that concern in the interview. It would seem that his general dissatisfaction with the home influences his sense of thermal comfort as well. Some answers seem ambiguous—first stating a preference for cooler temperatures in the winter, then complaining about it being too cold, and then expressing an unwillingness to turn up the thermostat.

The resident apparently expected the house to maintain a high comfort level without the use of any auxiliary heating and seemed concerned that they had found it necessary to use the electric heating system at all.

The interview confirmed one issue that seems to arise regularly in any discussion of energy use for heating and cooling—the disparity between individual perceptions of comfort. The interviewee seemed to have been comfortable in the winter even though indoor temperatures sometimes fell below the traditional comfort level, whereas his wife was not comfortable at those temperatures. The choice to keep the auxiliary heating use to a minimum was, of course, entirely theirs. (Had the house been heated to a normal comfort level of 68ºF—a 3ºF increase averaged over the winter—energy use would have risen by about 1500 kWh for the year at a cost of about $150. This would represent a 17% increase in the annual whole-house electricity use.)

The interviewee asserted that both he and his wife were uncomfortable in the summer, even though the temperatures in the house were usually within the standard comfort level. This can be seen as an issue for many people in the United States who are accustomed to living in homes that are totally climate-controlled in both winter and summer.

See Appendix C for complete data on temperatures within the home. In summary, the house is very stable. The house daily temperature swings average 4.3ºF in July and 1.5ºF in January—much less than in a typical house. Normally, these average swings are more pronounced downstairs. The average house temperature is 75ºF in July and 64ºF in January. The difference between rooms is not large—typically less than 4ºF. Day-to-day variations in average temperatures usually do not exceed 4ºF. The greatest extremes are in the east-upstairs bedroom, which was used as the master bedroom, where the average temperature is 76ºF in July and 64ºF in January. The highest temperature recorded anywhere is 84ºF in the upstairs bedroom in July. Except for a few days in January when the downstairs bedroom was left unheated, and the temperature in that room dropped to 55ºF (when the ambient temperature dropped to 1.3ºF), the lowest temperature experienced anywhere in the house was 58ºF.

Excerpts from the Interview

Hancock: Could you describe your general level of satisfaction with living in this house and would you point out features that you like most about the house?

Occupant: Satisfaction?… The design is great, but my biggest problem with this house right now is summertime when the heat is extreme on the upper level of this house. Again, satisfaction on design and layout is great!

Hancock: One of the thoughts that I had was to ask you to compare the features of this house with other houses that you recently lived in. In particular, are there any features that you would specifically avoid in a future house?

Occupant: Inside, the rooms are really small compared to where we were to the point where you can’t even put a bed or telephone and everything else in the order of which you would normally have one. A nice feature [is] having a bedroom or an office downstairs where you had your two bedrooms upstairs, but again the bathroom upstairs is extremely small. Garage**:** no problem except I think insulation would have been helpful.

Hancock: How [do] you use the downstairs bedroom?

Occupant: For guests. I'm going to have the director of the Park Service here this week and he is going to stay here, but it is, again, extremely small. But yet, you have a bathroom nearby so they can have some privacy. Some of the features that are probably not your problems but in the dining area, the light fixture is in the wrong place and things like that.

Hancock: Well, we would be interested in any comments you had on other than energy features if you feel they are important.

Occupant: I think the upstairs, again, is extremely hot! We suffer all summer. They put a fan in the bathroom which to me is just an exhaust fan and it isn't any help for us at all. In fact, I told my wife that we ought to have an air conditioner up there. It is really tough for us for sleeping.

Hancock: Can you give an estimate for how many weeks the uncomfortable condition exists?

Occupant: Probably 12 weeks!

Hancock: So June, July, and August?

Occupant: Yes!

Hancock: And high temperatures are daytime and nighttime?

Occupant: Yes!

Hancock: How about the downstairs temperatures?

Occupant: The downstairs seems comfortable as long as we are in the house and open the doors.

Balcomb: I'd like to follow a bit on the temperatures upstairs. Of course we have those temperatures measured. [See data plots in Appendix C.] The high temperature that we recorded in the upstairs west bedroom was about 84º. The typical high that we saw in June or July is about 80º and so I'm a little surprised that it is a big problem. I take note of it and…

Hancock: Well, here is my side comment. I think the house is intended for you and Marie to be comfortable and I think that since this has come up as an issue and you and I have talked about this since last year, we would recommend to try some further remediation for that problem. You are not supposed to experience discomfort.

Occupant: Oh, it is really… like tonight, right now, it is probably 80º and that is not really healthy for us.

Hancock: OK! One of the ways of dealing with higher temperatures in the summer is cross-ventilation and it may be that part of the problem here is a design issue. Just looking back at the plans…

Occupant: That west bedroom is, I think, is the hottest room in the house because it is upstairs to start with and it has north-facing and west-facing window that gets the most sun in the afternoon.

Balcomb: Is that the room that you use for sleeping?

Occupant: Yes! We have opened the windows that we can in all of the bedrooms and on the stairwell and it is still not doing it!

Balcomb: It's probably pretty still in the evening.

Occupant: Definitely!

Hancock: What kind of window coverings do you use and how do you adjust window coverings?

Occupant: We don't! We keep everything open. Again, we like the sun, we like the stars, so we keep everything open.

Hancock: We have talked about the problem with comfort in the summertime. Could you describe your comfort in the winter?

Occupant: I really think you should talk to Marie because I like things cold. We walk around the house definitely with sweatshirts on. She is not comfortable, but I am.

Hancock: OK!

Occupant: You have to remember that there is just two of us. We don't have kids and I would say that if anyone lives in this house with children, the utility bills would be greater than what they are without…

Balcomb: Yes. We noticed [in the data] that the average temperatures in the winter are in the range of 64º/65º, and certainly when we did our predesign analysis, we had it up around 68º or 70º, and that would be more typical. It is fine that you keep it cooler, but you are absolutely correct that helps you on the energy bills.

Occupant: But I am comfortable and Marie is not.

Hancock: In the winter do you notice, or are there hot spots in the house?

Occupant: I would say definitely that downstairs the tile and everything else is cold.

Hancock: You mean the floors?

Occupant: Yes! Upstairs is probably a little bit warmer.

Hancock: Part of that questions is: Are you aware of the Trombe wall? Inside? It makes a difference?

Occupant: No! I don't think it works! I don't think the Trombe wall heats the floor or heats the house to what you think it should.

Hancock: Well, we are aware of that. So, if you are sitting in your living room?

Occupant: We're cold!

Hancock: OK.

Balcomb: Would you prefer to set your thermostat at a different temperature?

Occupant: Probably should, but we don't because we are trying to experiment with what you have here and trying to make it work and unfortunately, I don't think it does.

Hancock: One of the things that we are thinking about is to continue our monitoring and we wanted to ask you if that would be OK!

Occupant: You know me! It is fine with me. I think we in the Park Service need to find better ways of doing this and I look at my neighbors and their utility bills and remember that there is just Marie and I don't think what we have here is the answer totally. We need to do some other things with these homes.

Hancock: What sort of things do you have in mind?

Occupant: I don't know! You are the experts. I don't think the Trombe wall is working. I think that as much sun as we have, especially in the wintertime is great, but yet I think we are cold here in the wintertime and hot in the summertime.

Hancock: One of the things that I would be interested in doing in the future tests is to make sure that you and Marie are more comfortable and try some operational choices that can improve your comfort and see what effect that does have on the utility bill. So, I think that after Doug and I review the discussion with you tonight, we may come up with some proposals that would be possibilities for different ways to operate the house next year and responding to the specific information that you are giving us.

With regard to the present operation of the house, we have talked a little bit about how you use the thermostat, but do you use the thermostat in particular from room to room?

Occupant: You mean the electric?

Hancock: Yes.

Occupant: Very seldom do we use the electric in the rooms. In the bedroom maybe more so than anywhere else and in the livingroom with the TV and so forth, we put it on. Other than that, we don't.

Balcomb: Did you change the settings between day and night or leave the thermostat set?

Occupant: We leave it set.

Hancock: That seems like a good way to do it. Doug, do you agree?

Balcomb: Yes! I certainly do.

Occupant: Now, if we get company like the director here, if it is too hot or cold, we make adjustments. Other than that, we keep the room down in temperature.

Hancock: It seems like an appropriate way to use the thermostat, but I think you are welcome to experiment and see what provides the best comfort for you.

With regard to the integrated mechanical system (IMS), how do you operate the thermostat for that unit?

Occupant: I very seldom touch it in either the summer or the winter. I let it do its thing.

Balcomb: Are you aware of whether or not there is warm air or cold air coming through the vents?

Occupant: Oh! I definitely do and we make adjustments like right now: we are having the air go in right now to try to cool the house down.

Hancock: Do you find that to be effective cooling in the house?

Occupant: Downstairs only.

Hancock: But, you do notice that it is at least somewhat effective in cooling the downstairs?

Occupant: Yes! Definitely.

Hancock: And, in the wintertime, is that system used for heating the house?

Occupant: Yes!

Balcomb: Do you notice warm air coming into the downstairs?

Occupant: Yes!

Hancock: With regard to the integrated mechanical system, do you find that it provides adequate quantity and temperature of hot water?

Occupant: Yes, we have!

Hancock: So you have never had a problem.

Occupant: Yes, we have! Don't ask any questions.

Hancock: We want to know good and bad about it.

Occupant: We have had a number of occasions where there is a lack of hot water but I would say that they have been few and far between.

Hancock: Are they associated with any particular events like more people in the house or...

Occupant: I don't [know] why. I would say that 6 months ago we were away for a week and came back and there was no hot water. Strange! In the early stages of moving in here, of course, we had that problem, but it was really funny: I would say that 6 months ago we were away and came back and it was cold for some reason. It then recovered.

Hancock: "A miracle occurred!"

Occupant: Again, I keep that system where it is: you have that button on top for the hot water: and I keep it up to heat it all.

Hancock: Can you describe how you set those things on the system?

Occupant: The only thing that I change, Doug, is that there is a button on the hot water heater and I make sure that it is heating the whole tank.

Balcomb: It is a little bit confusing here. That button is labeled. What mode do you leave it in?

Hancock: I think it is high. It is interesting. I always have to look at the book.

Balcomb: It's backwards from what you read.

Occupant: Yeah! It may be.

Hancock: Well, that switch is set too high. Is that right?

Occupant: Yes! To heat the whole [tank]. I have been getting advised to do it the other way and I won't do it because I am satisfied with what we are getting for hot water.

Hancock: I think that it is a satisfactory answer for us. Is that right, Doug?

Balcomb: Yes!

Hancock: Another function of that system is to provide ventilation for the house. Do you have a perception as to whether adequate ventilation is provided?

Occupant: No! I don't think it does. I really don't.

Hancock: You would believe that there should be more ventilation?

Occupant: Yes!

Hancock: Are there particular things that lead you to believe that like condensation on windows or things like that?

Occupant: Yes! Heat in the house or cold in the house.

Hancock: How about things like odors or feeling of stuffiness?

Occupant: No! Not really.

Hancock: Well, it is certainly adjustable to provide different levels of ventilation, and I think the way we left that was in a condition that we thought was appropriate but depending upon your perception of whether it is adequate or not, we may be able to adjust that. It may be that it has already been adjusted by Tom [Dressler] or others to try to provide better service.

Occupant: I think our biggest problem is the upstairs level where we have the heat in the summertime and it is cold in the winter, unless we turn on the electric and that shouldn't happen—it really shouldn't. I would like to see this house taken care of without the electric—you know, the baseboard—and just be comfortable, And I think if I had children in this house, it would be completely different than just the two of us and we work all day. My wife was talking to one of the girls from work the other day. She [my wife] is from Louisiana and it was like 80º outside and she was just dying of heat. She said that the truth is, I have never lived without air conditioning. It's going to be a

Hancock: We have covered the questions on the IMS systems, questions regarding the appliances, in particular the dishwasher and clothes washer. Could you give an estimate of how many times per week the dishwasher runs?

Occupant: Probably five.

Hancock: Would that typically be morning or evening?

Occupant: Evening.

Hancock: On a typical week, how many loads of clothes might be washed?

Occupant: You are asking me something that is really out of my ballpark.

Hancock: Do you know if anybody in the neighborhood uses a clothesline?

Occupant: Probably one or two neighbors.

Hancock: Is your present electric bill higher than, lower than, or about the same as other houses that you have recently lived?

Occupant: Total utilities? Electric? Gas? I would say lower.

Hancock: What are you comparing with?

Occupant: Comparing a home in Omaha, Nebraska, where it is a little colder. We had as much as 50º below in winter. In the summer we had very high temperatures and humidity, so I'm saying that our utilities here are cheaper than there.

Hancock: Do you have an idea of how your utility bill compares to other houses in the neighborhood?

Occupant: I think we are lower. Again, I don't match my neighbors, but I think we are. I think my neighbors need to learn how to use the systems.

Hancock: Do you have any discussions with the neighbors? Is this a topical conversation?

Occupant: Yes! I think there are some neighbors [whose] utility bills are about the same as mine, that know how to use the system.

Hancock: Those are all of the particular questions that I had on the list. Are there any other items that you would like to talk about?

Occupant: I would just like to see us find systems that would reduce the utilities but make people comfortable, and I think we are almost there, but we are not there. Deal with people with families.

Hancock: We appreciate you and Marie for being "guinea pigs."

Occupant: I appreciate you, Ed, for the work that you are doing. I think that it is important for us.

Hancock: And, again I would say, that it is not our intention at all for you to be uncomfortable and I think that we want to invite you to make adjustments that would make you more comfortable, and I think you and I will get together and possibly come up with some suggested follow-up.

Balcomb: If you looked at our draft report, this is a pretty unusual house—incredibly tight, low infiltration—one of the tightest houses we have ever measured. It is different than your neighbor's house in that regard. It is better insulated and probably much tighter in terms of air leakage and if you were not aware of that, I think maybe...

Occupant: I know this home is tight. There is no question about it.

Balcomb: One of the things that should be fairly evident is that it is fairly quiet. If it is windy outside or something, you probably don't notice that so much.

Occupant: The only area of this house that is not tight is the entrance way and in the winter time we have to stay out of that area where we have a closet which is extremely cold in that area of the house where you come in. It's really bitter. Even our coats. If we leave our coats in the wintertime in that closet, we go to put them on in the morning and it's cold. Really cold! So what we do is close the doors and put the coats inside the house.

Hancock: At one time there was an issue of missing insulation in the ceiling in that area.

Occupant: If they corrected it, it doesn't have any impact.

Hancock: Is there an electric heater in that area?

Occupant: Yes! We try to keep that on like 68º maybe, but it is like you are outside.

Hancock: Well, there could very well be something wrong with the house there.

Occupant: Right. But for tightness, I would say the rest of the house is pretty good.

Balcomb: I'd like to ask a little bit about one of our biggest quandaries with this house and that is the fact that you not getting the solar gain, the heat from the sun, that we expected. That is very clear from looking at the results, and one of the purposes for further monitoring is to try to track that down a little bit. We are observing that the solar gains are about half of what they should be and that makes a pretty profound difference on the house. If you had the solar gains that we expected, it would be much more like what you want it to be, that is, you would need almost no back-up heat. One of the purposes for keeping going is to try to track that down. Early on we had some discussions about the trees. I don't know whether you got involved in those discussions.

Our conversations were all with Tom Dressler about those, and we were worried that it might be a sensitive subject and we didn't want to come on heavy-handed. Quite frankly, it was oversight in the initial planning that there are any trees on the south. I was promised by the designers here in the service center that we would have a clear, unshaded south side of the house and was somewhat taken aback when we found out that there was a ponderosa out there on the southeast just off the lot. And I guess some trees were cut down. I'd appreciate your impression. The house still gets quite a bit of shade in the winter from those trees in the mornings, in particular, and we don't know, actually, how much of this diminished performance to ascribe to the shading. It is one of the things that we would like to find out by a little bit more careful evaluation.

Occupant: I really don't believe… I mean I love the trees, but you could cut them all down and maybe it would make some improvement, but I really don't think the trees are your problem. I really don't... a couple of trees [were cut] down that, in my opinion, went into the kitchen area of that panel that had a dishwasher and cabinets in front of it and it had no impact on the heat of this house.

Balcomb: I agree with that. The heat that goes into those cabinets keeps the pots and pans warm but it doesn't keep you warm.

Occupant: Right! It doesn't do anything for me. I am saying that what I see from this house, from the sun, was getting enough to heat that thing: the panel: but it is just not doing the job. Again, if we are in the desert and I cut them all down, we will probably make an improvement, but very little.

Balcomb: We are not going to come in and try to dictate whether you cut down the trees at your house, but we can probably advise you as to the consequences, and part of the purpose of the continuing evaluation is to get a better fix on that.

[The conversation from this point on related to future monitoring and is not recorded here. We thanked the occupant for his and his wife's help and patience and for the interview.]

ENERGY-10 Evaluation

ENERGY-10 is a design tool for low-energy buildings—generally 10,000 ft^2 or less—that can be characterized by one or two thermal zones. It features the integration of daylighting, passive-solar heating, and low-energy cooling strategies with an energy-efficient shell design and mechanical equipment. Although the program was developed primarily for evaluating nonresidential buildings, it is also applicable to residences (Clyne 1996; Clyne and Bodzin 1997; Balcomb 1997; Balcomb and Prowler 1997).

ENERGY-10 employs a thermal simulation engine that solves the energy balance equations using a thermal network approach. It is very similar to the technique used in the pretest analysis.

Weather Data

A special weather-data file was prepared based on the measured data. Researchers started with the TMY2 weather file for Flagstaff and used the WeatherMaker program to adjust the monthly-mean daily high and low temperatures to match the values measured at the house site. As noted earlier, the solar radiation values are nearly identical to the long-term values measured in Flagstaff. Thus, although the hourly temperatures are not the same as those measured at the site, the monthly-mean temperatures are correct and the solar-mean radiation values are very close.

This procedure was followed because three variables required to produce a weather file were not directly measured at the site—the dewpoint temperature, the diffuse solar radiation, and the direct-beam solar radiation.*

ENERGY-10 Model

The ENERGY-10 model was devised to replicate the actual conditions as closely as possible within the fixed structure of the program. The house geometry is modeled using the same area takeoffs that were calculated during design. The key parameter that is matched is the measured BLC, which is adjusted by fine-tuning the wall R-value. As in the STEM measurement of BLC, the value of 149 Btu/h•°F excludes the floor. The infiltration ELA was set to zero because this effect is subsumed in the BLC.

The window SHGC was reduced 41% from 0.56 (the original double-glazing value) to 0.33 to be consistent with the measured effective solar transmittance of 0.33, as discussed earlier. Because ENERGY-10 cannot simulate a Trombe wall, it was replaced with the same area of direct gain. This should have the effect of increasing the house temperature

* It would have been possible to estimate the missing solar variables based on the measured south-vertical solar radiation together with the global-horizontal radiation in a manner very similar to that developed by Burch for the STEM software. The dewpoint temperature could be estimated by developing a correlation between relative humidity and the solar-clearness index (K_T) using data from the TMY Flagstaff weather file. These adjustments would have entailed a major effort incommensurate with the benefit.

swings but should not affect the back-up heat because the direct gain and Trombe wall are about equally effective in reducing back-up heat.

The internal gains were adjusted to achieve a total-electric-use hourly schedule that matches the measured summer schedule and a total electric use of 16.08 kWh per day (corresponding to an annual use of 5869 kWh if maintained constant throughout the year). This was done by: (1) setting internal and external lights to zero; (2) adjusting the schedule of hot-water electric use to correspond to the measured schedule of average daily summer IMS electric use in the house and adjusting the corresponding peak value to result in a total hot-water input heat of 3.12 kWh per day; and (3) adjusting the schedule of "other" electric uses—which includes lights—to correspond to the schedule of average daily summer electric use in the house (excluding the IMS) and adjusting the corresponding peak value to result in a total internal gain of 12.96 kWh per day.

The actual house temperature varies throughout the year, whereas ENERGY-10 requires the same thermostat setting in each month. A setting of 66.3ºF was used to obtain a winter average. (66ºF is the degree-day weighted average of the monthly house temperatures during the October through April period.)

The HVAC system used was a baseboard-electric system with an efficiency of 100%. This was used because (1) ENERGY-10 cannot model the IMS system, and (2) the IMS system does not seem to make much of a difference in the house performance.

Simulation Results

The simulation results for the total predicted annual electric energy use were 8790 kWh; 5869 kWh were for internal gains and 2921 kWh for back-up heat. For the October through March period, the back-up heat is 2673 kWh. (The difference is primarily April heating.) This back-up heat can be compared directly to the 2089 kWh estimated in Table 3 because the two values are derived based on the same assumption—that the internal gains are constant throughout the year. The difference, 584 kWh, represents only 7% of the total house energy flow.

<u>Sensitivity to SHGC</u>

When the SHGC is set to its nominal value of 0.56, the annual predicted back-up heat drops from 2921 kWh to 1090 kWh. This demonstrates that the performance is very sensitive to the SHGC, as expected. The two performance values bracket the measured value of 2089 kWh.

<u>Sensitivity to Thermostat Setting</u>

When the thermostat is changed from 66.3ºF to 68ºF, the pretest assumption, the annual back-up heat increases from 2921 kWh to 3431 kWh, indicating a strong sensitivity to thermostat setting.

<u>ENERGY-10 Simulation using Preconstruction Assumptions</u>

An ENERGY-10 simulation was made with conditions set to duplicate as many of the preconstruction assumptions as possible.

- The thermostat was set to 68ºF.

- Internal gains were changed to 8.77 kWh per day.
- The wall was changed from 10-in. SIP to 8-in. SIP.
- The SHGC was set at 0.56.
- The infiltration ELA was set to 66 $in.^2$
- The simulation was run for the 6-month period from October through March.

With these changes, the predicted back-up heat is 4211 kWh, which compares to 1654 kWh predicted prior to construction. The difference is primarily a result of the difference in building heat loss coefficient, but also reflects differences in the effectiveness of solar gains.

The results of the “measured” and “predicted” ENERGY-10 simulations are presented in Figure 18 and Table 5.

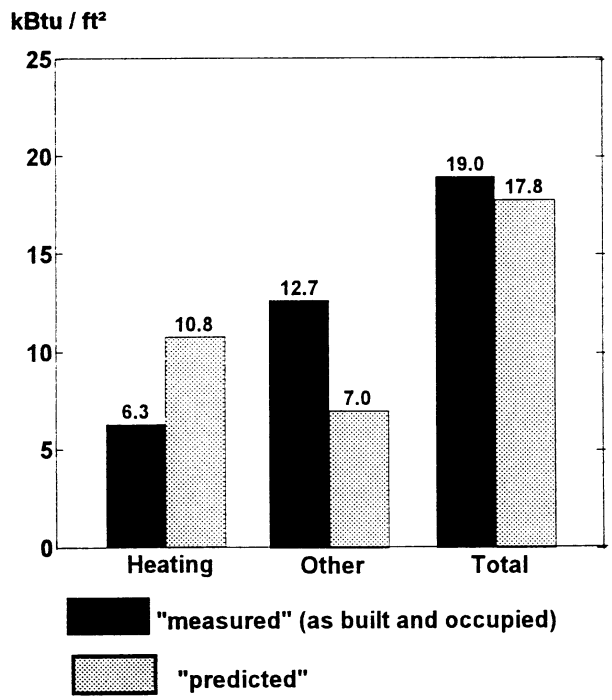


Figure 18. Annual energy use calculated using ENERGY-10, showing the best estimate of the house as built and as occupied and the preconstruction predictions.

Table 5. ENERGY-10 Simulation—Grand Canyon House

Description	Measured	Predicted
Floor area, ft²	1582.3	1582.3
Surface area, ft²	3966.8	3966.8
Total conduction UA, Btu/h•ºF	200.6	212.2
Average U-value, Btu/h•ºF•ft^2	0.051	0.053
Conduction UA, Btu/h•ºF, w/o TW* and floor	149.0	
Wall construction	10-in. SIP, R=36.6	8-in. SIP, R = 29.5
Roof construction	10-in. SIP, R=36.6	10-in. SIP, R = 36.6
Window construction	Grand Canyon, U=0.32, and so forth	3040 double, low-e, U=0.33, and so forth
Wall total gross area, ft²	1880	1880
Roof total gross area, ft²	1087	1087
Ground total gross area, ft²	1000	1000
Window total gross area, ft²	312	312
Windows (N/E/S/W:Roof)	3/3/18/2:0	3/3/18/2:0
Glazing name	Grand Canyon, U = 0.26	double low-e, U = 0.26
Operating Parameters for Zone 1		
HVAC system	Baseboard electric heat	Baseboard electric heat
Rated output (Heat/SCool/TCool), kBtu/h	17/0/0	23/0/0
Heating thermostat	66.3°F, no setback	68.0°F, setback to 66.3°F
Peak gains; HW, OT; W/ft²	0.17/0.45	0.17/0.20
Infiltration, in.²	Included in BLC	ELA = 66.0
Simulation dates	01-Jan to 31-Dec	01-Jan to 31-Dec
Energy use, kBtu	30,009	28,156
Total electric, kWh	8794	8251
Internal/External lights, kWh	0/0	0/0
Heating/Cooling/Fan, kWh	2921/0/0	4989/0/0
Emissions, CO_2/SO_2/NO_x lbs	12,092/69/36	11,345/65/34

*TW = Trombe Wall

Comparing the House with a CABO-MEC House

Within NREL's low-energy building research activities, it is standard practice to compare the performance of the building with a code-compliant building of the same size, located in the same climate, built in accordance with the Model Energy Code (MEC) of the Council of American Building Officials (CABO). Where the CABO-MEC criteria were not specific, the Home Energy Rating System (HERS) criteria were used. The comparisons were made using the same standard operating occupancy conditions (thermostat settings and internal gains).

Researchers started by adjusting the ENERGY-10 model described above to exactly replicate the back-up heat measured in the Grand Canyon house. This required only a minor adjustment, because the 2673 kWh of back-up heat predicted by ENERGY-10 is only slightly greater than the 2089 kWh of back-up heat measured during the October through March time period. The adjustment was made by increasing the window SHGC from 0.33 to 0.40.

Reference House Definition

Researchers created a house that exactly corresponds to the MEC standards for a 6500-degree-day climate. Wall and window area takeoffs are the same as those for the Grand Canyon house. This requires (prescribed values shown in italics):

1. *Glass area = 18% of the floor area equally distributed on all four facades.* This gives 71.2 ft^2 of glass per facade, corresponding to seven windows with 10.17 ft^2 of glass each. Researchers created a MEC 36" x 48" window with this glass area. *The glass SHGC is 0.55.*
2. *Overall wall U-value = 0.118 Btu/h•°F•*ft^2. To achieve this, researchers used a 2" x 6" wall (R17.7) and adjusted the window U-value to 0.36. As in the Grand Canyon house, there are two foam-core exterior doors.
3. *Roof U-value = 0.026* (R-38).
4. Perimeter insulation = 1 in. of foam (f-factor = 0.4 Btu/h•°F•ft^2). *R= 5.329.*
5. HVAC system of the reference house is an electric forced-air system with 100% heating efficiency, a COP of 1, no duct losses, and no fan energy requirements. This idealized model allows us to identify the thermal loads of the house, not muddied by the performance of the HVAC. The HVAC of the Grand Canyon house is electric baseboard without cooling because there was no overheating in the house despite having no cooling system. Although not specifically analyzed in this report, this good performance is no doubt a result of a successful passive cooling strategy that utilizes east and west tree shading and natural ventilation.

Occupancy Assumptions

Researchers then ran both houses using *identical standard occupancy conditions*. Researchers selected 70ºF as the heating thermostat setting and 78ºF as the cooling thermostat setting. The internal gains are the standard default schedules and peak values that are used in ENERGY-10. These replicate the national average residential energy use for lights, hot water, and appliances (Balcomb et al. 1994). The annual totals for each are 1243 kWh, 4536 kWh, and 6739 kWh, respectively, totaling 12,518 kWh (27,000 Btu/ft^2) for all three. In the ENERGY-10 model, only 31% of the hot-water energy is deposited in the house, the remainder being removed from the house via the drain. The 31% fraction accounts for typical standby losses from the tank and thermal and latent exchanges resulting from hot-water use.

Results

The ENERGY-10 annual simulation of the two houses produced the results shown in Figure 19. Heating loads are reduced by 67%, and cooling loads are eliminated. The combined heating and cooling loads, the measure used in low-energy buildings research activities, are reduced by 75%.

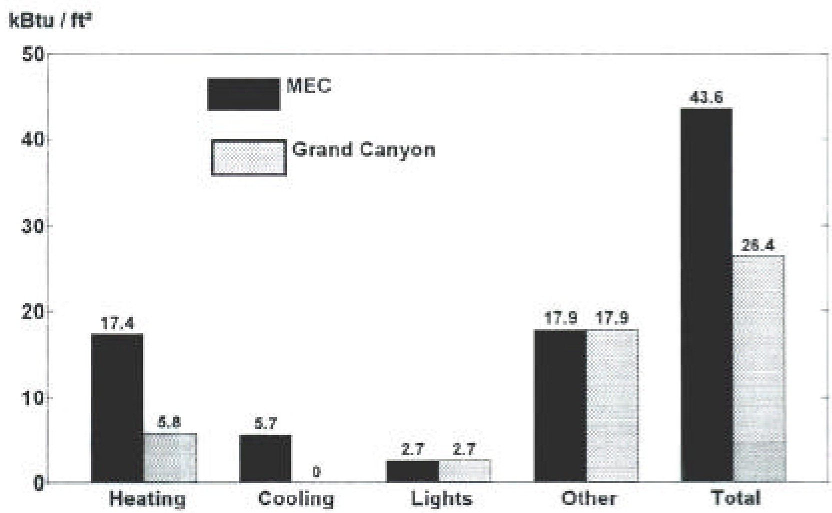


Figure 19. Annual energy use calculated using ENERGY-10, showing the best estimate of the house as built and as occupied and the preconstruction predictions.

Conclusions and Recommendations

Conclusions Regarding Grand Canyon House Energy Performance

1. The Grand Canyon house is an excellent energy performer. The overall annual energy use in 1997 was 29,203 Btu/ft^2, which represents a reduction of 46% when compared with the national average of 54,500 Btu/ft^2 (Balcomb et al. 1994). Most of the energy consumed was for normal internal gains—lights, water heating, and appliances. The primary goal of this project, to reduce heating energy, was met. The estimated annual heating energy was 1405 Btu/ft^2, which represents a reduction of 84% when compared with the national average of 28,800 Btu/ft^2.

2. The primary reason for the excellent performance is an extremely low building loss coefficient—149 Btu/h•°F—significantly less than the design estimate of 186 Btu/h•°F (adjusted to be on a comparable basis). Part of the reason for the low actual BLC is that the walls were built using 10-in. SIP panels instead of the 8-in. panels used for the design estimate.

3. Passive solar performance was disappointing. Net direct-gain performance is only 40% of expected, and the Trombe wall contribution is only 44% of expected. Some of the poor performance is a result of the mid-winter morning shading by pine trees left standing to the southeast of the house. A minor factor affecting the Trombe wall is that kitchen cabinets cover the wall over part of its east end. Heat flux through this portion of the wall, which represents 30% of the area, is 40% of the heat flux through the western, unimpeded portion. Other factors that might be responsible for the poor solar performance are not known at this time.

4. Floor heat losses are small, representing only 12% of the envelope heat losses. This is probably a result of effective under-slab insulation. The IMS system provided nearly all of the heat for domestic hot water.

5. The STEM results proved to be vital in the data evaluation. Without the STEM test, researchers would not have been able to isolate the effect of the direct gain, which was determined by regression on the energy-balance errors.

6. Heating and cooling energy consumption was reduced by 75%, comparing the house as monitored with a reference house built in accordance with the CABO-MEC and HERS criteria and using standard occupancy assumptions for both houses.

7. It was very difficult to interpret the data from the house when it was occupied. This was exacerbated by the fact that the energy flows of interest were much smaller than the internal gains, which vary wildly in any occupied house. It was difficult to make sense of small signals in a background of large "noise." Had additional measurements been made, the task would have been easier and the results less ambiguous. Two particular measurements that proved to be vital were the temperatures measured in the Trombe wall and on both sides of the floor-slab insulation. Without these measurements, there would have been no way to separate the performance of these elements.

8. The instrumentation worked very well, with almost no data loss.
9. The cost of monitoring is dominated by the time spent in the analysis.

Observations Regarding Monitoring and Evaluation

It was difficult to work with the data. The problem is inherent in evaluating any occupied building but is amplified in this case by the low energy consumption of the house. The information desired regarding overall performance is buried within large fluctuations in the total power consumption that result from normal occupancy. The key problem is that the back-up electricity to the baseboard heaters and the heat contribution of the IMS system were not measured directly, leaving us in the situation of estimating these values through regression using a model. Had these numbers been available, the analysis would have not only have been much easier but could have been done with far less uncertainty.

Recommendations

1. Changes should be made in the data acquisition installation, and the monitoring should be continued for another year.
2. The cause of the poor solar performance should be investigated. This will entail taking more data during the next winter. The issue of the shading must be addressed, either by removing the trees (which may not be possible) or, as a less desirable alternative, by making several incident solar radiation measurements along the length of the south facade. Tests should also be done on the Trombe-wall glazing to determine its transmittance. This would entail removing one of the glazing units, which would not cause a problem in the summer. When this glass is removed, an additional measurement of the outside surface temperature should be taken (just under the selective-surface foil). If the glass is found to have a low transmittance, all the Trombe-wall glazing should be replaced with high-transmission glass, as originally specified.
3. To collect additional data, several more instrumentation channels should be added.
   - Back-up heat should be measured directly. (This is difficult because the electrical connections to the baseboard heaters are not grouped in the electrical distribution box.)
   - Hot-water consumption should be measured to evaluate the IMS performance. The IMS system should be set so that it only heats the water (i.e., the unit is never used in the space-heating mode). This will remove a critical uncertainty from the analysis.
   - One-time measurements should be made of the IMS system exhaust air temperature and the IMS exhaust airflow.
   - The ground reflectance should also be measured by installing a downward-facing pyranometer.

One additional STEM test should be performed during mid-winter. The period should include both sunny days and cloudy days and could be done when the house is unoccupied.

APPENDIX A. —THE STEM/PSTAR METHOD

Successful short-term energy monitoring (STEM) tests have been conducted on more than 100 residential buildings and six commercial buildings. The method provides a means of separating effects that tend to be mixed together in the conventional monitoring of building data. In the case of the Grand Canyon house, the STEM test provided an accurate measure of the BLC of 149 Btu/h•°F to determine other heat flows that otherwise would have been inextricably mixed with shell heat losses. This value excludes heat losses to the ground, which can be determined independently.

The term STEM refers to the test itself and the subsequent analysis. PSTAR refers to the mathematical formalism used to separate building energy flows into convenient categories (Subbarao et al. 1988). This separation allows the user to identify the three primary thermal characteristics of the building: (1) the BLC, (2) the effective building mass, and (3) the effective solar-gain area. An adjusted model can then be used to predict future building performance. The PSTAR method minimizes cross talk between the three characteristics, an important advantage.

An approximate thermal simulation model of the building is developed, based on a quick audit of the plans. NREL uses the SUNCODE simulation program (Palmiter 1985), although, in principle, one could use any simulator. The advantage of starting with a detailed simulation model of the building (instead of taking a black-box approach) is that known building characteristics amenable to direct observation are imbedded in the model. Of primary importance are the distribution of primary mass elements and the size, orientation, and shading of all windows. The former allows one to predict an appropriate mix of fast and slow dynamic responses; the latter allows data from a short-term test carried out during one season to be used to predict performance in another season, even though sun angles may be quite different. Accurate modeling of other details, such as thermal bridges and the effectiveness of insulation, is not as important because the BLC will subsequently be re-normalized.

In the PSTAR procedure, the heat flow into the room air is mathematically separated into nine terms relating to the effect causing the heat flow. This disaggregation of terms is unusual, but is central to the PSTAR method. During the test, these are the only terms considered. Therefore, if energy is to be balanced, the sum of the nine terms should be equal to zero at each hour. The sum is called Q_{net}, calculated as an hourly data stream throughout the test. Non-zero values of Q_{net} indicate the inability of the model to balance energy at that particular hour.

In a typical application, three of the major energy-flow terms are determined. This is accomplished by multiplying each of these terms by a constant re-normalization factor. The constants are chosen to force the average value of Q_{net} to zero during carefully chosen periods of the test. The re-normalization is done in three steps.

Step one is performed during a period of 2 to 4 hours at the end of a night when the inside temperature has been maintained in a reasonably steady fashion (i.e., the co-heating period). The dominant terms during this period are the heat input from the electric heaters and the heat losses by conduction and infiltration. Heat storage, solar, and other effects are small, but not negligible. The steady-state conduction term is multiplied by the re-normalization factor to achieve an exact energy balance for the co-heating period.

Steps two and three are similar. The energy-flow term caused by discharge of building mass is dominant during the cool-down period. The solar-gain term is usually large during the day-time hours. Re-normalization factors for these terms are determined based on the whole data period.

The three steps are repeated until the re-normalization constants stabilize. If the model is reasonably accurate, Q_{net} should be small throughout the test period. Root mean square values of Q_{net} for residential tests typically have been in the range of 100 Btu/h at night and 1700 Btu/h during the day.

APPENDIX B.—TROMBE WALL EVALUATION

Temperatures were measured at three points through the Trombe wall in two locations, one at at the west end (abutting the living room) and the other at the east end (abutting the kitchen cabinets). Inside surface, outside surface, and center temperatures were measured.

To evaluate heat flow through the wall, which is more interesting than the temperatures, researchers solved the one-dimensional diffusion equation for heat flow perpendicular to the wall surface. If the inside and outside surface temperatures are known, both the temperatures at intermediate points, as well as the heat fluxes at the surfaces, can be calculated. The method follows that of Balcomb (Balcomb 1981; Balcomb and Crowder 1995).

Theory

Consider a homogeneous wall section for which the wall height and width are much greater than the thickness so that the heat diffusion is primarily one dimensional. The wall is mathematically sliced into four slabs of equal thickness. (Any number of slices can be used, but it was convenient to use four slices in this case.) The surface temperatures, T_a and T_b, are known, and interior temperatures, T_1 through T_4 (located at the center of the slices), are to be determined. Lumped-parameter heat balances on each slice are as follows:

$\rho\ c_p\ \Delta x\ (dT_1/dt) = (T_2 - T_1)\ H + (T_a - T_1)\ 2H$ (inner slice)

$\rho\ c_p\ \Delta x\ (dT_2/dt) = (T_3 - T_2)\ H + (T_1 - T_2)\ H$ (second slice)

$\rho\ c_p\ \Delta x\ (dT_3/dt) = (T_4 - T_3)\ H + (T_2 - T_3)\ H$ (third slice)

$\rho\ c_p\ \Delta x\ (dT_4/dt) = (T_3 - T_4)\ H + (T_b - T_4)\ 2H$ (outer slice),

where: ρ = density; c_p = heat capacity

$H = k/\Delta x$; k = thermal conductivity

Δx = thickness of slice = L/4

L = wall thickness.

Each wall temperature on the right-hand side of the above equations is averaged over a time step, T_i is replaced by $(T_i+T_i')/2$, where T_i' is the temperature at the beginning of a time step and T_i is the temperature at the end of the time step. Each derivative on the left-hand side is approximated as $dT_i/dt = (T_i-T_i')/\Delta t$, where Δt is the time step (one hour in our case). The resulting equations can then be expressed in matrix notation as follows:

$$A \bullet T = B \bullet T' + C \bullet T_s$$

where the tri-diagonal matrices *A*, *B*, and *C* are dimensioned 4 x 4 as follows:

$$\begin{bmatrix} r & s & 0 & 0 \\ s & t & s & 0 \\ 0 & s & t & s \\ 0 & 0 & s & r \end{bmatrix};$$

where:

Matrix	r	s	t
A	2G+3H	-H	2G+2H
B	2G-3H	H	2G-2H
C	2H	0	0

where: $G = \rho\, c_p\, \Delta x/\Delta t$,

and the vectors *T*, T', *and* T_s are dimensioned 1×4 as follows:

$$T = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} \qquad T' = \begin{bmatrix} T_1' \\ T_2' \\ T_3' \\ T_4' \end{bmatrix} \qquad T_s = \begin{bmatrix} T_a' + T_a \\ 0 \\ 0 \\ T_b' + T_b \end{bmatrix}.$$

The solution is:

$$T = A^{-1} \bullet (B \bullet T' + C \bullet T_s)\ .$$

The matrix A^{-1} is calculated just once. The calculation proceeds as a marching solution of matrix multiplications. The initial wall temperatures must be estimated to begin the calculation (usually as a linear interpolation between T_a and T_b). The effect of errors in this estimate will die out with a time constant of about $\rho c_p L/6k$. This problem can be easily overcome by starting the solution a sufficient time prior to the time when heat fluxes are needed. The heat fluxes at the inner and outer surfaces, q_a and q_b, are as follows:

$q_a = 2H(T_a - T_1)$ and

$q_b = 2H(T_4 - T_b)$

Application to the Grand Canyon Trombe Wall.

For the wall, researchers used L = 6.8 in., ρ = 140 lbs/ft^3, c_p = 0.2 Btu/lb•ºF, and k = 1.0 Btu/h•ºF•ft^2. A plot of the temperatures in the west wall on December 25 is given in Figure B-1, showing the three measured temperatures as solid lines and the four calculated temperatures at the centers of the slices as dotted lines. This is a very sunny day. Note that the inner measured temperature is a good match to the second calculated temperature.

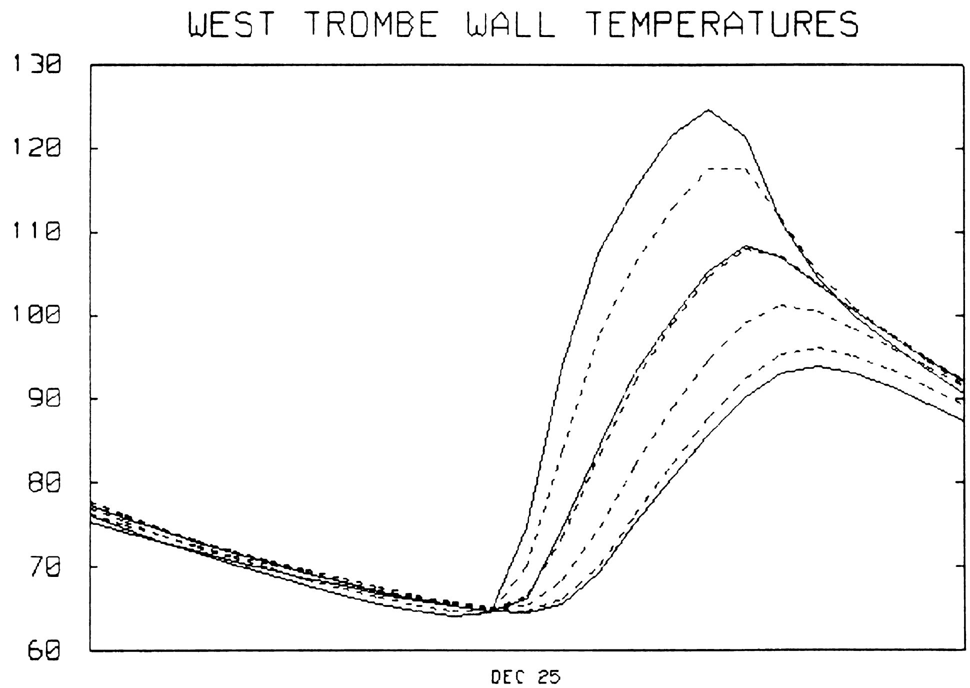


Figure B-1. Temperatures measured (solid) and calculated (dashed) in the Trombe wall (west end), ºF.

Researchers plotted many such curves for both the east and west walls for different days. The thermal conductivity, k, was adjusted until a good match was made (k = 1.00 Btu/h•ºF•ft^2) between the calculated and measured temperatures at the center of the east wall. The temperature measurement is at the center at the east end. This provides, in effect, an in situ measurement of the thermal conductivity. At the west end, as mentioned earlier, the forms failed during the pouring of the concrete with the result that the location of the "center" temperature measurement is not well known. It is apparently from an inspection of Figure B-1 that the probe is located slightly toward the outside, roughly at the center of the second mathematical slice. The close match of these center temperatures throughout the entire day gives us confidence in the calculation. The values of ρ and c_p are reasonable values for concrete. In any case, there is only one undetermined parameter, and researchers chose to use this degree of freedom to estimate k, which varies significantly from one batch of concrete to another. It is important to have a good estimate of k because the heat fluxes scale directly with it.

The calculated heat flux at the inner surface is shown in Figure B-2. Note that the heat flow into the room drops to a minimum at about sundown and peaks in the evening at about 9:00 p.m.. The heat flux at the outer surface is shown in Figure B-3, which also plots the solar radiation incident on the south side of the building. This plot clearly shows the effect of the morning shade. After about 10:00 p.m., the heat flux into the wall tracks the shape of the incident solar radiation. Plots like these in October and March, when the sun angles are higher, do not show this shading effect. The effect of the shading is greater on the east end than on the west end (about 1 hour longer).

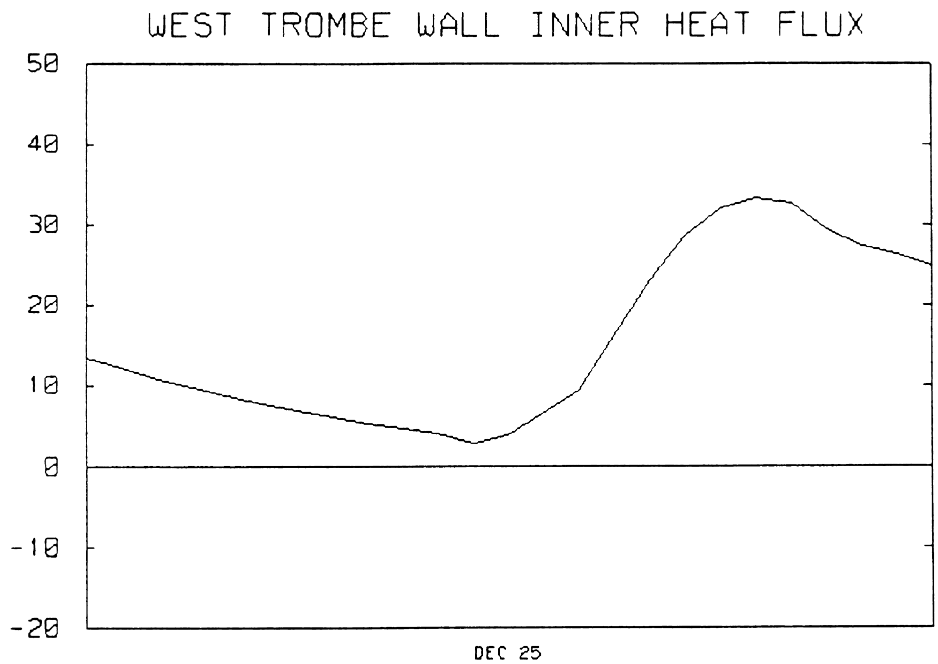


Figure B-2. Heat flux for 1 day, based on measured temperatures (west end), Btu/h•ft^2.

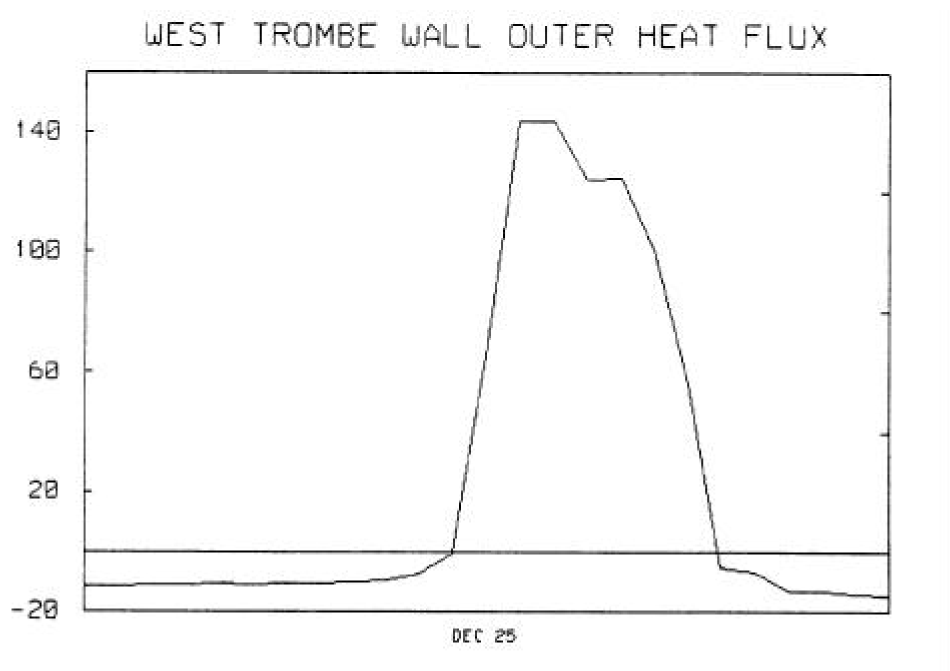


Figure B-3. Heat flux into the outer surface of the Trombe wall for one day, based on measured temperatures (west end), Btu/h•ft^2. The incident solar radiation on the vertical south-facing pyranometer is shown dotted.

This technique was used to calculate the heat fluxes throughout the year. Figure B-4 shows the heat flux from the Trombe wall into the room for 2 months in mid-winter. Note that at the end of a sequence of 3 or 4 days, the heat into the room drops to approximately zero. There is no significant heat flow from the room to the wall even after a protracted period of cloudy weather.

Table B-I and Figure B-5 show summary results of the calculated heat flow to the room for the west end for the entire year. This shows that the wall does not provide much heat to the room in the summer months (when it is not wanted) because of the high sun angles. The wall performance peaks in October, is quite high in November, February, and March, and drops somewhat in December and January (because of colder temperatures and shading). The average heat flux to the room over the 6-month period from October through March is 14.8 Btu/h•ft^2, which totals 64,290 Btu/ft^2. The same data for the east end of the wall, which backs onto the kitchen cabinets, show an average heat flux from October through March of 6.5 Btu/h•ft^2, which totals 28240 Btu•ft^2, just 44% of the west-wall performance.

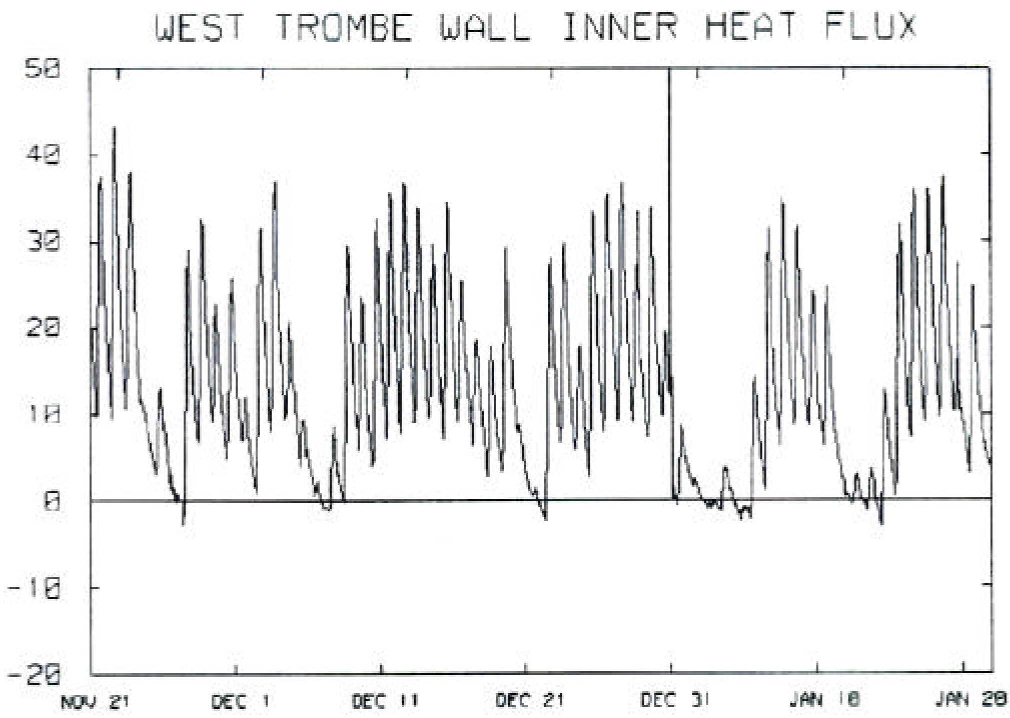


Figure B-4. Heat flux from the Trombe wall into the room for 2 months, based on measured temperatures (west end), Btu/h•ft^2.

Table B-1. Calculated Heat Flow to the Living Room, West End, for the Year.

GRAND CANYON HOUSE DATA (1997)
Channel # 25 QTWW

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	9.1	20.9	2.6	94.1	-2.8
2	15.3	26.4	6.9	38.6	-.1
3	15.3	25.4	7.9	36.2	4.6
4	7.0	11.3	3.2	16.8	-1.7
5	6.1	9.5	3.4	15.0	1.3
6	4.7	7.4	2.5	19.3	-1.6
7	5.7	9.0	3.4	23.5	1.3
8	6.9	11.2	3.7	31.3	-7.8
9	10.3	18.0	4.3	38.1	-30.6
10	18.6	32.2	9.0	42.9	-5.7
11	16.4	29.3	6.8	47.6	-3.8
12	14.1	25.8	5.3	36.9	-2.3
Year	10.8	18.8	4.9	94.1	-30.6

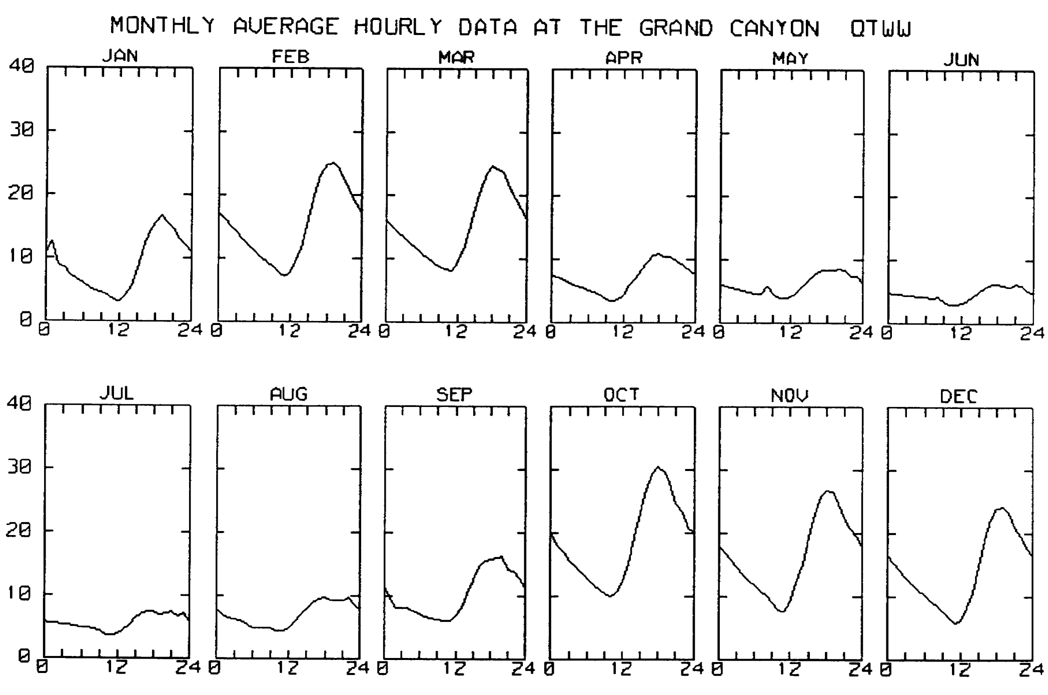


Figure B-5. Heat flux from the Trombe wall into the room for the entire year, based on measured temperatures (west end), Btu/h•ft^2.

Outer Wall U-Value Estimate

With the heat flux from the outside of the wall, the U-value from the wall surface to the ambient air can be determined using the equation:

$$U = (\text{heat flux, q})/(T_{surface} - T_{air}).$$

This estimate is not valid during the day when there is an added heat flux at the external surface casued by solar radiation. Figure B-6 shows the result of this calculation for December 25, showing an average U-value of 0.175±0.014 ^{2} based on 12 points. Figure B-7 shows results for 2 months; the average U-value is 0.174 ± 0.016 Btu/h•°F•ft^2 based on 731 points. The east wall gives very similar results—the 2-month average is 0.212±0.021 Btu/h•°F•ft^2. The difference between these two values is not significant given the uncertainties in wall characteristics.

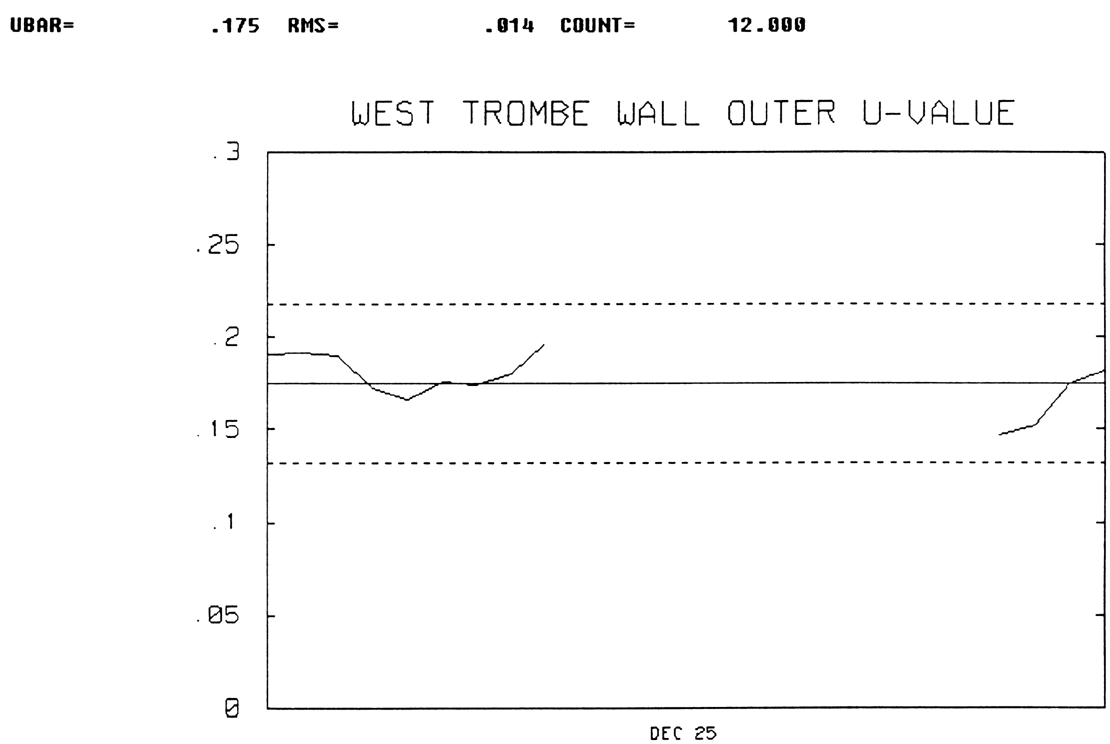


Figure B-6. Trombe wall exterior U-values for 1 day based on measured temperatures (west end).

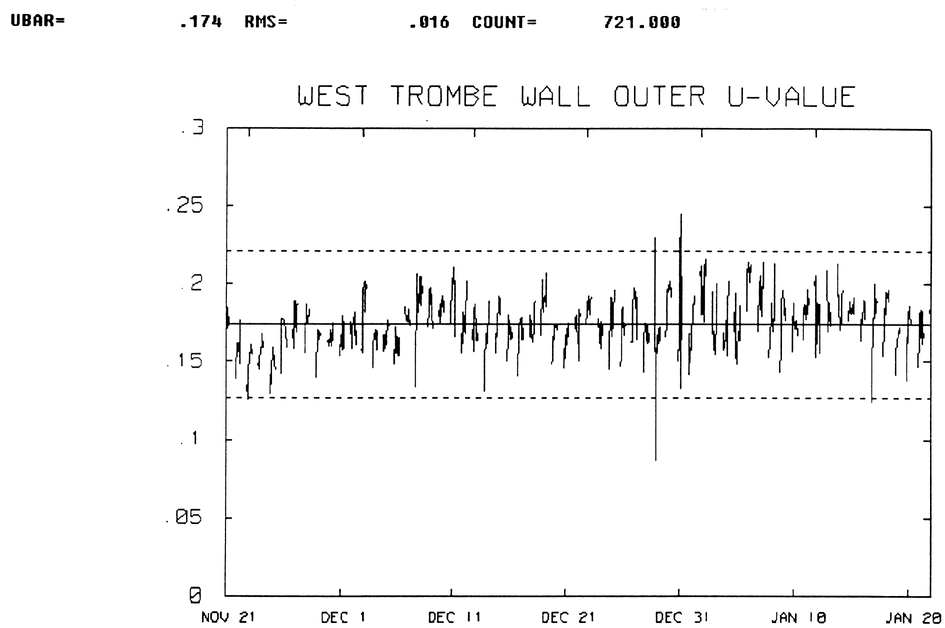


Figure B-7. Trombe wall exterior U-values for 2 months, based on measured temperatures (west end).

This low loss coefficient is not expected. Measurements made using the same technique in test rooms at Los Alamos, New Mexico, in 1981 gave values of 0.29 Btu/h•°F•ft^2 for the same configuration of double glazing and a selective surface (Balcomb 1981). It is possible that this discrepancy signals a methodological error in the data, indicating that the heat fluxes at the Grand Canyon are larger or that the glazing system is different than the system specified.

Inner Wall U-Value Estimate

In a similar way, researchers can infer the U-value from the inner wall surface to the room air. The same equation is used, substituting the inner wall heat flux, the inner wall surface temperature, and the living-room air temperature. The plots are similar to the previous plots of exterior U-values, except the numbers are larger. The resulting U-values, based on 2 months of data, are as follows:

West wall: U = 0.99±0.06 Btu/h•°F•ft^2

East wall: U = 0.50±0.08 Btu/h•°F•ft^2.

The value for the west wall is about as expected and a U-value of about 1.5 for radiation and convection combined is anticipated. A somewhat lower value could be attributed to the effect of a layer of drywall adhered to the wall surface. To explain the difference, the R-value of the drywall would need to be 0.35 h-ft^2/Btu. A 5/8-in. layer of drywall has an R-value of about 0.21. A less than perfect bond between the drywall and the wall could easily make up the difference.

The reason for the lower value on the east end is undoubtedly the presence of kitchen counters that back on the wall for the last 7 feet of the 32-ft length of the wall. To explain the difference, the effective R-value of the cabinets would need to be 1.25. This is a credible number for the effect of a dead air space, a layer of wood, and an air film.

The low U-value on the inner side provides the main explanation for the lower performance of the east wall compared to the west wall. Differences in shading of the two ends could easily account for the rest of the explanation.

These results highlight the importance of minimizing the heat-flow impedance between the outer wall surface and the inside of the room. Using a high-density material for the wall not only increases the wall heat capacity, but increases the wall thermal conductance. The best situation is one in which the inside wall surface is exposed directly to the room.

<u>Correlations between Delivered Heat and Incident Solar Radiation</u>

Researchers expected to see a direct relationship between the solar radiation incident on the wall and the heat delivered to the room. To study this, they integrated the data over 1-day periods by using a shifted day that starts and ends at 6 a.m. The reason for this is that most of the heat absorbed by the wall is delivered to the room before 6 a.m. the following morning. (The conventional definition of a day, starting and ending at midnight, makes no sense for this analysis.)

Figure B-8 shows results for the December-February period for the west end of the wall. Each of the 90 points on the plot represents the integral over the day. The ordinate on the plot is the total daily solar gain measured by the vertical-south pyranometer. The abscissa is the total daily heat flow to the room, calculated as described above. The line shows a least-square straight-line fit through the data points. Although there is a large scatter in the data (partly because of day-to-day carryover of heat), the line accurately represents average performance. The line crosses zero at an incident solar gain of about 100 Btu/ft^2. This is the “break-even” amount of solar radiation required to overcome the thermal losses to the outside air. Note that there are only 5 days out of the 90 days plotted during which the wall loses heat, and then only by a small amount (much less than an insulated wall would lose).

The average for these 90 days is shown as a solid point on the graph, indicating an average daily gain of 308 Btu/ft^2 on a day with 1509 Btu/ft^2 incident solar radiation. This corresponds to an average efficiency of 20.4%. For comparison, the Bruce Hunn Trombe wall in Los Alamos, which was carefully studied, had a winter efficiency of a nearly identical 20.3% (November through April) (Balcomb and Hedstrom 1981). However, the Trombe wall on the Hunn house did not have a selective surface and did not use water-white glazings. Researchers had expected much better performance for this wall—more in the range of 39%—and are disappointed in the result.

Corresponding results for the east wall are shown in Figure B-9. The average daily gain is 121 Btu/ft^2. The average efficiency is only 8.3%. The wall loses heat on 16 of the 90 days. The “break-even” daily incident solar radiation is about 500 Btu/ft^2. As discussed earlier, the principal explanation for this poor performance is the kitchen cabinets, which impede heat flow to the room.

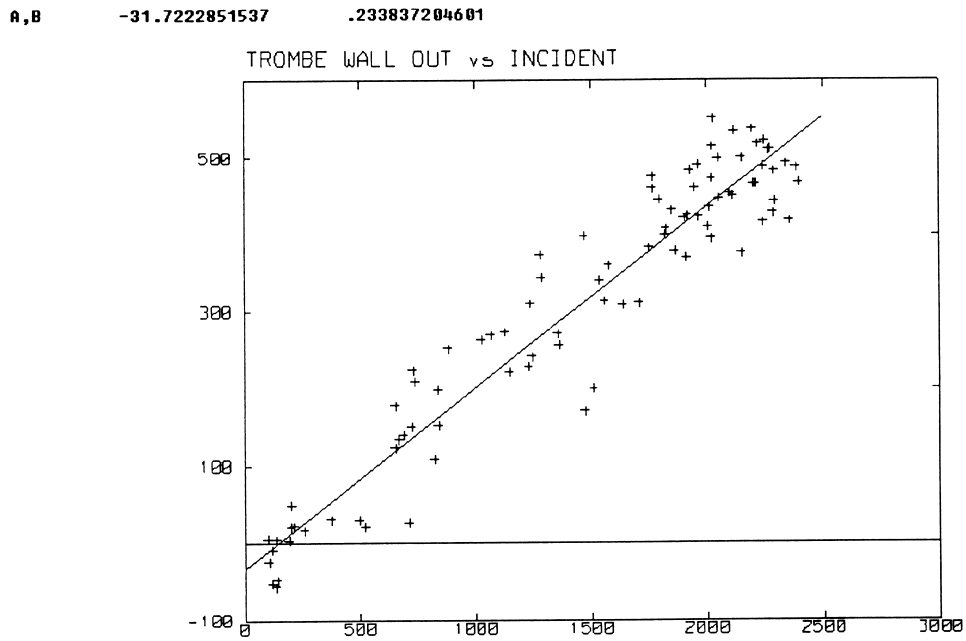


Figure B-8. Correlation of Trombe wall heat flow with incident solar radiation (west end). A typical insulated wall (R19) would lose about 43 Btu/hr/day, corresponding to the measured 34.3ºF inside-outside temperature difference.

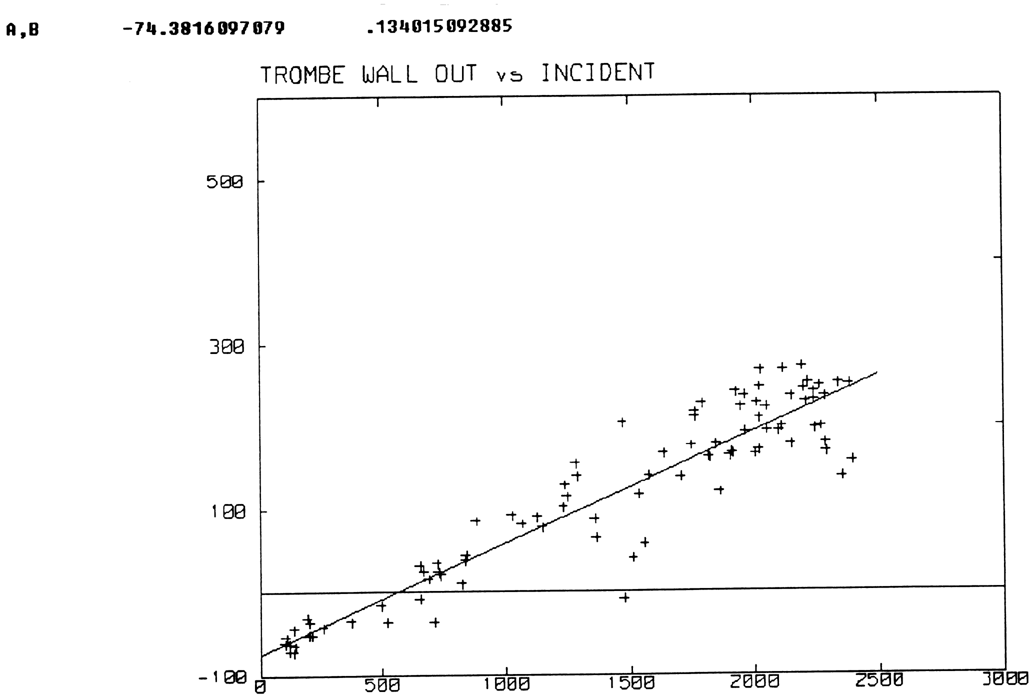


Figure B-9. Correlation of Trombe wall heat flow with incident solar radiation (east end).

Heat Absorbed on the Outer Wall Surface

The outer surface heat flux and the outer U-value can be used to infer the heat absorbed by the wall surface during the day. (At night, the heat absorbed should be zero.)

The heat absorbed should be equal to the sum of the heat flux into the wall and heat lost to the ambient air. The latter term is $U(T_s - T_a)$, where T_s is the surface temperature and T_a is the air temperature. The U-value is 0.18 Btu/h•°F•ft^2, as determined before. (Actually, U will increase some with temperature during the day—this effect was ignored.)

Figure B-10 shows the heat absorbed on December 25 and also shows the measured solar radiation incident on the south facade. As expected, the heat absorbed is zero at night. The ratio of the two daytime values, also shown plotted, is the product of the transmittance of the glazing and the absorptance of the surface.

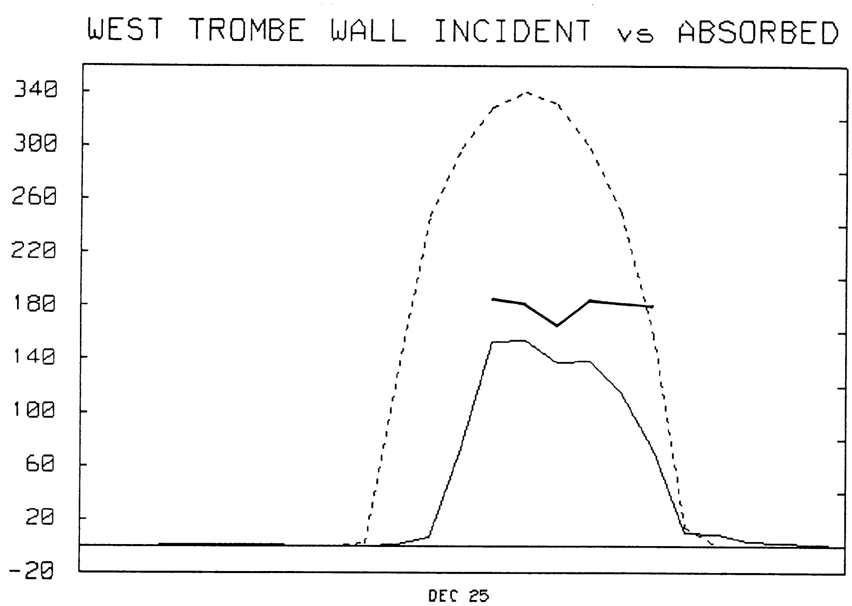


Figure B-10. Trombe wall exterior absorbed solar heat compared with the incident solar radiation.

The disturbing observation in this plot is the low value of the ratio. During the 6 hours after about 10:00 a.m., when the shading by the trees stops, and at about 3:00 p.m., the ratio remains constant at about 0.45. Because the absorptance of the selective surface is about 0.93, this implies that the glazing system transmittance is about 0.48. This would be a reasonable value for a low-e window but is quite low for the double water-white glazing specified.

One explanation that could account for both the lower-than-expected U-value and the lower-than-expected transmittance is that the glass is treated with a low-e coating.

APPENDIX C. ¾ DATA PLOTS

The following tables and plots show both raw data, presented first, and then derived data based on the model.

Tables show averages, average daily peaks, average daily minima, hourly peaks, and hourly minimal, by month and for the year.

There are two types of plots. Not all variables show both types.

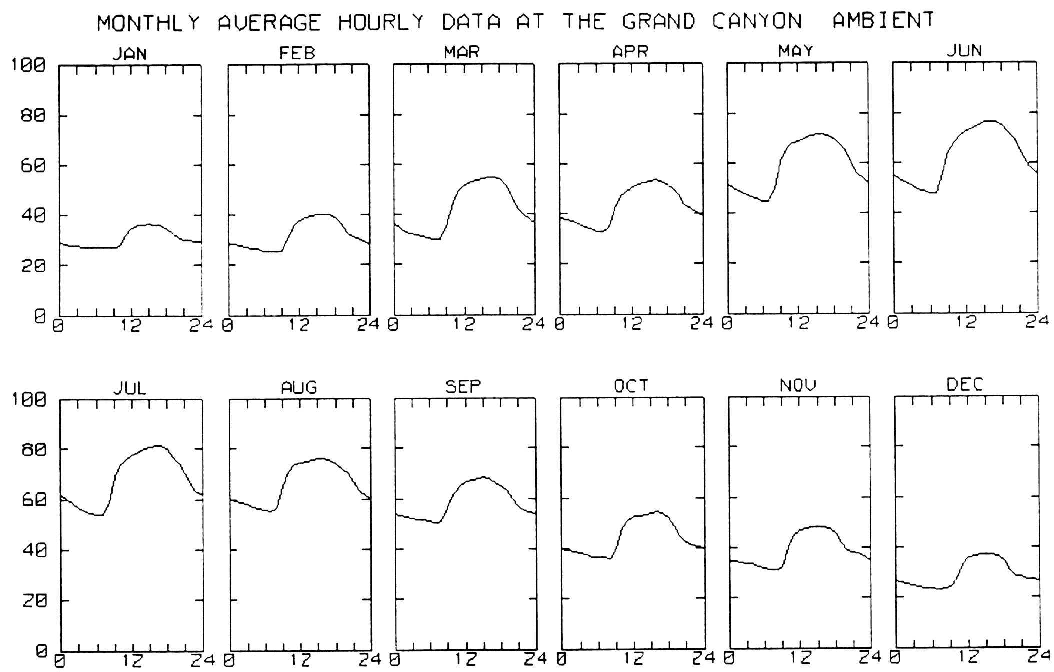
1. Average daily values are plotted for each day of the year. The abscissa is the day of the year. The scale of the ordinant is given in the figure caption.
2. Monthly average values for one day are plotted separately for each month. This represents a typical day in the month. The abscissa of each plot is the hour of the day. The scale of the ordinant is given in the figure caption.

A table is included with some of the graphs. These tables show statistics of the plotted variable by month: the average value, the average daily maximum value, the average daily minimum value, the maximum value, and the minimum value. The same calculations are also printed for the whole year.

GRAND CANYON HOUSE DATA (1997)
Channel # 31 AMBIENT

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	30.9	37.4	23.7	53.0	5.0
2	32.0	40.8	23.5	54.0	11.7
3	42.4	55.3	28.8	67.5	1.9
4	43.7	54.5	31.4	71.9	21.2
5	59.1	73.2	43.3	88.6	31.2
6	63.2	78.0	46.6	86.3	36.0
7	68.5	82.9	52.6	91.4	43.0
8	66.1	78.7	54.3	85.1	46.8
9	58.8	70.0	49.2	80.6	34.5
10	44.6	55.4	33.2	71.3	20.3
11	39.2	49.1	28.9	62.6	21.0
12	29.3	37.9	20.0	49.4	1.3
Year	48.2	59.5	36.4	91.4	1.3

Figure C-1. Ambient temperature. The scale of the ordinate is ºF.



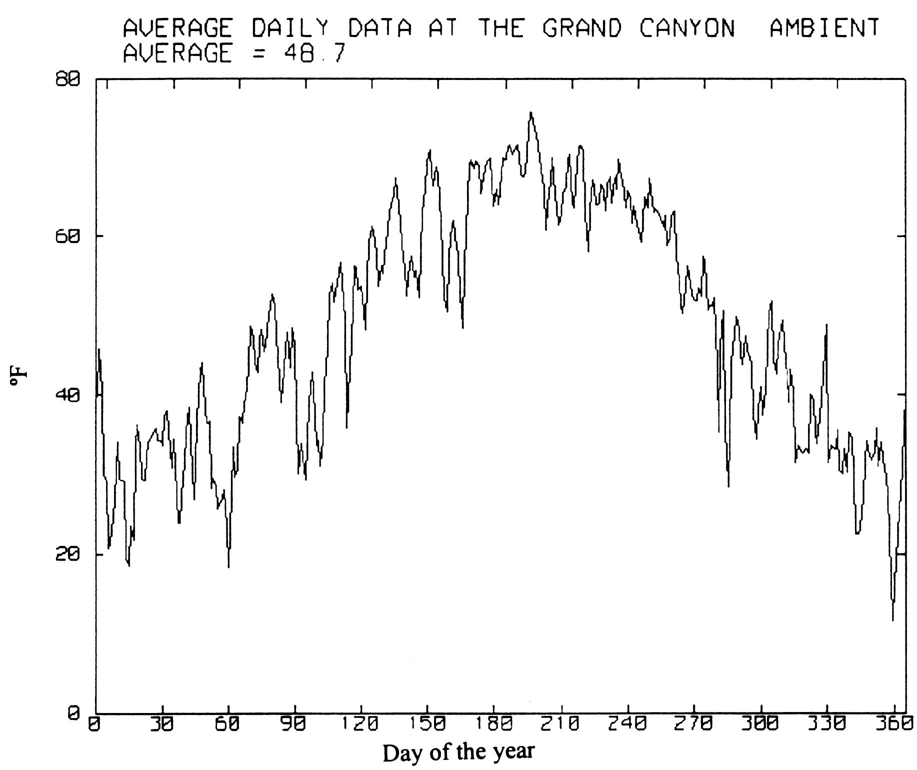


Figure C-1. (continued) Ambient temperature. The scale of the ordinate is ºF.

GRAND CANYON HOUSE DATA (1997)
Channel # 21 QHOR

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	30.2	129.3	0.0	213.2	0.0
2	53.9	213.6	0.0	282.6	0.0
3	82.1	278.7	0.0	307.2	0.0
4	79.4	271.6	0.0	320.8	0.0
5	92.4	299.0	0.0	345.1	0.0
6	100.3	304.3	0.0	345.3	0.0
7	93.2	297.8	0.0	334.6	0.0
8	72.5	262.3	0.0	325.0	0.0
9	63.9	246.1	0.0	288.4	0.0
10	63.2	230.4	0.0	258.2	0.0
11	41.4	168.3	0.0	216.8	0.0
12	35.9	156.0	0.0	188.0	0.0
Year	67.4	238.2	0.0	345.3	0.0

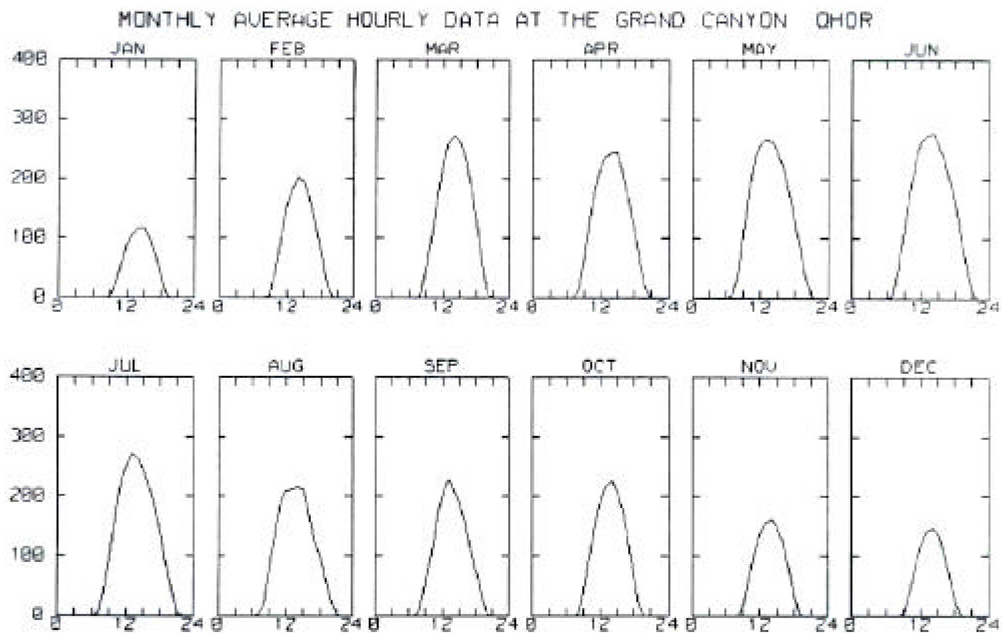


Figure C-2. Global horizontal solar radiation. The scale of the ordinate is Btu/h•ft^2.

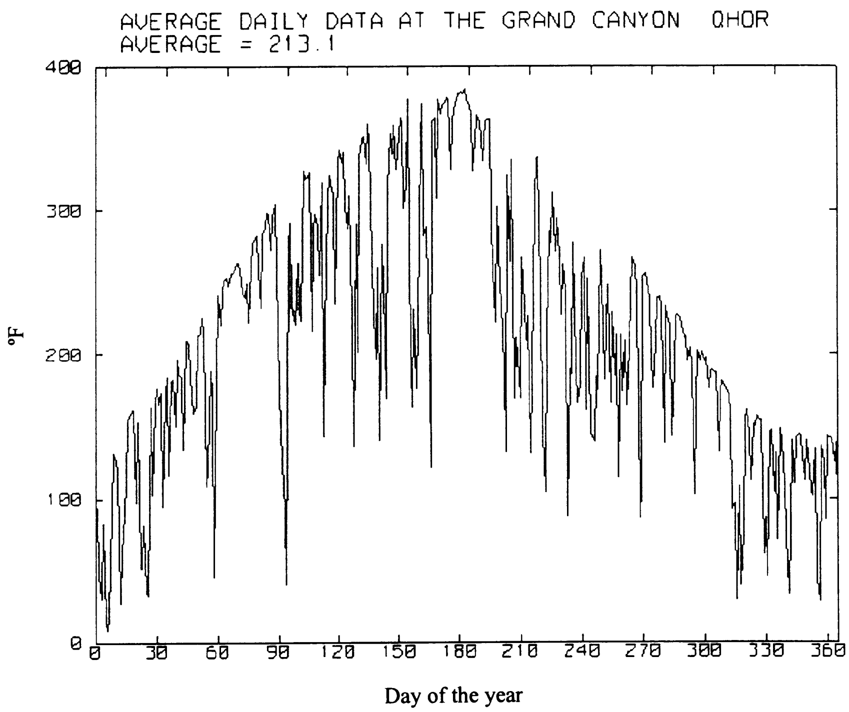
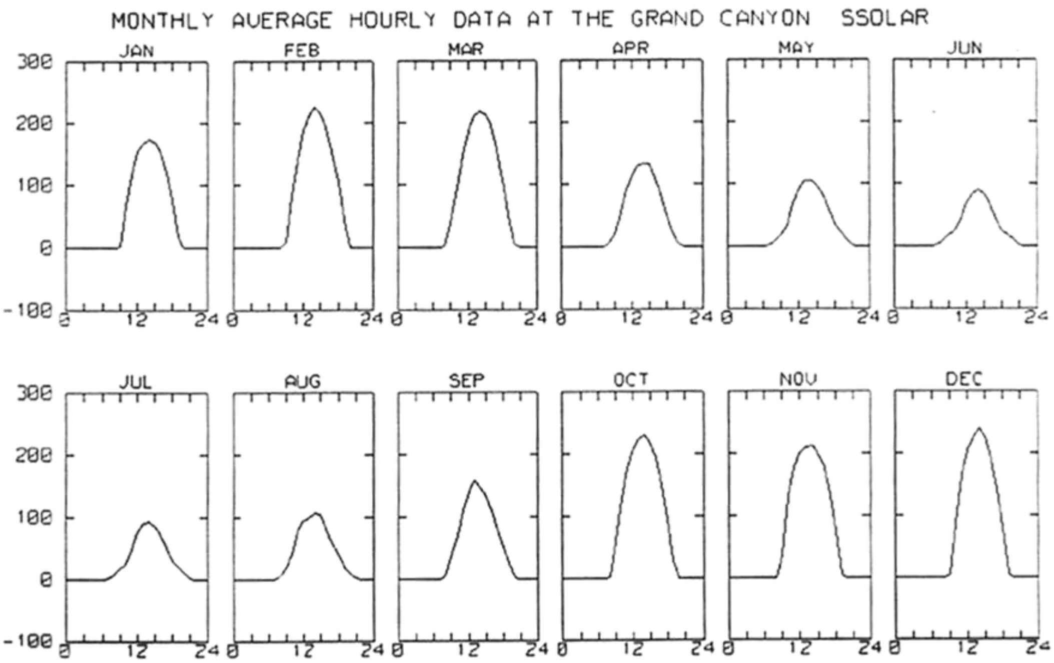


Figure C-2. (continued) Global horizontal solar radiation. The scale of the ordinate is Btu/h·ft^2.

GRAND CANYON HOUSE DATA (1997)
Channel # 29 SSOLAR

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	50.7	199.1	-0.0	350.3	-0.0
2	65.3	244.3	-0.0	307.6	-0.0
3	67.9	226.1	0.0	283.6	0.0
4	39.8	149.4	-0.0	246.2	-.7
5	30.7	115.6	-0.0	151.2	-0.0
6	24.6	95.2	-0.0	121.6	-.1
7	26.3	103.3	-0.0	141.3	-.2
8	31.5	126.9	-0.0	179.7	-.1
9	44.1	172.5	-0.0	223.1	-.2
10	71.1	241.7	-0.0	273.9	-0.0
11	64.3	233.9	-0.0	300.6	-.4
12	65.1	259.5	-0.0	351.8	-.2
Year	48.4	180.3	-0.0	351.8	-.7

Figure C-3. Solar radiation incident on the south-facing vertical plane. The scale of ordinate is Btu/h·ft^2.



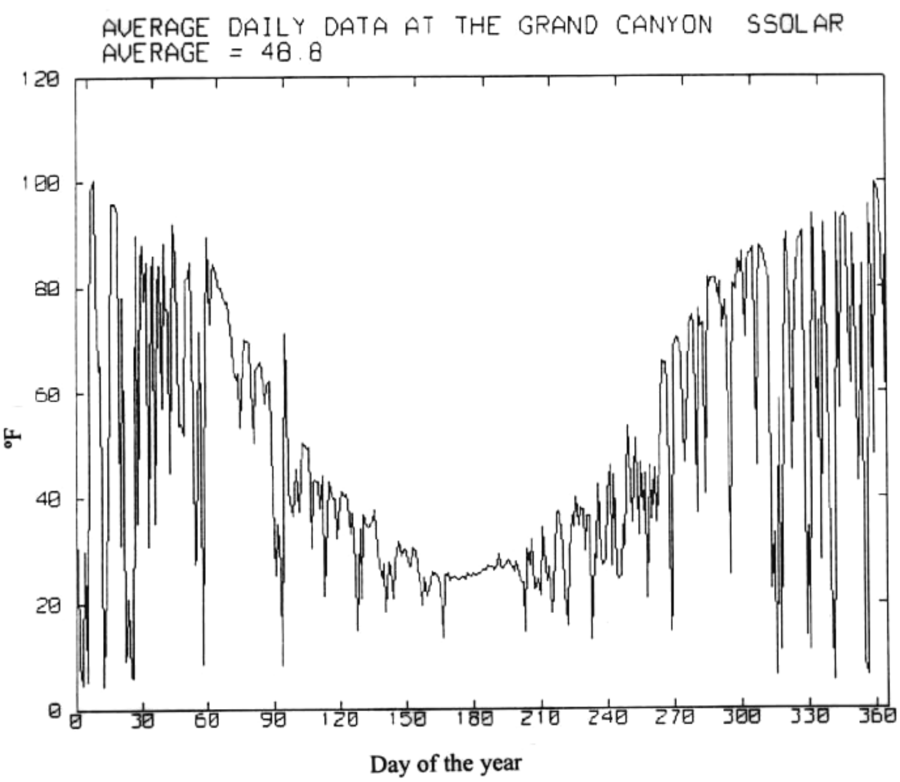


Figure C-3. (continued) Solar radiation incident on the south-facing vertical plane. The scale of ordinate is Btu/h·ft².

GRAND CANYON HOUSE DATA (1997)
Channel # 27 TOTHEAT

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	6099.8	13276.0	2560.2	28510.3	437.6
2	4352.6	10200.3	1122.2	20261.5	427.5
3	3745.8	11227.1	942.6	26581.2	490.7
4	3628.2	11083.3	994.5	22959.3	467.1
5	2369.5	8381.5	685.3	14851.8	498.0
6	2272.6	8007.3	757.0	13449.8	560.8
7	2275.5	8323.0	857.7	16381.0	649.2
8	2308.8	7645.9	826.3	15176.9	613.9
9	2397.7	9466.5	738.7	16268.4	585.1
10	2412.5	9875.4	598.0	16604.8	454.8
11	3171.7	10362.7	706.9	24072.3	379.8
12	4994.3	11821.4	1130.7	20470.6	389.0
Year	3332.5	9973.3	994.4	28510.3	379.8

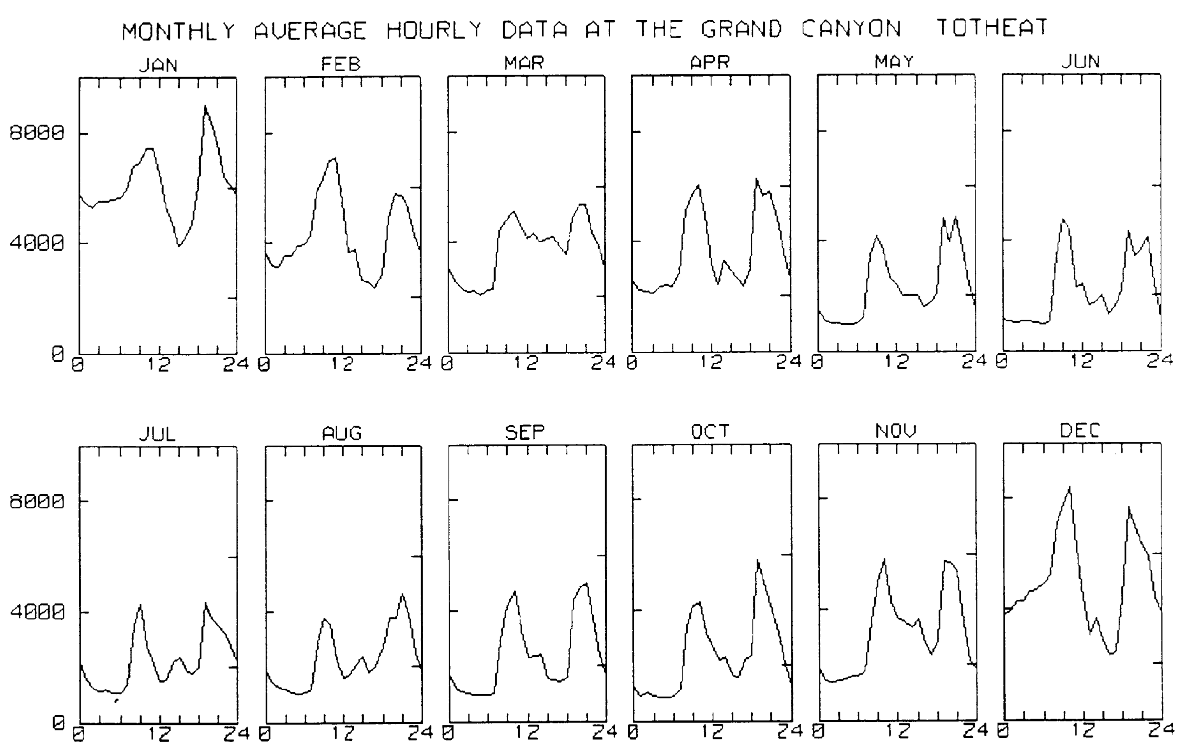


Figure C-4. Total electric consumption of the house. The scale of ordinate is Btu/h.

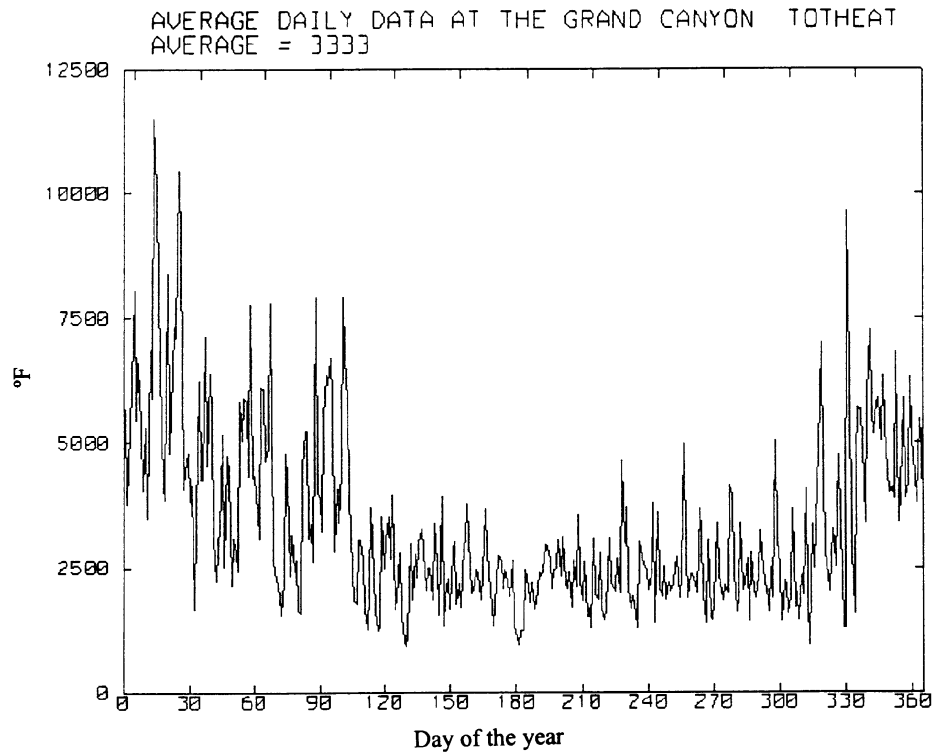
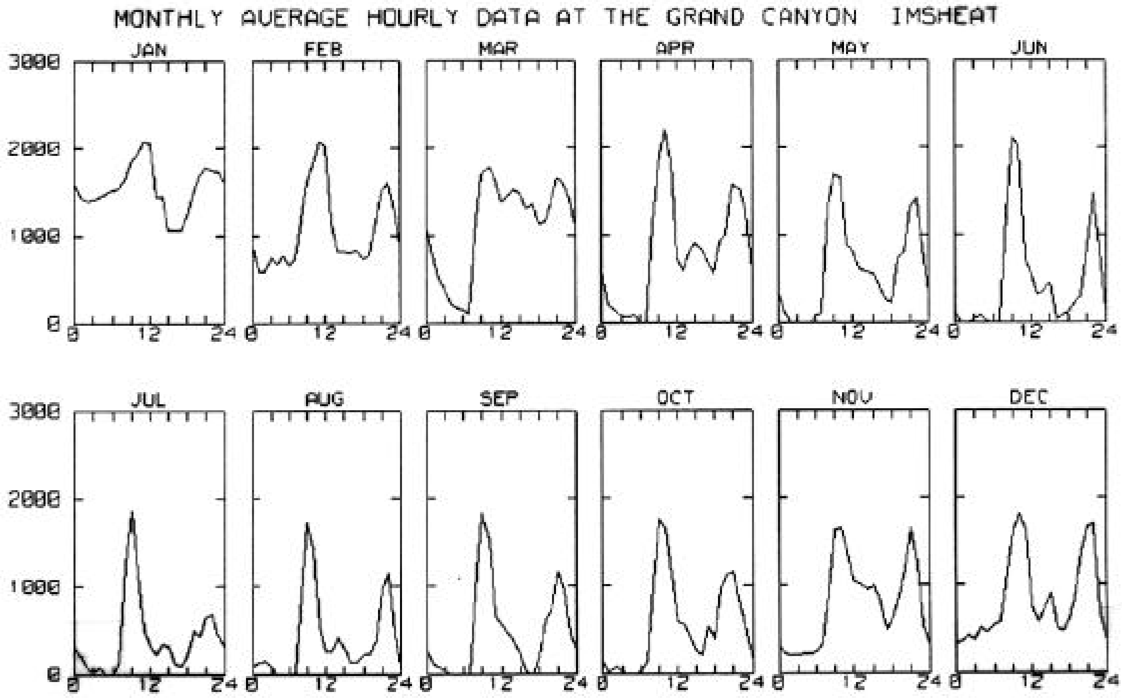


Figure C-4. (continued) Total electric consumption of the house. The scale of ordinate is Btu/h.

GRAND CANYON HOUSE DATA (1997)
Channel # 28 IMSHEAT

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	1549.5	2913.1	556.5	9732.4	.2
2	1078.3	2772.4	87.1	8634.3	.2
3	1098.4	4033.0	7.1	14753.8	.3
4	815.2	3032.2	.3	10219.6	0.0
5	614.8	2393.9	0.0	4220.8	-0.0
6	495.2	2499.6	-0.0	9466.3	-0.0
7	416.6	2416.0	0.0	2620.9	0.0
8	416.4	2283.5	0.0	2568.7	0.0
9	466.2	2417.7	-0.0	2516.9	-.1
10	557.0	2662.7	0.0	10078.8	0.0
11	792.8	2530.5	84.5	5851.1	0.0
12	864.9	2413.1	0.0	4869.5	0.0
Year	762.5	2697.5	61.5	14753.8	-.1

Figure C-5. Electric consumption of the IMS unit. Obtained by multiplying the measured current by 240 volts.



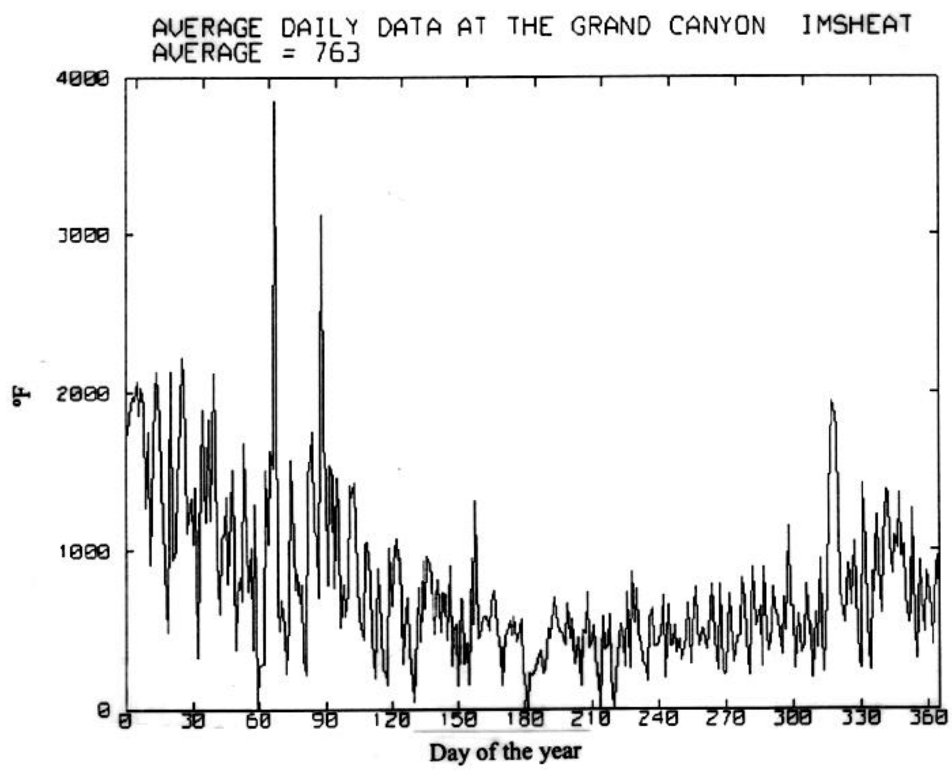


Figure C-5. (Continued) Electric consumption of the IMS unit. Obtained by multiplying the measured current by 240 volts. The scale of ordinate is Btu/h.

GRAND CANYON HOUSE DATA (1997)
Channel # 30 HOUSET

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	64.0	65.5	62.8	70.4	58.7
2	65.7	67.5	64.3	70.1	61.6
3	67.9	69.8	66.1	73.1	61.1
4	65.5	66.8	64.4	70.1	62.3
5	69.5	71.1	68.1	76.8	64.8
6	71.6	73.5	69.9	77.0	64.8
7	74.7	76.9	72.6	80.2	69.5
8	73.7	75.4	71.9	78.8	65.2
9	71.2	72.8	69.5	76.8	65.0
10	68.5	70.9	66.3	76.1	60.4
11	68.7	70.8	66.7	77.6	60.7
12	65.5	67.3	64.1	70.9	61.6
Year	68.9	70.7	67.2	80.2	58.7

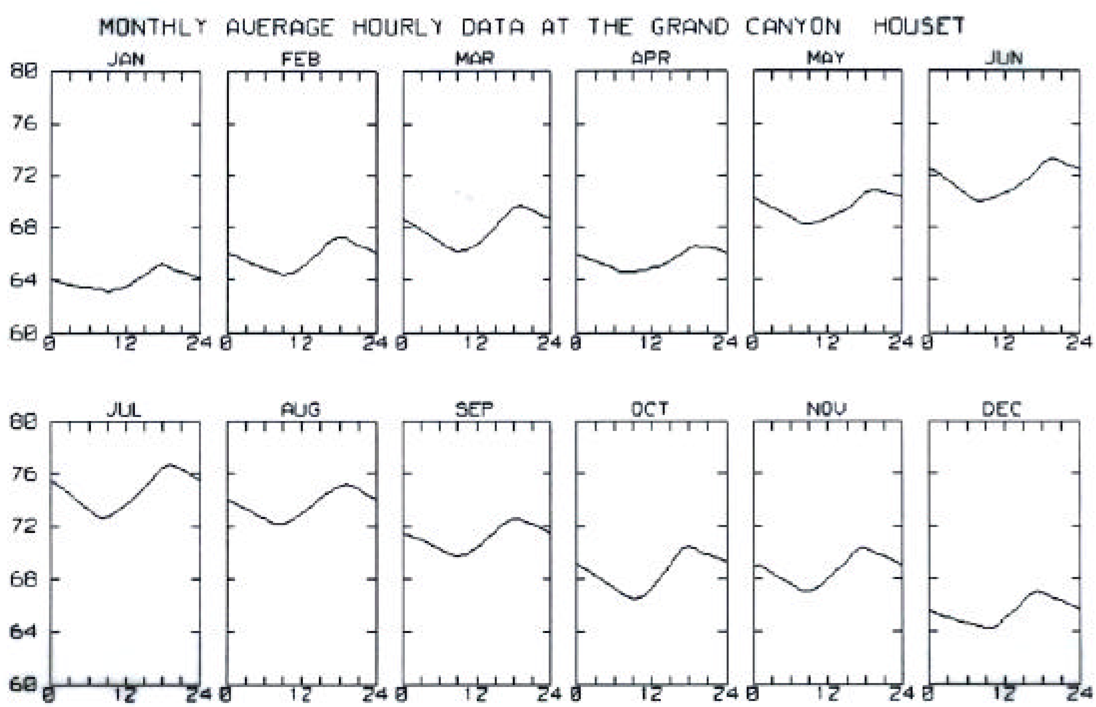


Figure C-6. Average of the four measured house temperatures. The scale of the ordinate is ºF.

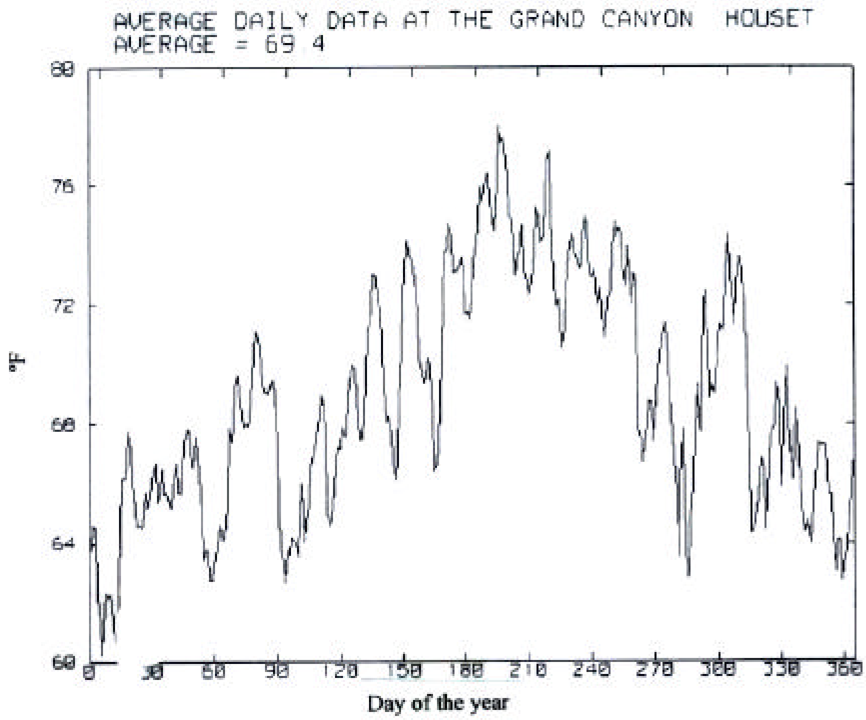
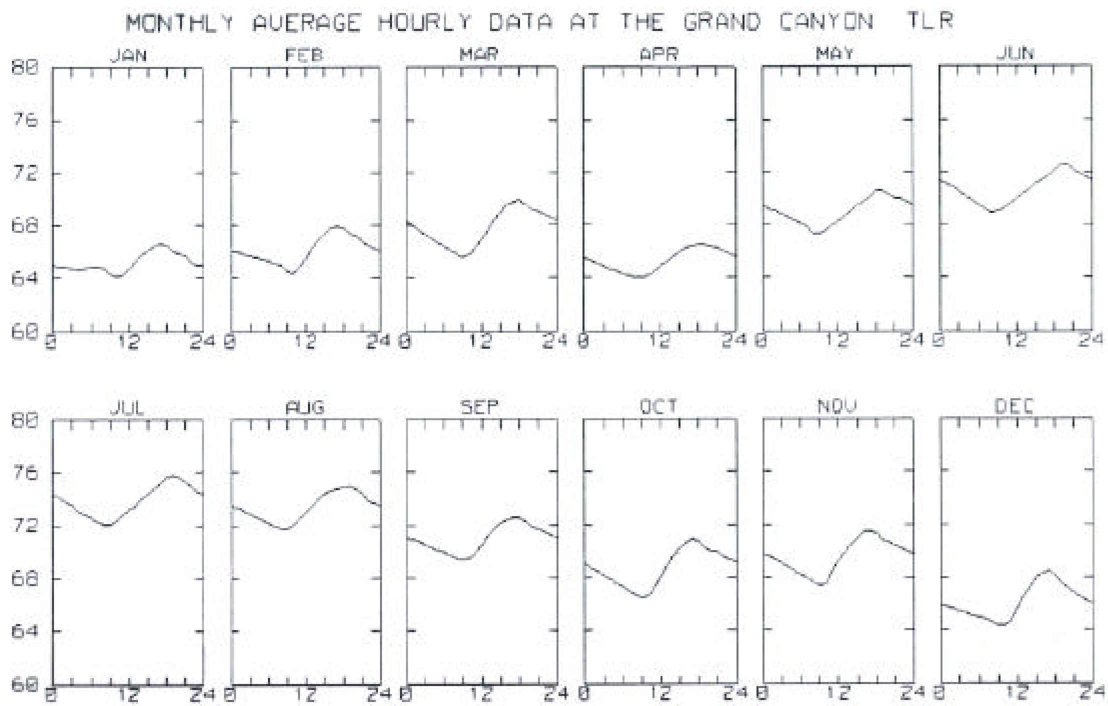


Figure C-6. (continued) Average of the four measured house temperatures. The scale of the ordinate is ºF.

GRAND CANYON HOUSE DATA (1997)
Channel # 15 TLR

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	65.2	67.2	63.3	72.0	58.5
2	66.1	68.2	64.2	70.5	60.6
3	67.8	70.1	65.6	73.1	60.5
4	65.3	66.8	63.9	70.1	61.5
5	69.0	70.8	67.1	75.4	64.0
6	70.8	72.9	68.8	76.6	62.8
7	73.9	76.2	71.8	79.6	69.4
8	73.4	75.3	71.3	78.4	64.3
9	71.0	72.8	69.0	76.7	65.3
10	68.7	71.3	66.2	76.5	61.2
11	69.6	71.9	67.1	78.2	61.3
12	66.2	68.8	64.2	71.3	62.8
Year	68.9	71.0	66.9	79.6	58.5

Figure C-7. Measured temperature in the living room. The scale of ordinate is ºF.



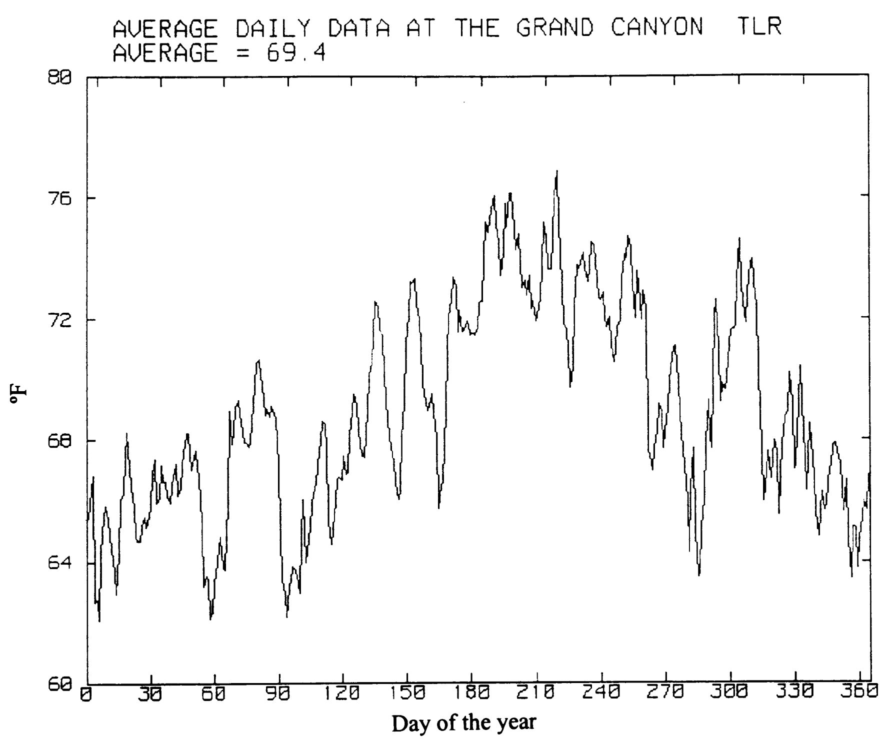


Figure C-7. (continued) Measured temperature in the living room. The scale of ordinate is ºF.

GRAND CANYON HOUSE DATA (1997)
Channel # 16 TMBR

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	61.4	62.6	60.5	66.8	55.1
2	64.2	65.2	63.6	67.1	62.6
3	66.0	67.3	64.9	70.4	62.7
4	63.7	65.0	62.7	67.4	59.9
5	66.8	68.6	65.3	73.6	63.0
6	69.0	71.2	66.5	75.0	61.1
7	72.5	74.9	69.9	77.5	63.9
8	71.5	73.5	69.4	76.0	59.5
9	69.2	70.9	67.4	74.9	62.7
10	66.4	68.3	64.7	72.7	58.5
11	66.4	68.3	64.9	74.1	58.7
12	63.1	64.5	62.0	71.5	60.7
Year	66.7	68.4	65.1	77.5	55.1

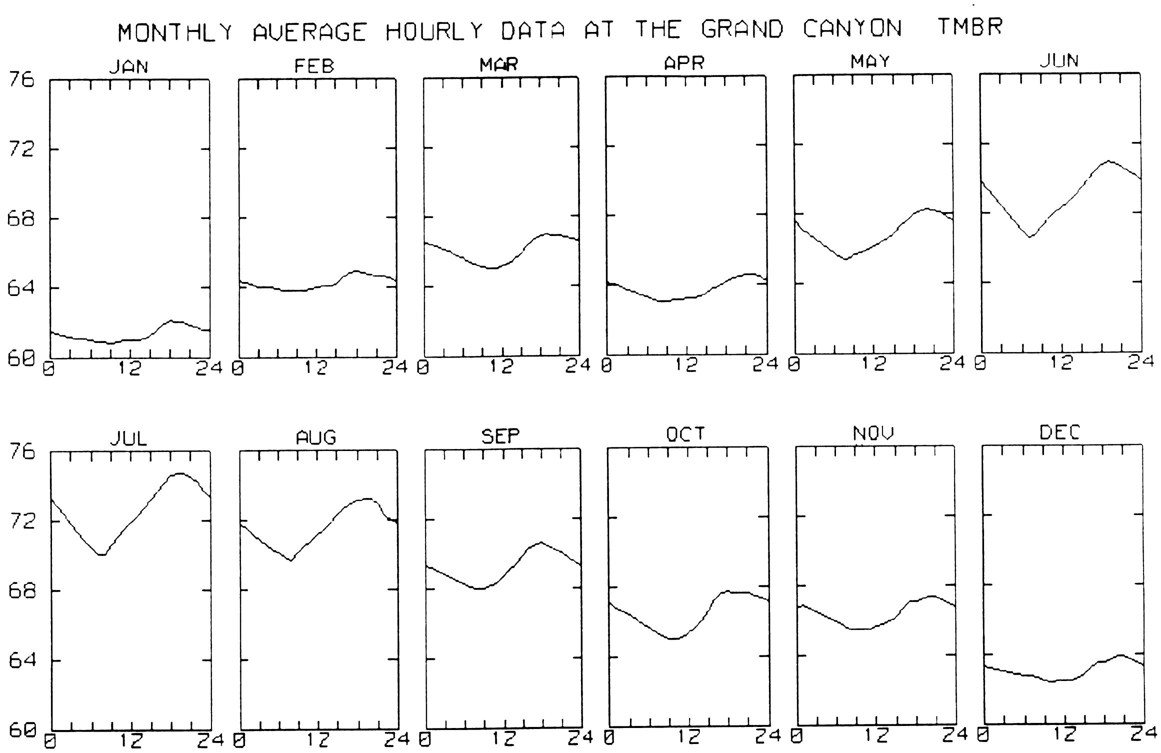


Figure C-8. Measured temperature in master bedroom. The scale of ordinate is ºF.

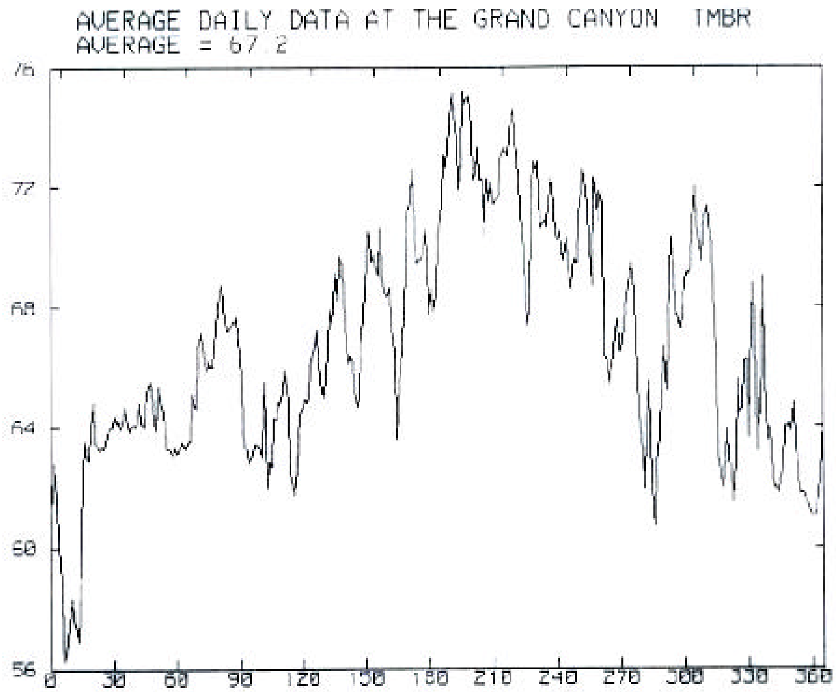
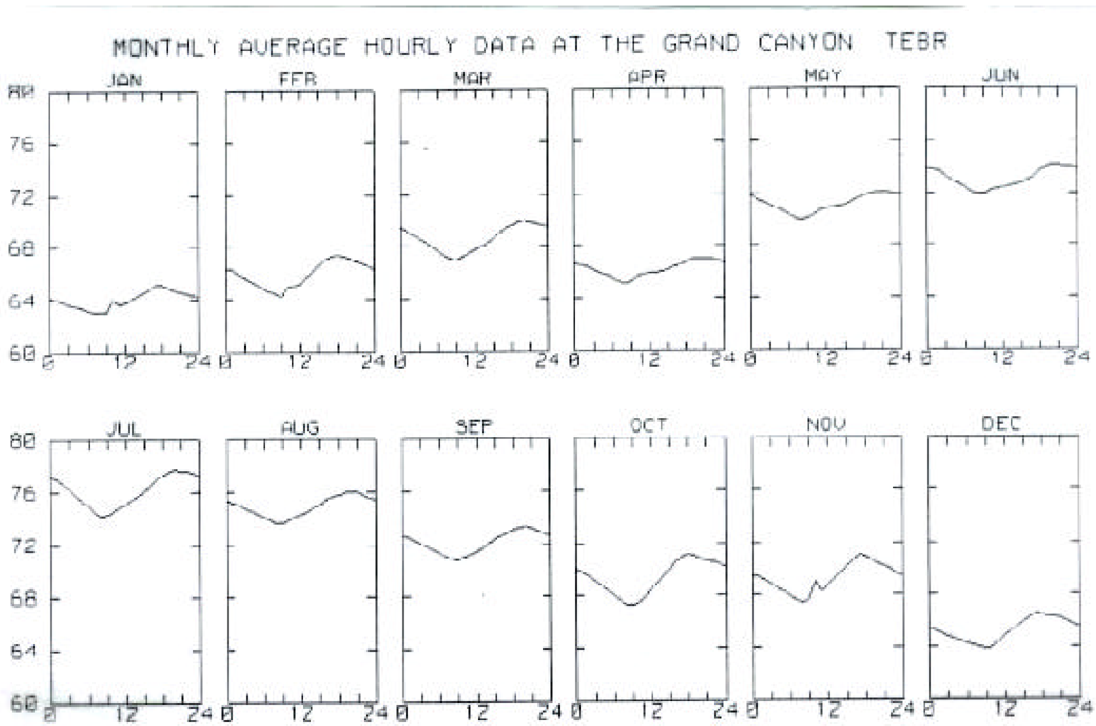


Figure C-8. (continued) Measured temperature in master bedroom. The scale of ordinate is ºF.

GRAND CANYON HOUSE DATA (1997)
Channel # 17 TEBR

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	64.1	65.7	62.8	72.2	57.7
2	65.9	67.8	64.2	70.6	60.2
3	68.6	70.2	66.9	73.8	59.7
4	66.2	67.3	65.1	71.5	61.8
5	71.2	72.5	69.9	78.5	65.5
6	73.1	74.5	71.8	77.9	65.2
7	76.2	78.0	74.2	82.7	70.8
8	74.9	76.5	73.3	80.2	68.6
9	72.1	73.6	70.7	77.8	64.7
10	69.3	71.6	67.0	76.9	61.0
11	69.3	71.5	67.0	78.6	61.2
12	65.3	67.2	63.7	71.2	57.7
Year	69.7	71.4	68.1	82.7	57.7

Figure C-9. Measured house temperature in east bedroom. The scale of ordinate is ºF.



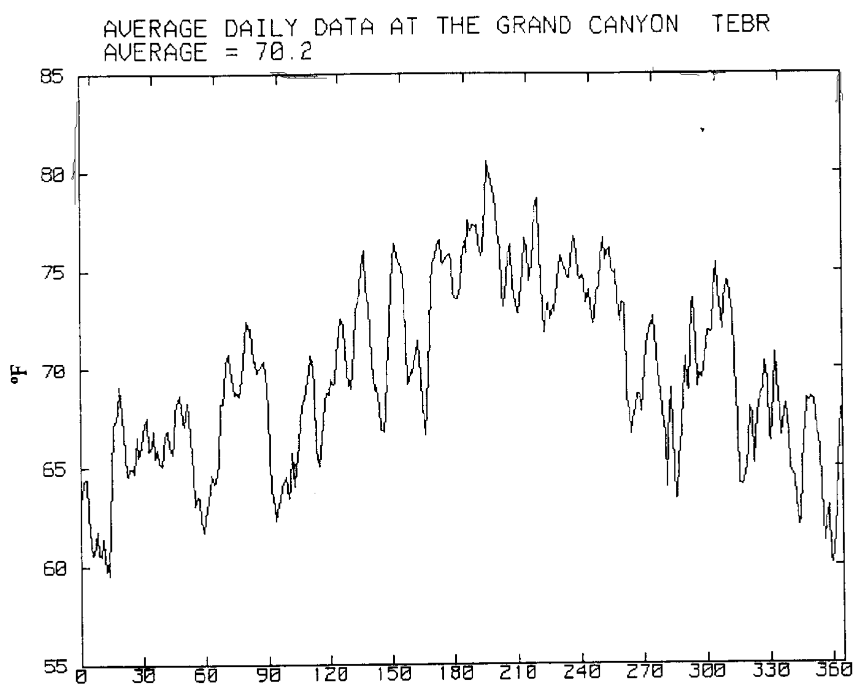


Figure C-9. (continued) Measured house temperature in east bedroom. The scale of ordinate is ºF.

GRAND CANYON HOUSE DATA (1997)
Channel # 18 TWBR

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	65.5	67.7	63.8	74.0	59.5
2	66.7	69.6	64.7	73.2	62.2
3	69.1	72.3	66.7	75.4	61.6
4	66.9	68.8	65.6	72.7	62.7
5	71.2	73.3	69.4	80.3	64.2
6	73.6	75.9	71.6	79.7	66.4
7	76.3	79.1	73.8	83.9	70.9
8	74.8	77.0	72.9	81.7	68.5
9	72.3	74.5	70.5	78.5	65.4
10	69.5	72.9	66.6	78.4	60.6
11	69.6	72.6	67.1	80.1	61.8
12	67.5	70.0	65.9	72.4	64.7
Year	70.3	72.8	68.2	83.9	59.5

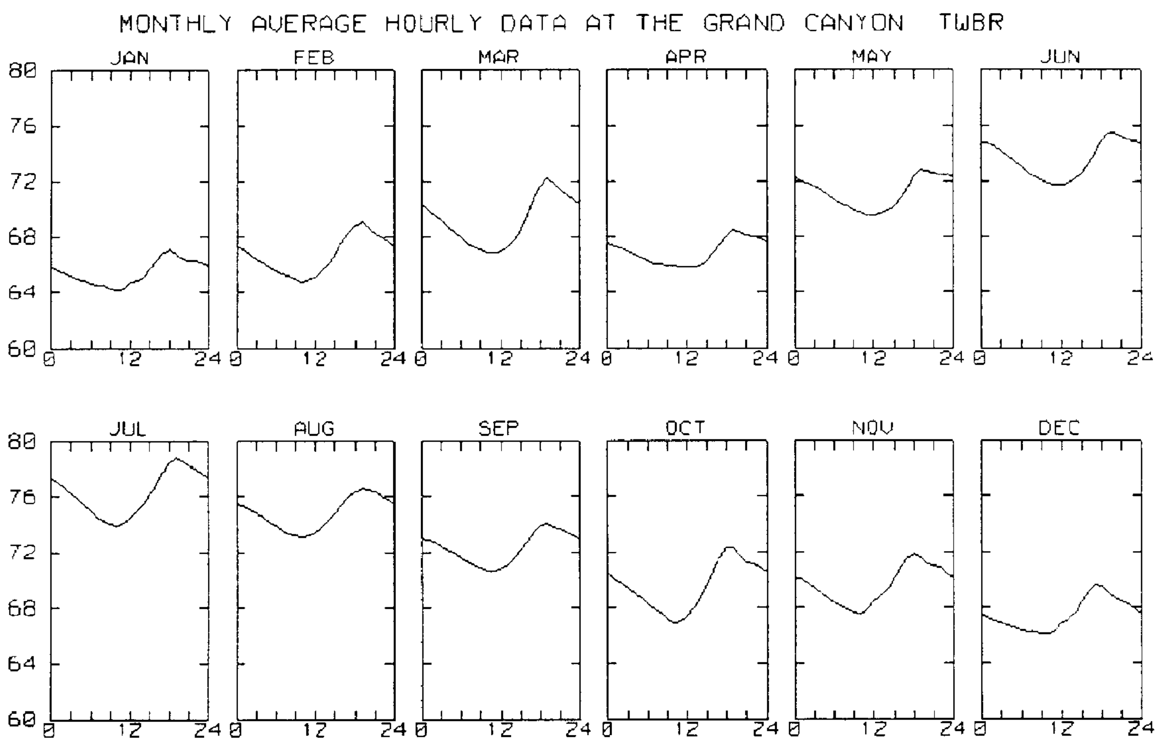


Figure C-10. Measured temperature west bedroom. The scale of the ordinate is ºF.

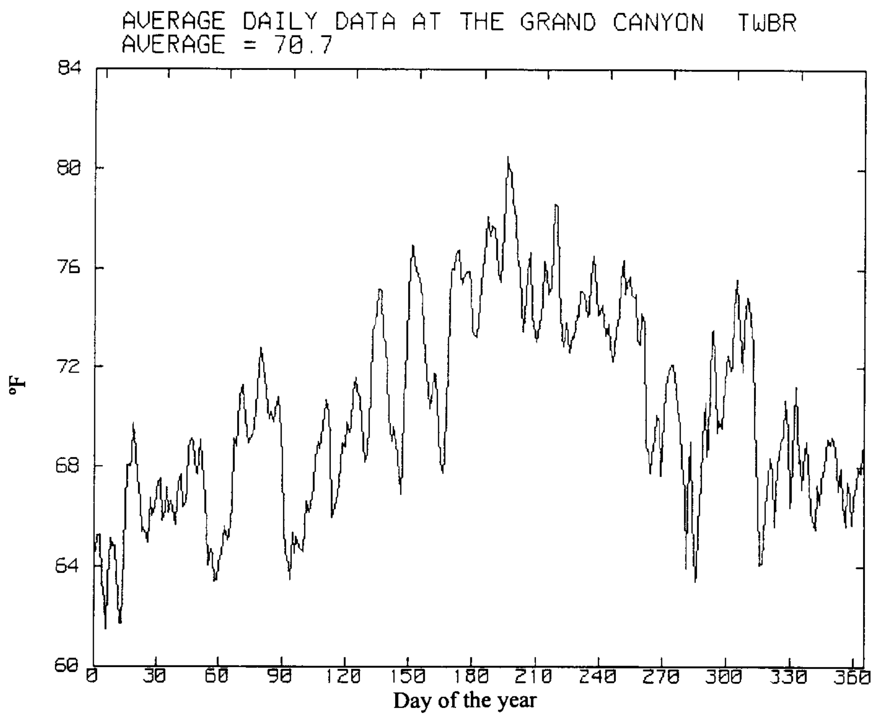


Figure C-10. (continued) Measured temperature west bedroom. The scale of the ordinate is ºF.

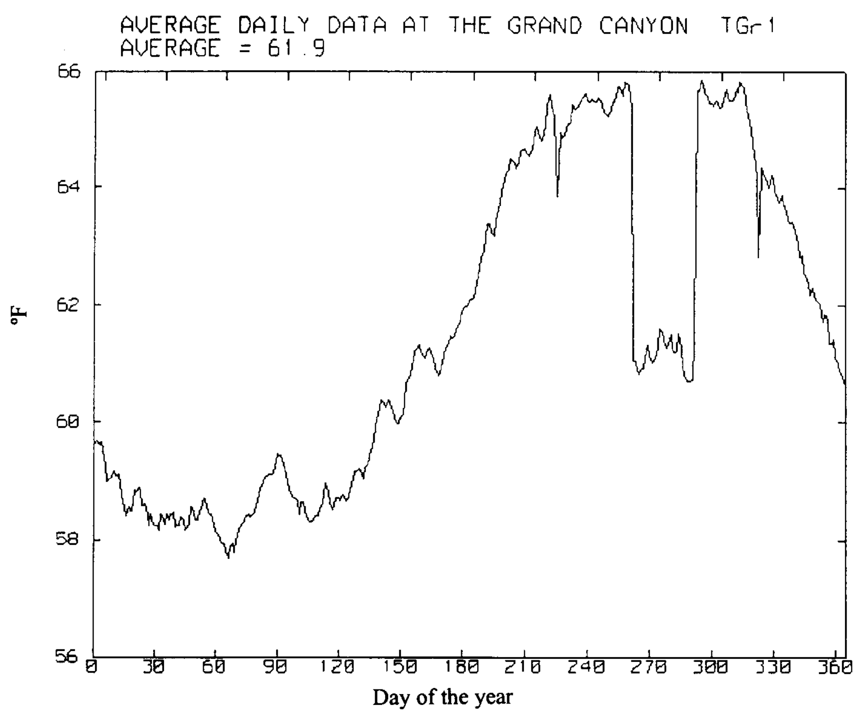


Figure C-11. Measured ground temperature center of house. The scale of the ordinate is ºF

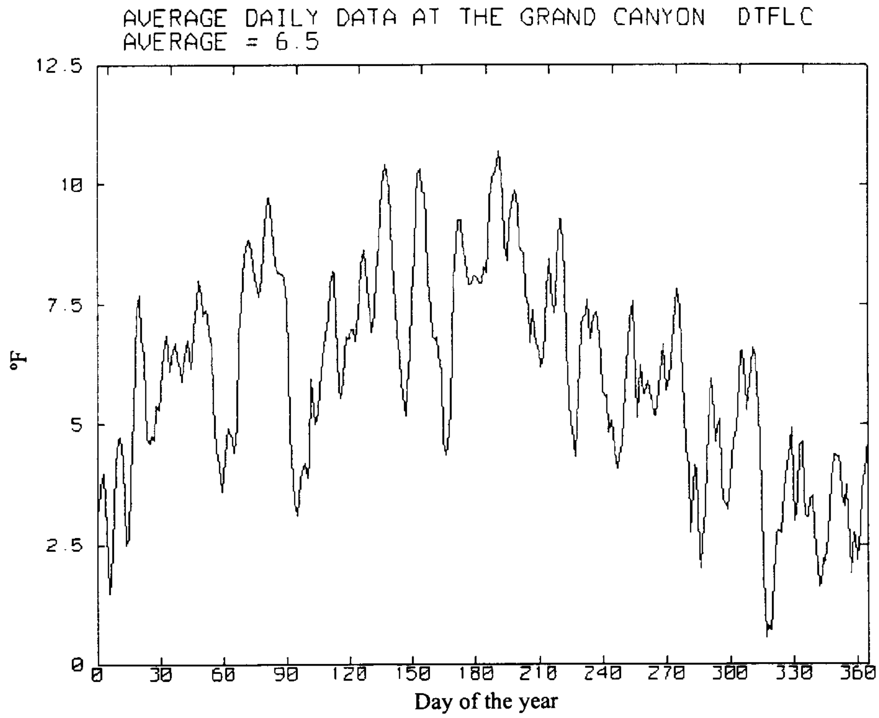


Figure C-12. Temperature difference between the top of the under-floor insulation and the bottom of the insulation, center of house. The scale of ordinate is ºF

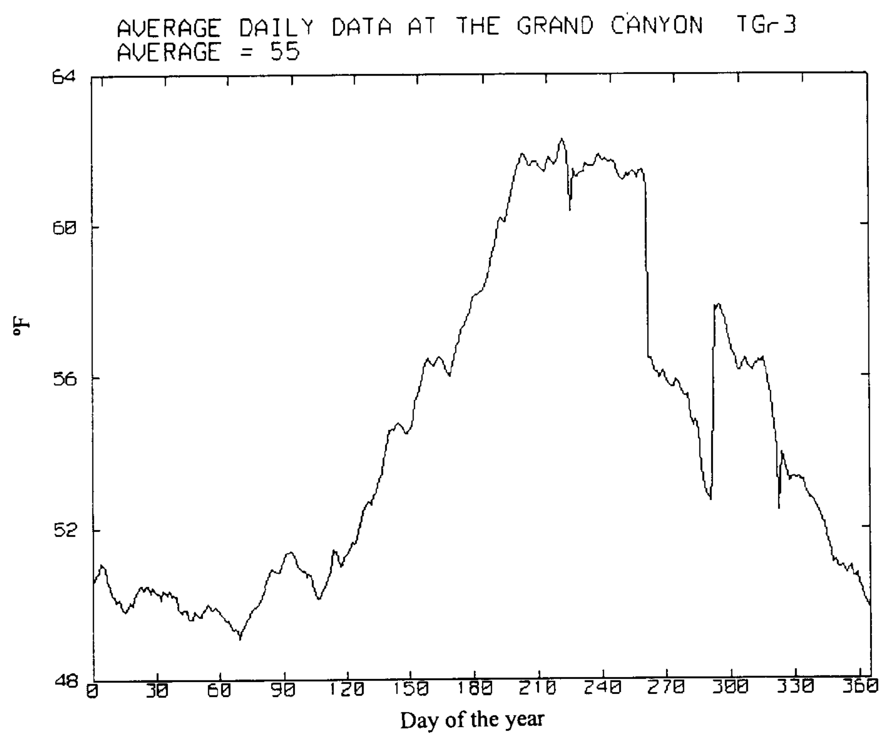


Figure C-13. Measured ground temperature at the edge of the house in the master bedroom. Scale of the ordinate is ºF.

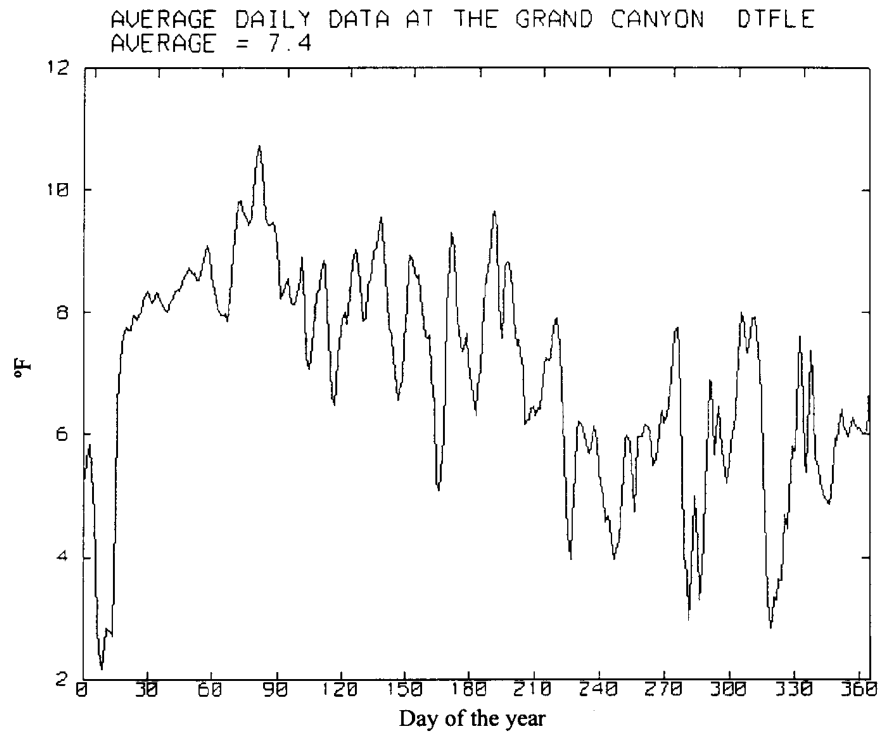


Figure C-14. Temperature difference between the top of the under-floor insulation and the bottom of the insulation, edge of house, in the master bedroom. The scale of ordinate is °F

GRAND CANYON HOUSE DATA (1997)
Channel # 38 QFL

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	477.0	520.8	451.2	812.8	161.8
2	676.7	709.1	652.2	829.2	443.8
3	786.0	822.0	759.1	1018.5	455.9
4	608.1	642.8	585.1	847.9	405.8
5	783.0	819.6	760.1	1037.4	521.1
6	775.8	819.4	746.4	1023.5	420.7
7	837.6	874.0	812.3	1062.5	602.7
8	667.0	709.3	637.5	938.5	377.4
9	569.4	604.8	546.2	747.3	380.5
10	472.7	522.4	437.0	789.2	194.5
11	430.8	479.0	395.9	733.9	90.9
12	370.9	413.8	341.4	542.0	205.4
Year	621.1	661.3	593.5	1062.5	90.9

Figure C-15. Heat flow to ground. Scale of ordinate is Btu/h. Computed by combining the edge and center heat flows, using 800 ft^2 for the center and 200 ft^2 for the edge and a thermal conductance of the slab insulation of 0.1 Btu/h·°F·ft^2.

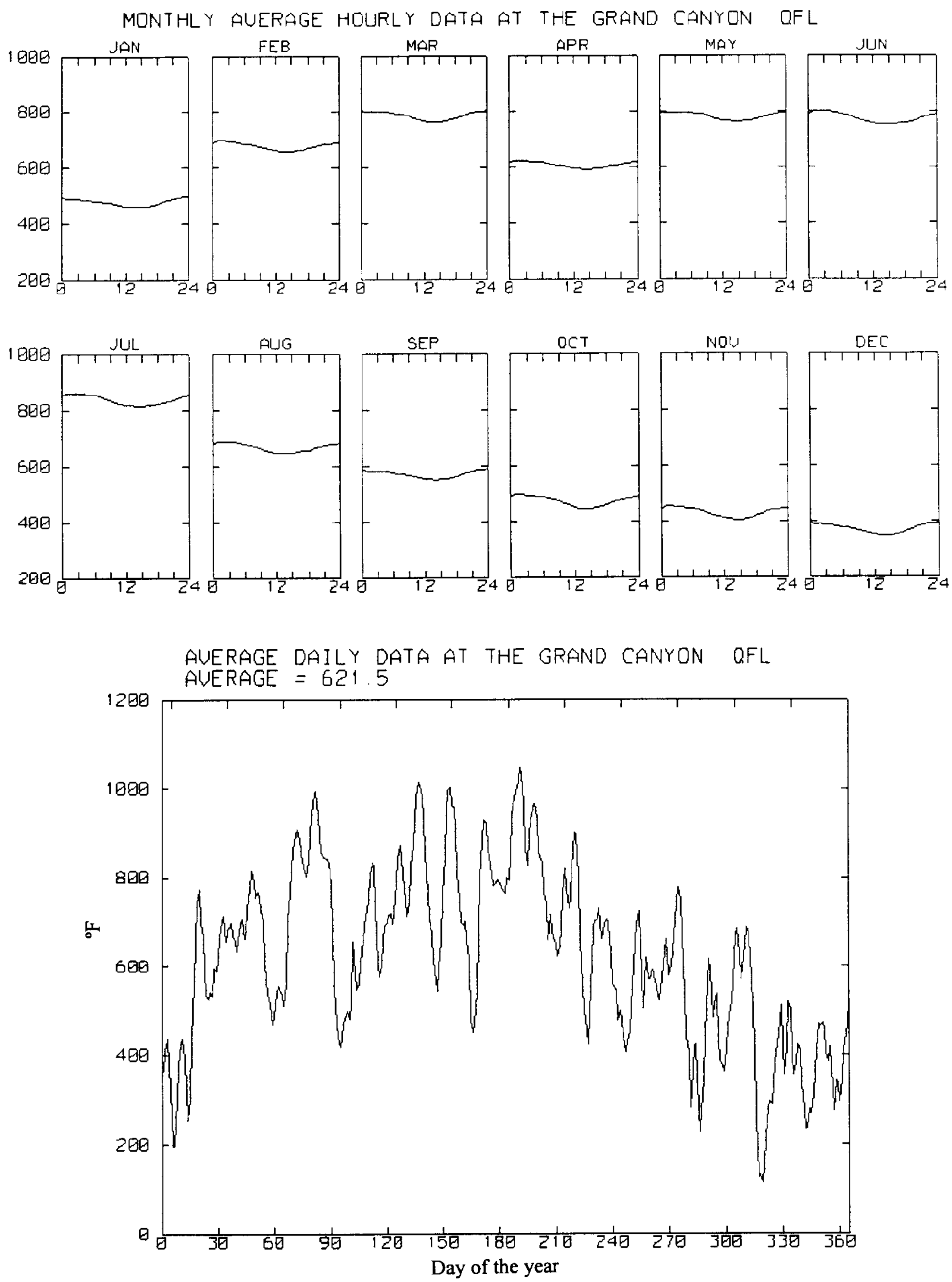


Figure C-15. (continued) Heat flow to ground. Scale of ordinate is Btu/h. Computed by combining the edge and center heat flows, using 800 ft^2 for the center and 200 ft^2 for the edge and a thermal conductance of the slab insulation of 0.1 Btu/h·°F·ft^2.

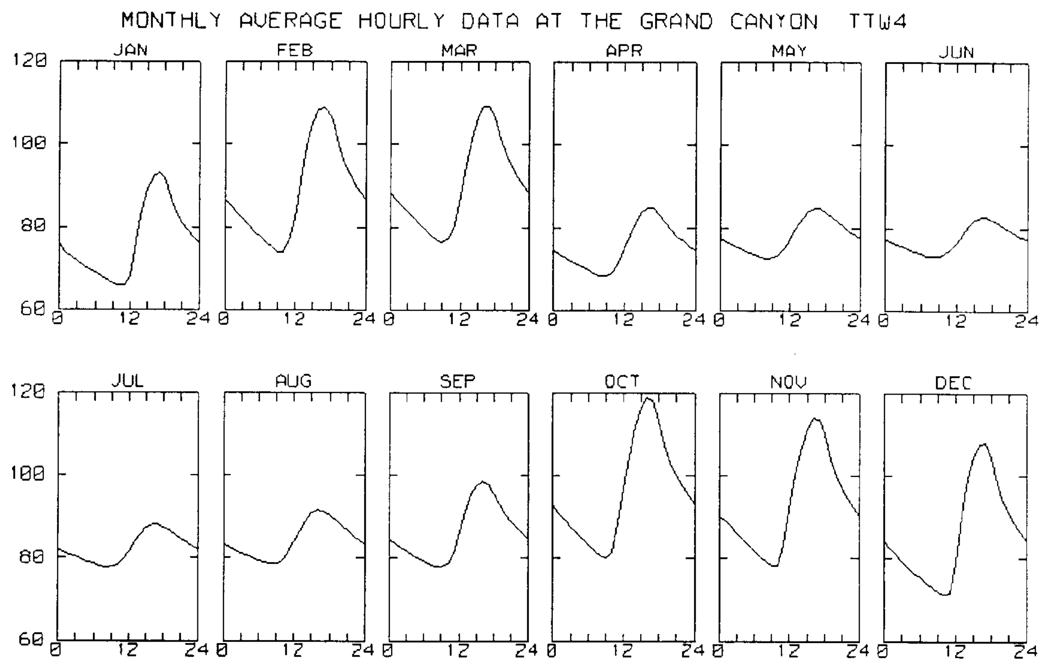


Figure C-16. Temperature measured on the outer surface of the Trombe wall at the west end. Scale of ordinate ºF.

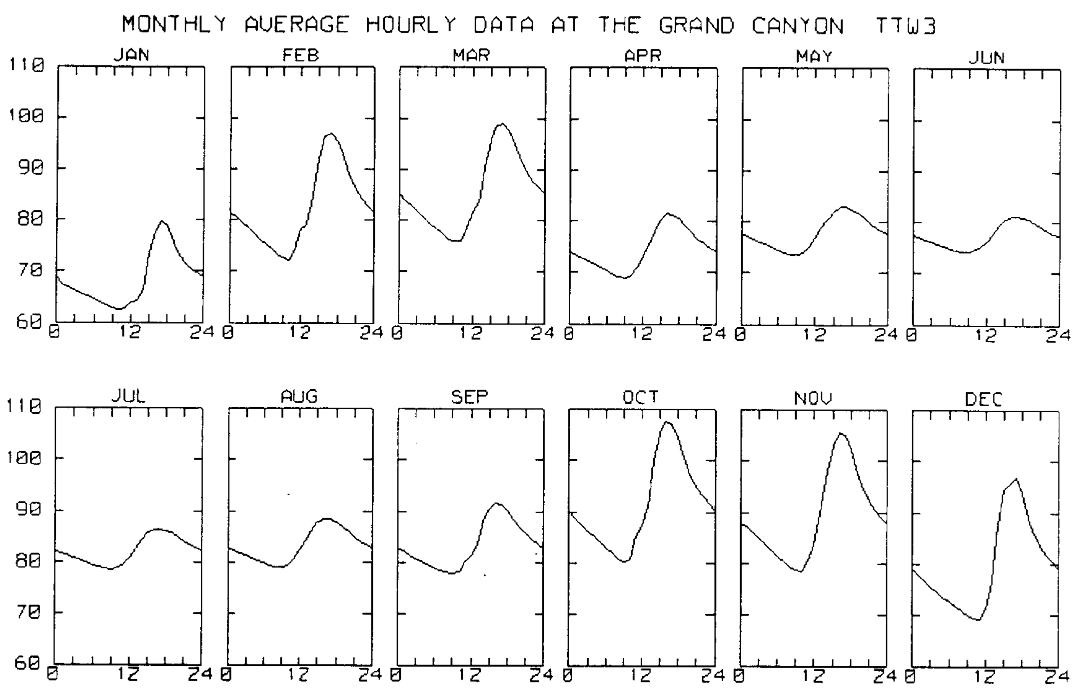


Figure C-17. Temperature measured on the outer surface of the Trombe wall at the east end. Scale of ordinate is ºF.

GRAND CANYON HOUSE DATA (1997)
Channel # 36 QDIRG

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	1622.3	6370.5	0.0	11208.6	0.0
2	2089.8	7817.2	0.0	9843.5	0.0
3	2171.4	7236.5	0.0	9074.6	0.0
4	1274.0	4780.2	0.0	7878.1	0.0
5	981.0	3698.7	0.0	4838.0	0.0
6	788.6	3047.7	0.0	3891.6	0.0
7	841.0	3304.3	0.0	4522.1	0.0
8	1008.2	4059.3	0.0	5750.4	0.0
9	1411.3	5520.9	0.0	7140.1	0.0
10	2274.4	7733.6	0.0	8765.4	0.0
11	2058.6	7484.0	0.0	9617.7	0.0
12	2082.6	8302.5	0.0	11258.3	0.0
Year	1547.7	5769.1	0.0	11258.3	0.0

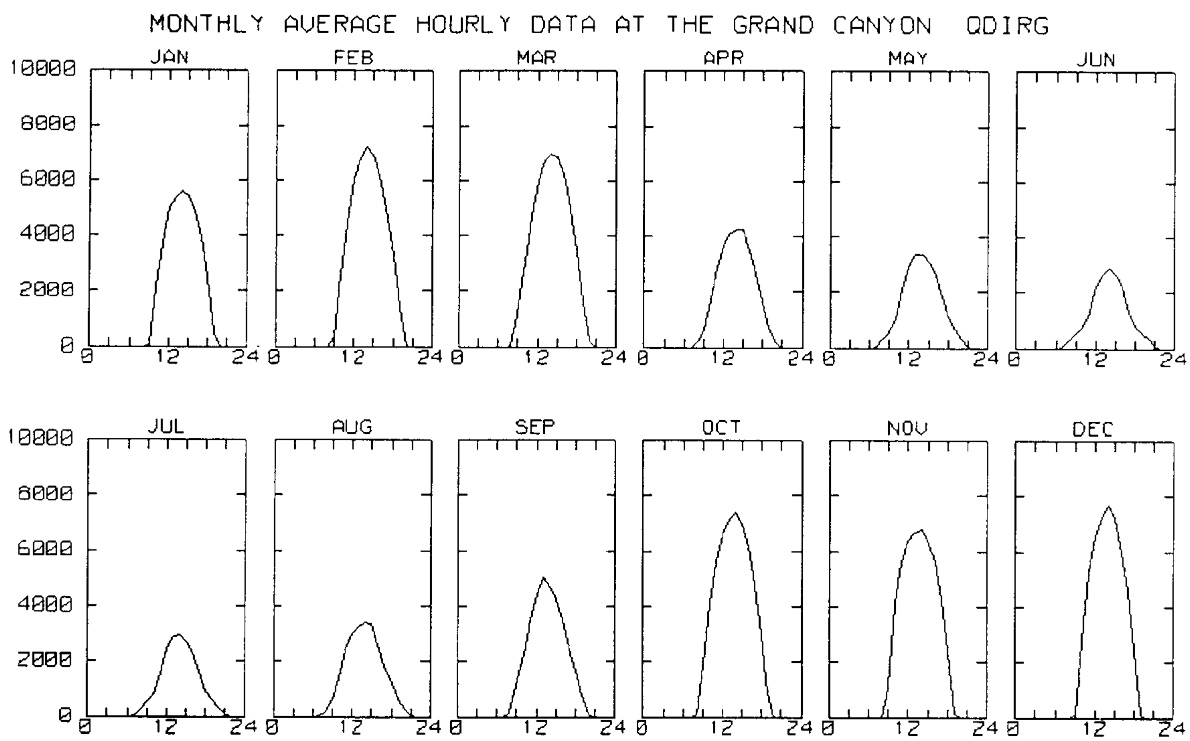


Figure C-18. Direct-gain solar computed by multiplying the incident solar radiation (Figure C-3) by 70 ft^2, the effective solar gain area determined by regression. The scale of ordinate is BTU/h•ft^2.

GRAND CANYON HOUSE DATA (1997)
Channel # 34 QSIM

Month	AVER	AVE MAX	AVE MIN	MAX	MIN
1	5124.8	8522.7	1437.1	13958.8	-2373.8
2	3896.8	7881.4	-277.7	11004.6	-2759.3
3	2328.2	6763.5	-2050.2	10547.5	-3652.4
4	2805.1	6406.3	-557.2	16716.1	-3188.6
5	1184.8	3977.4	-2007.0	6169.0	-3383.4
6	1039.7	3484.5	-1716.9	7147.5	-2881.0
7	611.5	2621.5	-1676.0	4001.7	-2749.0
8	422.8	2426.1	-1938.3	4604.8	-4489.0
9	510.6	3081.1	-2476.7	4952.7	-5756.0
10	996.8	4553.4	-2760.6	7539.8	-5616.8
11	2458.8	6481.9	-1307.5	13462.4	-4394.1
12	3882.9	7972.6	-389.3	11104.9	-3132.9
Year	2094.9	5332.2	-1316.3	16716.1	-5756.0

Figure C-19. Simulated heat required by house as calculated by:

$$Q_{sim} = U (T_h - T_a) - F_1 (A_s Q_s + Q_{tw}) - U_m (T_m - T_h) + Q_{air}$$

$$M (dT_m/dt) = (1 - F_1) (A_s Q_s + Q_{tw}) - Q_{fl} + U_m (T_m - T_h)$$

where: Q_{sim} = heat required, Btu/h
U = building loss coefficient (BLC) = 149 Btu/h•ºF
T_h = house temperature, measured
T_a = ambient temperature, measured
F_1 = fraction of solar and floor heat going into the air (assumed to be 20%)
A_s = effective solar gain area, ft^2, to be determined
Q_s = solar gain on the south vertical facade, measured, Btu/h
Q_{tw} = heat from Trombe wall, calculated in the last section, Btu/h
Q_{fl} = heat loss from the floor, calculated in a previous section, Btu/h
T_m = temperature of the massive element in the house, calculated
M = mass heat capacity of the massive element, assumed to be 4900 Btu/ºF
Q_{air} = heat required to condition air brought in by the IMS unit, Btu/h

(see page 29)

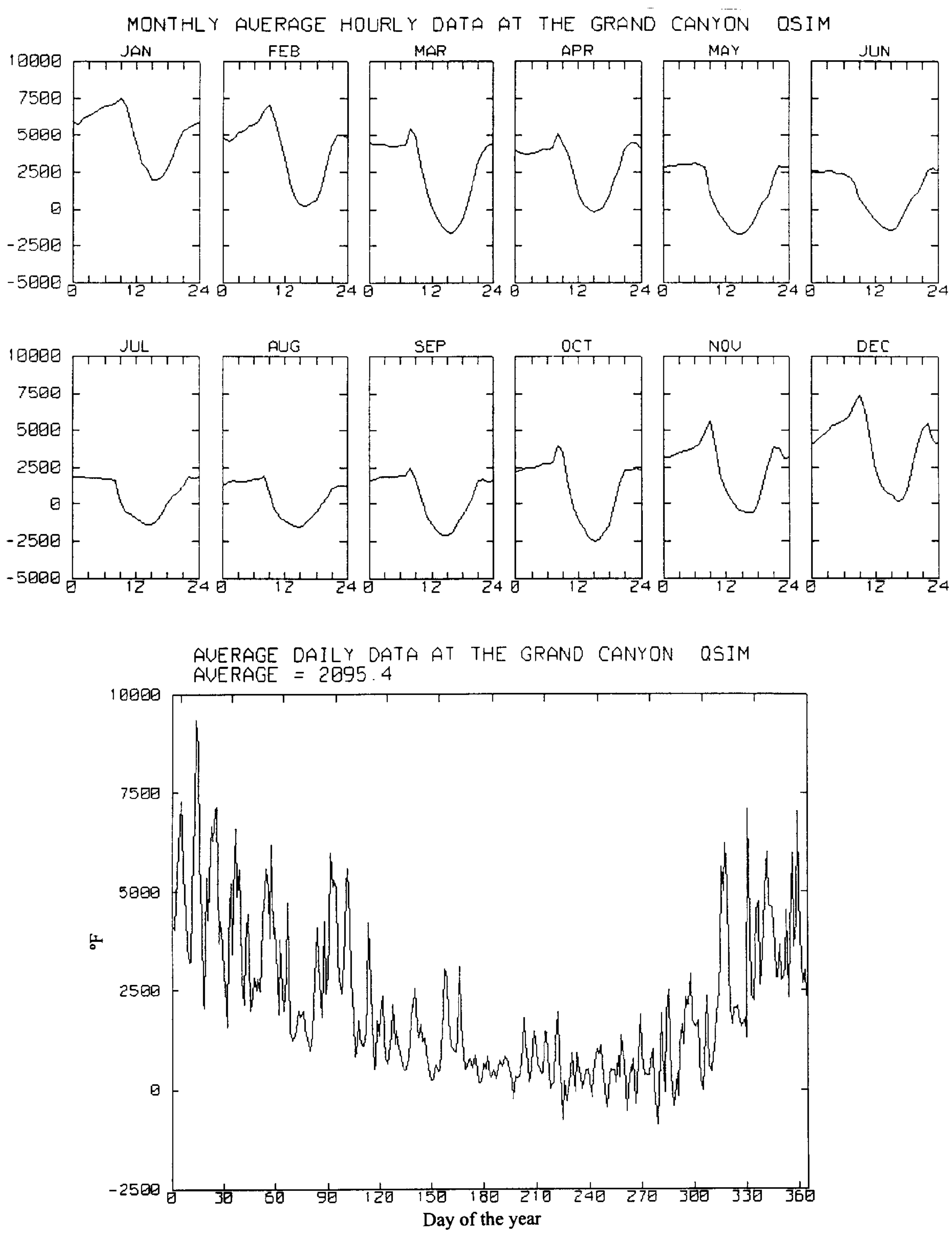


Figure 19. (continued) Simulated heat required by house as calculated by Q_{sim}

(see page 29).

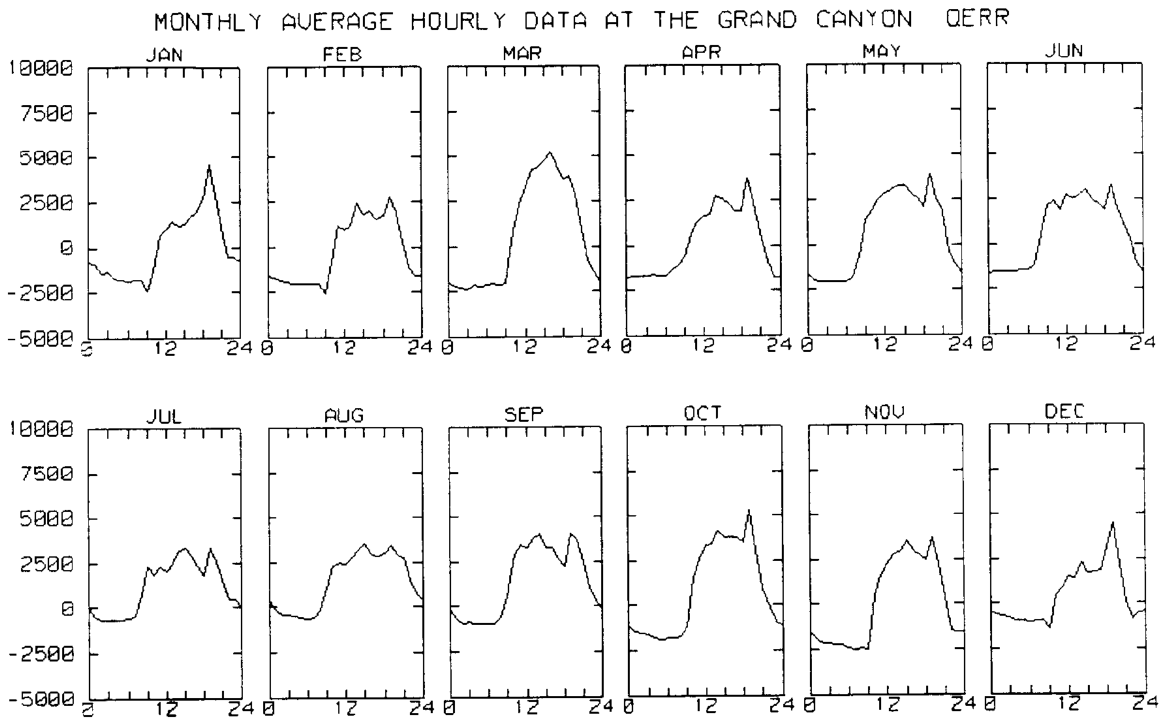


Figure C-20. Energy error of the model. This is attributed to ventilation as calculated by Q_{err} (see pages 31 and 32). The scale of the ordinate is Btu/h.

$Q_{err} = Q_{total} - (1 - K_{IMS})\, Q_{IMS} - Q_{sim}$

where:

Q_{err} = error in heat, the quantity researchers sought to minimize, Btu/h

Q_{total} = total electric heat into the house, measured, Btu/h

Q_{IMS} = 3.412 (IMS watts – 130), Btu/h

K_{IMS} = fraction of the IMS electric energy that is deposited in the house

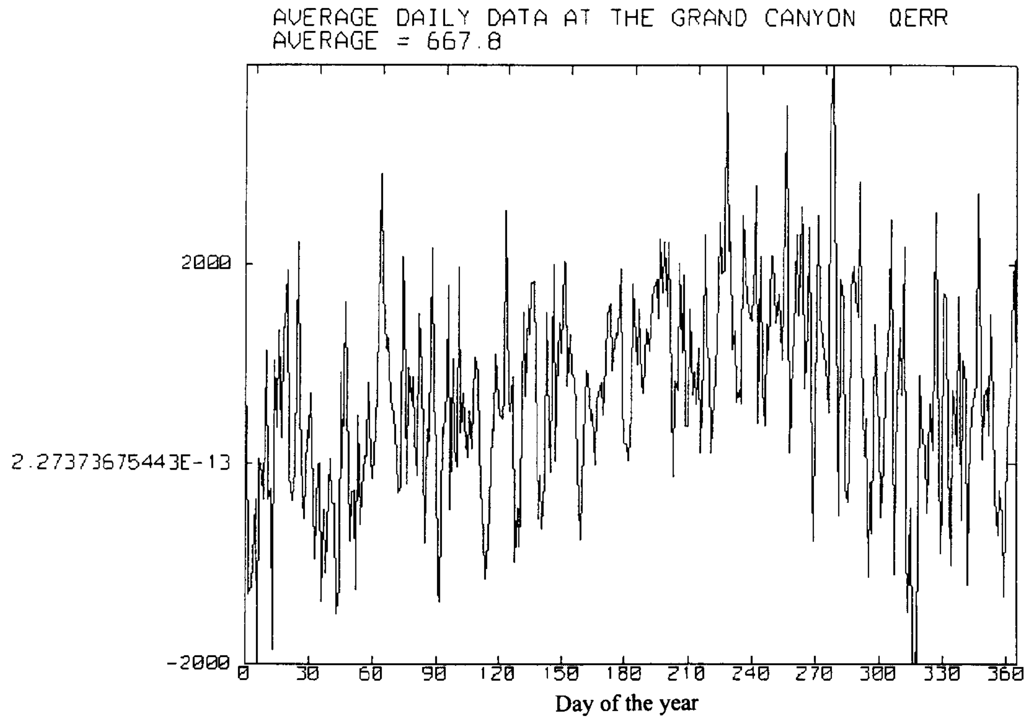


Figure C-20. (continued) Energy error of the model. This is attributed to ventilation as calculated by Q_{err} (see pages 31 and 32). The scale of the ordinate is Btu/h.

ACKNOWLEDGMENTS

The authors wish to thank:

- The members of IEA Solar R&D Task 13 for their help in the design
- Mary-Margaret Jenior, DOE program manager for the Low-Energy Buildings Program, for advice and for editing the draft
- Janet Youngberg, Denver Support Office, for excellent cooperation
- Tom Dressler, the National Park Service person on site, for insisting on quality construction, particularly regarding achieving the air-infiltration specification
- Joe Levy and David Carson, OZ Architecture, for the design
- The house residents, for cooperation during the monitoring and for the interview
- Paul Torcellini, NREL project manager for the Low-Energy Buildings Program, for help during the construction and the monitoring and for editing the draft
- Ron Judkoff, director of NREL's Center for Buildings and Thermal Systems, for encouragement and advice
- David Crawford, NREL Technical Information Office, for editing the manuscript and for preparing the report for publication.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1999	NREL Technical Report

4. TITLE AND SUBTITLE

Toward Net Energy Buildings: Design, Construction, and Performance of the Grand Canyon House

5. FUNDING NUMBERS

Task #: BE804003

6. AUTHOR(S)

J. Douglas Balcomb
C. Edward Hancock
Greg Barker

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NREL/TP-550-24767

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

UC-600

13. ABSTRACT *(Maximum 200 words)* The Grand Canyon house is a joint project of the DOE's National Renewable Energy Laboratory and the U.S. National Park Service and is part of the International Energy Agency Solar Heating and Cooling Programme Task 13 (*Advanced Solar Low-Energy Buildings*). Energy consumption of the house, designed using a whole-building low-energy approach, was reduced by 75% compared to an equivalent house built in accordance with American Building Officials Model Energy Code and the Home Energy Rating System criteria.

14. SUBJECT TERMS Low-energy buildings, passive solar, Energy-10, NREL, IEA Programme Task 13, Grand Canyon

15. NUMBER OF PAGES
108

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT