TITLE: LOS ALAMOS NATIONAL LABORATORY PASSIVE SOLAR PROGRAM

AUTHOR(S): Donald A. Neeper

SUBMITTED TO: 1981 Passive and Hybrid Solar Energy Program
Update Meeting
Washington, D.C.
August 9-12, 1981

By acceptance of this article, the publisher recognizes that the
U.S. Government retains a nonexclusive, royalty-free license
to publish or reproduce the published form of this contribu-
tion, or to allow others to do so, for U.S. Government pur-
puses.

The Los Alamos Scientific Laboratory requests that the pub-
lisher identify this article as work performed under the au-
spons of the U.S. Department of Energy.

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663  Los Alamos, New Mexico 87545
An Affirmative Action/Equal Opportunity Employer
ABSTRACT

Progress in passive solar tasks performed at the Los Alamos National Laboratory for FY-81 is documented. A third volume of the Passive Solar Design Handbook is nearly complete. Twenty-eight configurations of sunspaces were studied using our solar load ratio method of predicting performance; the configuration showing best performance is discussed. We have noted and measured the minimum level of insolation needed to generate convective flow in our thermosiphon test rig.

We also include information on test room performance, off-peak auxiliary electric heating for a passive home, free convection experiment, monitored buildings, and technical support to the US Department of Energy.

SUMMARY

The Los Alamos National Laboratory performed work on eight passive tasks for the Department of Energy, Office of Solar Applications for Buildings, during FY-81.

A third volume of the Passive Solar Design Handbook is being compiled, and a draft will be ready before the end of FY-81.

Using the solar load ratio (SLR)** method for predicting performance of sunspace-type passive buildings, we studied 7 different geometries each with 2 configurations of storage wall and the presence or absence of night insulation. The comparative performances of the various configurations were obtained.

Previous Los Alamos work in free convection confirmed the validity of the similarity approach. Having already established the importance of doorway air convection to heat transfer in passive solar buildings, we are now simulating larger rooms and studying the effect of room length and width, transoms, and vents on heat transfer by free convection.

Thermosiphon collector experiments performed on our convective loop suggest that a certain threshold of solar energy is required to operate convective flow. This measured level of minimum insolation is approximately 40 to 50 Btu/h ft².

In FY-81 we studied 14 test cell configurations. A set of these experiments led to the discovery that a masonry Trombe wall can be used as a heat flux meter. This technique enables us to determine the U-values of the outer surface and glazing during night periods.

As part of our program of instrumented buildings, we have completed a comprehensive analysis of the Balcomb house. Our conclusion is that the overall performance of the house has been exceptionally good.

We are currently analyzing and evaluating data from our study of off-peak auxiliary heating for a passive solar house. The control system has performed fairly well; however, excessive and unexpected heat losses suggest that additional insulation should be installed during home construction to isolate the ground storage in order to insure greater heating efficiency.

I. INTRODUCTION

The Los Alamos National Laboratory began its studies of passive solar systems in early 1976 with the idea that such historically sound methods for residential heating were most appropriate for the imperatives of today's energy-saving society. However, modern times and technology dictated that the performance of passive solar systems be optimized, the behavior be well understood, and the technology itself placed on a firm engineering foundation.

The Laboratory began passive systems studies with the use of small test boxes and larger test rooms. The purposes of both the boxes and the rooms were the same: to provide a simple, inexpensive method of evaluating individual passive concepts, techniques, geometries, and materials and to provide accurate experimental results against which to validate theoretical numerical modeling and simulation methods.

The following four interconnected elements have continued to form the cornerstone of the Laboratory's passive solar program:

- Laboratory experiments consisting of carefully controlled evaluations of one or more passive

**Solar load ratio (SLR) is defined as solar radiation absorbed in the solar system divided by building heating load.
techniques through the use of physical models or test rooms (special small structures);
- Evaluation of various passive techniques through year-round, hour-by-hour monitoring of the performance of a number of residential and light commercial passively heated buildings in New Mexico and elsewhere;
- Development of theoretical and numerical models for predicting the thermal performance of buildings employing passive techniques, and the use of these models to evaluate their utility in various latitudes and climates and their sensitivity to variations of design parameters;
- Dissemination of useful information on passive solar heating to the architectural and building community in the form of handbooks and computer codes.

II. PASSIVE SOLAR DESIGN HANDBOOK (R. W. Jones)

The Passive Solar Design Handbook, Vol. 3, is in preparation as a sequel to Vol. 2. It will supplement Vol. 2 by the addition of extensive new data. There will be chapters on the optimum mix of conservation and solar, direct gain, and sunspaces. Also included will be appendices containing extensive new data on thermal-storage walls and solar radiation.

The optimum-mix chapter will present information on the optimum mix of conservation and passive solar strategies in building design. Guidance will be available within this section on selecting the appropriate conservation level for a given location.

The direct gain chapter will contain extensive new information relative to the Vol. 2 coverage. There will be SLR correlations for nine high-mass reference designs (as opposed to two in Vol. 2). Analysis methods will also be presented for a low-mass, sun-tempered design, and numerous new sensitivity curves will be presented.

The sunspace chapter will present SLR correlations for 28 reference designs. An extensive set of sensitivity data will also be included.

We will present 57 solar load correlations (as opposed to the 4 in Vol. 2), including 15 water wall, 21 vented Trombe wall, and 21 unvented Trombe wall correlations.

The solar radiation data will be more accurate and comprehensive than in Vol. 2. A second correlating parameter, the average monthly clearness ratio, will be added to relate radiation incident on and transmitted through tilted surfaces to the radiation incident on a horizontal surface. There will also be data to relate absorbed solar radiation to transmitted solar radiation, a feature not present in Vol. 2 (see Ref. 1).

III. SOLAR LOAD RATIO FOR SUNSPACES (R. D. McFarland, G. Lazarus)

It is vital that we understand and can predict the behavior of the sunspace- or greenhouse-type of passive design. It is fast becoming the most popular passive design with homeowners because of the amenities it offers in extra living space and plant growing, in addition to collecting solar energy.

We continued development of performance predictions for sunspace types of passive solar heated buildings. We based these predictions on hour-by-hour computer simulations using computer models developed in the framework of the Los Alamos passive solar energy simulation program (PASOLE). We determined SLR correlations for a total of 28 sunspace configurations. These are comprised of four geometries for attached sunspaces (Fig. 1) and three geometries for semi-enclosed sunspaces, all with and without night insulation and for two wall/storage types. "Semi-enclosed" is a term used for geometries in which the residence encloses the sunspace on three sides--the east and west ends and the north wall.

The two basic geometries for attached sunspaces are shown in Fig. 1. We studied these basic geometries with opaque, insulated end walls and with glazed end walls for a total of four attached-sunspace geometries.

Figure 2 shows the three semi-enclosed geometries selected for development of SLR correlations. East, west, and north walls of the sunspace incorporate provisions for natural circulation of warmer sunspace air into the residence.

![Geometry A](image1)

![Geometry B](image2)
Fig. 2. Section through semi-enclosed sunspace geometries.

Annual simulations were made for each of the configurations for 5 heating load coefficients for each of 24 US cities using typical meteorological year weather data, a total of 3360 simulations.

We found that Geometry D, with a single plane of tilted glazing, gives the best performance of the seven geometries investigated. It should be noted that Geometry D also presents the worst potential overheating problem.

The monthly solar savings fraction (SSF) results of the simulations were used to determine least-squares correlations of monthly SSF as a function of a modified monthly SLR (SLR'). These correlations were determined to minimize the standard deviation in annual SSF. The correlations are of the form:

\[ \text{SSF}_m = 1 - a \exp (-b \cdot \text{SLR}') \]

\[ \text{SLR}' = (S-L)/(DD \cdot \text{LCR}) \]

where S is the solar radiation absorbed in the sunspace per unit collector area; L is the loss from the sunspace per unit collector area, approximated by \( L = \text{LCR} \cdot DD \cdot H \), where LCR is the sunspace load coefficient per unit collector area; DD is the monthly number of heating degree-days; LCR is the building load coefficient per unit collector area; and H, a, and b are empirical constants found for each of the 23 configurations.

*Solar savings fraction (SSF) is defined as 1 - auxiliary heating required, divided by building heating load.

The table below compares the annual performance of two sunspace systems with that of unvented double-glazed Trombe wall systems with and without a selective surface. None of the systems has night insulation.

<table>
<thead>
<tr>
<th>City</th>
<th>LCR</th>
<th>(1) SSF</th>
<th>(2) SSF</th>
<th>(3) SSF</th>
<th>(4) SSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>36</td>
<td>0.60</td>
<td>0.72</td>
<td>0.52</td>
<td>0.69</td>
</tr>
<tr>
<td>Caribou, ME</td>
<td>24</td>
<td>0.29</td>
<td>0.26</td>
<td>0.17</td>
<td>0.33</td>
</tr>
<tr>
<td>Madison, WI</td>
<td>24</td>
<td>0.27</td>
<td>0.33</td>
<td>0.22</td>
<td>0.39</td>
</tr>
<tr>
<td>Nashville, TN</td>
<td>24</td>
<td>0.43</td>
<td>0.56</td>
<td>0.40</td>
<td>0.57</td>
</tr>
<tr>
<td>Santa Maria, CA</td>
<td>60</td>
<td>0.64</td>
<td>0.77</td>
<td>0.50</td>
<td>0.64</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>24</td>
<td>0.36</td>
<td>0.40</td>
<td>0.30</td>
<td>0.45</td>
</tr>
</tbody>
</table>

1. Sunspace Geometry A with opaque ends
2. Sunspace Geometry D
3. Unvented Trombe wall with no selective surface
4. Unvented Trombe wall with selective surface

IV. SIMILARITY STUDIES OF INTERZONE CONVECTION (J. E. Perry)

The understanding of how passive buildings behave depends, in large part, on understanding the heat transfer within the structure. For this reason, we have, for the past 2 years, investigated this phenomenon.

In the computation of heat transfer within multizone structures, and especially in the quantitative computer modeling of this heat transfer, it is particularly important to understand the heat transfer by free convection through open doorways between rooms that are at different temperatures. We can calculate, by well-known techniques, heat conduction through walls, and radiation energy flow through openings. But the calculation of this kind of convection in any convenient and quantitative form has remained intractable since Navier and Stokes published their original equations of fluid motion in 1827 and 1845, respectively.

Recently, doorway convection has been found to be an important mechanism for heat transfer. Refer to the energy-flow study of the Balcomb house in Section VI-B of this paper.

The problem can be approached through similarity studies, but even this technique has not had wide applicability to inter-room or inter-zone cases. In this similarity method, the fluid flow equations are set up in nondimensional form with two nondimensional groups of constants appearing as coefficients in the equations. The solutions of the equations are similar for those fluids and equivalent geometries for which the two coefficients have the same values. In the case of convection, the "similar" solutions are the flow velocity fields and the temperature distributions.

The two coefficients pertinent to free convection are the Grashof (Gr) and Prandtl (Pr)
numbers. Given two connected rooms \( r \) and a scale model of these rooms \( m \), the convection between rooms can be calculated by studying the convection in the model provided \( \text{Gr}(r) = \text{Gr}(m) \) and \( \text{Pr}(r) = \text{Pr}(m) \). To achieve these equalities, assuming air in the gas and establishes the similarity of the two rooms, \( \Delta T(r) \), it is necessary to use a different gas and an altered \( \Delta T(m) \) in the model.

\[ \text{Nu} = h H / k \]

where \( h \) is the heat transfer coefficient (Btu/h ft²°F), \( H \) is the characteristic length (e.g., the height of the doorway), \( \Delta T \) is a temperature difference (e.g., between rooms or between the top half of the door and the bottom half), \( T \) is the average absolute temperature of the gas, and \( \rho \) is the density. The Prandtl number, which establishes the similarity of temperature distributions between model and rooms, is given by

\[ \text{Pr} = \frac{v}{a} = \frac{\rho C_p}{k} = \frac{C_p}{k} \]

where \( v \) is the kinematic viscosity of the gas.

The current experiments are an extension of those undertaken recently by Dennis Weber at Los Alamos. The model is an insulated box of inside dimensions 100 in. long, 48 in. wide, and 24 in. deep. An electrically heated end plate simulates a Trombe wall, a water-cooled end plate simulates a north building wall, and a 1-in.-thick Styrofoam sheet with doorway simulates the east-west room-divider wall. To insure equality of Grashof and Prandtl numbers, a dense gas, Freon 12, is used in the model, and \( \Delta T(m) = 3.2 \Delta T(r) \). Under these conditions, the room linear dimensions are 5.65 times those of the model.

To discuss convection heat transfer, it is necessary to invoke a third similarity number, the Nusselt Number \( (\text{Nu}) \). This is given by

\[ \text{Nu} = h H / k \]

where \( h \) is the heat transfer coefficient (Btu/h ft²°F). In this case \( h \) is the natural convection heat transfer coefficient averaged over the doorway area.

Analysis shows that for inter-room convection, the three similarity numbers are related by the expression

\[ \text{Nu} = C \text{Pr} \text{Gr}^{1/2} \]

where \( C \) is a discharge coefficient related to the sharpness of the edges of the door opening. Empirically this relation has been found to hold for \( C \) in the range of 0.65 to 1.0.

From his model and also from doorways in actual buildings, Weber found \( \text{Nu} = 0.26 \text{PrGr}^{1/2} \). By substituting in the appropriate values for air, the corresponding convection heat flow through a doorway is given by

\[ \frac{dQ}{dt} = \frac{4 \rho C_p}{k} \text{Gr}^{1/2} \]

where the heat flow is in Btu/h, \( w \) is the width of the door in ft, \( H \) its height in ft, and \( \Delta T \) in °F is the measured difference between the air temperature in the upper half of the door area and that in the lower half of the area.

Weber's results confirmed the validity of the similarity approach. His formula for convective flow as a function of the air temperatures in a doorway is an important result for calculating heat flows in multroom buildings. However, his work was for a limited set of room-door geometries. The present experiments will undertake to confirm and extend his results. Whereas his model applied to two rooms 8 ft high by 13.5 ft square, the present model can represent rooms up to 11 ft high, 22 ft wide, and a total of 45 ft long. The following variables can be studied: room lengths, widths, heights, and different heights room-to-room, door heights, transoms, upper and lower vents, and doors that are off-center in the dividing walls. As with the previous experiments, the objective is to derive an empirical algorithm or algorithms that can be used for mathematical modeling.

V. THERMOSIPHON COLLECTOR EXPERIMENTS

(F. Biehl)

The goal of this program is to devise design guidelines for air thermosiphon heating systems to be used in large building retrofit applications. The results of a test system will be compared with analytical results in order to verify the analytical approach. This method will permit us to evaluate performance of system configurations not actually tested. Additionally, we will use the analysis to generate the optimum configuration for various localities.

We test two parallel, side-by-side test loops simultaneously so that a selected design parameter may be evaluated relative to a reference configuration. Details regarding the test setup are available in Ref. 5.

Test data were obtained for the three channel depths of 3.5, 6.5, and 10.5 in. Channel depth is the narrow dimension for air flow behind the absorber of a flat plate collector. The test results for the 3.5-in. and 6.5-in. depths are presented in Figs. 3 through 6 and show the collector efficiency and flow Reynolds numbers for the 3.5-in. and 6.5-in. channels. Figure 3 depicts the collector efficiency as a function of stress factor (defined as the difference between collector inlet temperature and ambient temperature, divided by the incident solar insulation). Test points and analytical predictions are indicated in all four figures. Constant ambient temperature, solar incidence angle, and optical properties were employed in the analysis. The majority of test data were obtained at ambient temperature between 40 and 50°F. Analytical calculations at 40°F and 50°F are shown for the west collector (6.5-in. channel) to illustrate the impact upon collector performance of the assumed ambient temperature.
An examination of the figures reveals that the predictions are more accurate for the 6.5-in. channel than for the 3.5-in. channel. Further inspection of Figs. 4 and 6 show that the Reynolds number is considerably higher for the 6.5-in. channel. Since the heat transfer between the collector plate and airstream depends on the flow Reynolds number, the simulation requires an acceptable analytical model for this relationship. The model employed in the analysis was extrapolated from measured data in heated flow channels operating at higher Reynolds numbers and, therefore, the greater the extrapolation from the reference values, the more likely it is that the extrapolation will deviate from the correct value. Nusselt number experimental results are absent in the low turbulent-flow regime (or transition regime) for asymmetrically heated rectangular ducts in thermally developing flow. The collector plate employed consisted of a sheet metal panel with attached extended surfaces perpendicular to the collector surface (fins). In order to achieve correlation between test and analysis, a factor of 0.7 was used for fin efficiency.

The three previously discussed collectors are all 15 ft in length. The length of the 3.5-in. deep collector was changed to 7.5 ft in order to evaluate collector length upon performance. An analysis that simulated the proposed length change showed a substantial attenuation in flow Reynolds number accompanied by a corresponding loss in performance. Since the analysis is suspect at a low Reynolds number (less than 3000) and a poorly performing collector would yield little information, a few design changes were incorporated into the shorter configuration. We modified the bottom of the airflow channel from square corners to quarter-round corners and painted the interior of the collector flow channel. The former change reduces the corner flow resistance from 40 to 10% of the total system resistance, whereas the paint improves radiant heat transfer from the absorber plate to the rear of the channel, which is also exposed to the air stream.

The weather pattern that prevailed during the tests of the short collector included few clear-sky days. These weather conditions provided an
opportunity to evaluate collector response to low intensity solar radiation. Unfortunately, the insolation tended to change from low to moderately high intensity over relatively short time periods so that the collectors rarely reached steady-state conditions. However, we did observe a threshold of insolation below which no energy is extracted from the air stream. This suggests that a certain level of solar energy is required to generate convective flow. This measured level of minimum solar radiation is approximately 40 to 50 Btu/h ft² (where the diffuse radiation component predominates) and has been confirmed by the computer simulation. Computer results are depicted in Fig. 7 showing the per cent energy loss (heat losses in the system divided by the collector section heat gain) as a function of incident solar radiation and collector inlet temperature.

FIG. 7. Per cent energy loss vs insolation.

VI. COMPONENTS AND BUILDINGS (R. D. McFarland)

A. Test Rooms

Since 1976 the Laboratory has been using small, side-by-side test cells, designed to be reconfigurable, to evaluate passive heating techniques and to obtain thermal performance data for validating computer codes and models. In FY-81, we studied 14 test cells designed as follows:

<table>
<thead>
<tr>
<th>Cell</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unvented masonry wall, flat black.</td>
</tr>
<tr>
<td>2</td>
<td>Unvented masonry wall, selective surface.</td>
</tr>
<tr>
<td>3</td>
<td>Double-wide sunspace, glazed aperture sloped at 60° from horizontal.</td>
</tr>
<tr>
<td>4</td>
<td>Commercial water wall, selective surface. Crimsco, Inc., heat wall module.</td>
</tr>
<tr>
<td>5</td>
<td>Texxor chips of phase-change calcium chloride thermal storage with selective surface.</td>
</tr>
<tr>
<td>6</td>
<td>Sun-tempered building model of Navy housing, with adjustable parameters.</td>
</tr>
<tr>
<td>7</td>
<td>Double-wide sunspace, glazed aperture vertical, with glazed roof sloped at 30° from horizontal.</td>
</tr>
<tr>
<td>8</td>
<td>Unvented masonry wall without thermostat per international agreement of the Committee on Challenges of Modern Society.</td>
</tr>
<tr>
<td>9</td>
<td>Nonsolar reference cell for load determination.</td>
</tr>
<tr>
<td>10</td>
<td>Heat-pipe wall (developed in the passive program) supplied by Battelle Columbus Laboratory.</td>
</tr>
</tbody>
</table>

All of the test rooms have been revised and were in operation with 180 channels of data working well on our new data logging system. This system has already detected and helped eliminate errors that would have been difficult to find in previous years. With the new system, the laboratory operator can obtain a plot of any parameter upon command.

The glazed aperture has been standardized on most of the rooms to increase the LCR to about 26, using patio door glass. See Ref. 6.

The heat-pipe wall in Test Room 14 proved to be somewhat troublesome. The five-heat-pipe unit from Battelle was too large for the test-room aperture, leaving one heat pipe partially covered. Shipping damage to Los Alamos rendered one pipe useless; subsequently, a second heat pipe failed. In spite of these problems, we collected data from this test room during the heating season. The results indicated that the heat-pipe concept works well with all heat pipes in operation.

The cell showing best performance in terms of collection efficiency was Cell 5, the water wall with selective surface. The phase change cell (Cell 6) performed well, but tended to overheat once the phase-change salt was melted. The performance of the direct gain cell (Cell 11) was improved markedly by the addition of night insulation.

During the winter, comparative tests were run between Cell 1 (unvented masonry wall with flat black paint) and Cell 2 (unvented masonry wall with selective surface foil). Table II summarizes the general results. Cell thermal performance is measured by the collection efficiency during a selected two-week period in each month listed on the table. Also compared is the performance of Cell 5, the water wall.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>COMPARATIVE PERFORMANCE OF CELLS 1, 2, AND 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>Number of Glazings (All 3 Cells)</td>
</tr>
<tr>
<td>12/80</td>
<td>2</td>
</tr>
<tr>
<td>1/81</td>
<td>2</td>
</tr>
<tr>
<td>2/81</td>
<td>1</td>
</tr>
<tr>
<td>3/81</td>
<td>1</td>
</tr>
</tbody>
</table>
We have discovered that a masonry Trombe wall can be used as a heat flux meter. From temperatures measured at the two surfaces of the masonry wall, one can determine the heat fluxes by applying the diffusion equation. This technique enables us to determine the effective U-values of the outer surface and glazing during night periods, when there is no insolation on the wall. This is emerging as a very nice analysis tool. The U-values given in Table III were determined by this method and illustrate the advantage of a selective surface as compared with double glazing. Measurements at the top, middle, and bottom of the wall show temperature stratification. The stratification would lead to erroneous results if one attempted, for example, to determine an effective emissivity of the surface from temperature measurements at a single level.

<table>
<thead>
<tr>
<th>Number of Glazings</th>
<th>Night Insulation</th>
<th>Selective Surface</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>No</td>
<td>No</td>
<td>0.46</td>
</tr>
<tr>
<td>1</td>
<td>No</td>
<td>No</td>
<td>0.80</td>
</tr>
<tr>
<td>1</td>
<td>No</td>
<td>Yes</td>
<td>0.36</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>Yes</td>
<td>0.29</td>
</tr>
<tr>
<td>1 or 2</td>
<td>Yes</td>
<td>No</td>
<td>0.14</td>
</tr>
</tbody>
</table>

B. Instrumented Buildings

For the past several years, we have studied 14 privately owned passive solar buildings to record the thermal comfort and energy savings characteristics and to provide validation data for calculations of the behavior of the monitored portions of the buildings.

We have completed a comprehensive analysis of the Balcomb house and will do a review of other houses.

The Balcomb solar house is located in Santa Fe, New Mexico, at an elevation of 7200 ft and a latitude of 35.6°N. It is a two-story building with a total living area of 1950 ft² of floor area. The solar heating is primarily passive but also incorporates an active system for supplemental heat storage. Warm air is drawn through ducts from the top of the greenhouse and forced by two 250 W fans through rock beds located beneath the downstairs living area floors; distribution is passive by conduction up through the floor. The house is very well insulated, with an overall measured heat-loss coefficient of 14,300 Btu/°F-day (counting the greenhouse as an unheated space). There is ample mass for heat storage in the masonry (adobe) wall that separates the greenhouse from the house, the rock-on dirt floor of the greenhouse, the rock beds, and a partially bermed north wall.

Performance data on the house have been collected for the period November 1, 1978-April 24, 1979, and more detailed information was obtained over a 6-week period in spring 1980. Daily energy flows have been calculated for the following elements:

- Heat flow through the adobe wall that separates the house from the greenhouse;
- Convection through the doorways that separate the house from the greenhouse;
- Heat storage in the plaster walls and also in the wood roof beams and furniture of the house;
- Heat generated by a small wood-burning stove (was estimated);
- Heat required for the evaporation of water from plants and other sources of water within the house (was estimated);
- Heat transferred by the fans from the greenhouse to the rock beds, heat flow up through the floor slabs covering the rock beds into the dining room and living room, and heat flow into the ground underneath the rock beds; and
- Heat flow from the water heater to the house (was estimated as 11,780 Btu/day plus 25% of the electrical energy into the water heater).

The overall performance of the house has been extraordinary. It has provided good comfort conditions in a cold climate with very small requirements for auxiliary heat. Solar heating fraction is 89%; operation is simple and reliable.

The greenhouse is an efficient solar collector. Approximately 31% of the solar radiation transmitted into the greenhouse is subsequently transferred to the house. In addition, the greenhouse is adequately heated, maintaining conditions well above freezing, without auxiliary heat. A critical design feature that leads to greenhouse effectiveness is the ability to thermally isolate the house from the greenhouse by closing doors.

The predominant mode of heat transfer between the greenhouse and the house is by convection through doorways that are opened during the daytime. The fact that the greenhouse serves as a major traffic area is important to the effectiveness of this control mechanism. Typical convection through a doorway is 50,000 Btu on a sunny day for the upstairs bedrooms and 23,000 Btu for the downstairs; this difference is due to the slightly colder room temperatures and higher greenhouse temperatures upstairs. The typical driving AT upstairs is 15°F. Much of this heat goes to satisfying daytime loads, but about 40% is stored in plaster walls, wood-beamed ceiling, and house furnishings.

The primary importance of the massive adobe wall between the house and the greenhouse is for direct-gain storage in the greenhouse. Most of the heat absorbed by the wall is released back to the greenhouse at night and is essential to maintaining reasonable temperature conditions in the greenhouse. The amount of night transmitted through the wall to the house is 1.4 million Btu for the year. This effect is larger upstairs due to less shading of the wall, slightly lower room temperatures, and a thinner wall (10 in. vs 14 in. downstairs).
Heat storage in the plaster walls, wood-beamed ceiling, and furnishings of the house is significant. Carryover heat from one day to the next is observed on 89 of the 176 days of the analysis period, averaging 49,200 Btu per day. Diurnal heat storage (heat stored and released during the same day) occurs nearly every day and averages 89,800 Btu/day.

The effect of water evaporation in the greenhouse is significant in improving the living quality by increasing the humidity into the 20 to 50% comfort range; this humidity increase is at the expense of about 57,000 Btu or 10% of clear-day solar gains.

The rock bed definitely appears to have a positive effect on the heating of the house and especially on the comfort characteristics, although these effects are less than originally estimated. About 53% of the heat deposited in the rock bed is conducted up through the floor slab into the living area. The remaining 47% is conducted into the ground underneath the rock bed (the perimeter of the rock bed is insulated with 2 in. of foam, but it is not insulated underneath). The average floor-surface temperature above the rock bed is 69.2°F, which compares with 50°F measured on the floor, well away from the rock bed. The beneficial effect of this increase in floor temperature allows a decrease in air temperature of the room of about 20°F in order to maintain equivalent comfort conditions. It is also important to note that heat would be lost from the floor, even if the rock beds were not present. The net benefit of the rock bed to the house is estimated as 30,000 Btu per day or 5.3 million Btu per year, combining the direct and two indirect effects. Another benefit of the system is the 10-15°F reduction in greenhouse temperatures observed when the fan is operated. Reverse thermosiphon from the rock bed to the greenhouse can significantly impair the effective performance of the system; backdraft dampers prevent this degradation.

Summer weather in Santa Fe is mild with large diurnal swings. Maximum house temperatures are 82°F upstairs and 78°F downstairs without air conditioning. Overheating that might be caused by the greenhouse is prevented by sun control, good ventilation, and night-vent cooling of the large house Mass. The greenhouse roof and second-floor balcony effectively shade the adobe wall. Cross ventilation and stack ventilation remove excess heat.

Excellent agreement was achieved using the monthly SLR method to estimate auxiliary heat based on the actual observed solar radiation and net heating requirements. The house was treated as a mixture of semi-enclosed sunspace (to account for the greenhouse) and direct gain (to account for the SE, SW, NW, and NE house windows). See Ref. 8.

VII. COOLING (R. D. McFarland)

We are in the process of determining the cooling implications of solar gains and thermal storage as the first step in integration of residential cooling, heating, and daylighting. We will go on to review climate data for the broad potential of reducing residential cooling loads by suitable use of passive architecture. We sent a letter to DOE Headquarters in June 1980 including data showing some of the cooling load impacts of passive heating systems.

At this time we have just begun work on a comprehensive study of the total energy savings of various schemes of preventing solar overheating—a study that we hope will result in general methods for design. Figure 8 shows typical results obtained for simulations with south glazing overhangs on a water wall passive heating system. These are lines of constant energy savings relative to the same system with no overhang. The numbers on the lines represent thousands of Btu/year/ft² of collector. This particular graph is for a heating load-collector area ratio of 28 Btu/DD ft² and a cooling system COP of 1.0. The overhang ratio is the width of the overhang, X, divided by the height of the aperture being shaded, H; the separation ratio is the distance between the top of the aperture and the bottom of the overhang, Y, divided by H.

![Fig. 8. Effects of overhangs on a water wall passive heating system in Albuquerque, NM.](image)

VIII. STUDY OF OFF-PEAK AUXILIARY HEATING FOR A PASSIVE SOLAR HEATED RESIDENCE (H. S. Murray)

Introduction

The auxiliary energy for passive solar heated structures may be provided by storing energy in the ground underneath the structure during utility off-peak hours. This approach is attractive to builders of passive solar heated homes due to the relative ease with which electrical resistance mats may be placed on the ground during excavation for the foundation, and due to improved aesthetics achieved by eliminating baseboard electrical heaters. This auxiliary heating method is attractive to the electrical utilities because the system uses only off-peak power for heating and would thus alleviate concerns that passive solar heated homes would aggravate utility load peaking problems.

The use of off-peak storage released passively to the heated enclosure leads to significant control problems. Energy must be expended before it is
needed to heat the structure due to the thermal lag of the storage medium. The success of this approach depends upon the development of a control system that regulates the room temperature sufficiently while using energy at a cost lower than that for a conventional electrical backup system.

Project History and Objectives

This is a joint project between the Los Alamos National Laboratory; the Public Service Company of New Mexico (PNM), the electric utility company; and Commcico, Inc., a builder of passive solar heated homes in Santa Fe, New Mexico. The objective of the project is to determine the feasibility of a passive, off-peak electrical auxiliary heating system. The role of Los Alamos is to provide system analysis, instrumentation support, control system design, and performance analysis.

The house under study is a 1200 ft² passive solar house with direct gain and Trombe wall components, located in the La Vereda subdivision of Santa Fe, New Mexico. Construction of the house was undertaken in late 1979. A number of temperature measurements are made in the ground heating system, interior of the house, and in the Trombe wall to determine system performance. Complete hourly electrical load data for the entire system, heating subsystem, and hot water subsystem are provided by PNM. We took data on the system from October 1, 1980, through April 30, 1981. During this period, control system operation was studied using different modes of operation.

System Analysis

Prior to installation of the heating system, simulation studies were performed on the system using actual solar and weather data to determine design parameters and to examine the effect of control strategy on system performance. The performance of an intelligent controller that knows the weather the following day but operates the heating system only off peak (10:00 a.m. to 8:00 p.m.) compared to conventional thermostat control of baseboard heaters. The findings of the simulation studies were as follows:

1. Optimum depth of the mats should be 9 in. below the floor slab.

2. The optimally controlled ground heating system uses 17% more energy than the baseboard system but at an 18% cost savings due to the off-peak rate differential (approximately one-half of the on-peak rate).

The simulation analysis was performed for a wide range of system parameters, such as ground and fill conductivity. We assumed that peripheral losses would be minimal due to the use of rigid insulation. We calculated that the ground thermal storage system losses should be less than 24% for the system to be clearly economically superior to a conventional system.

Control System

Because the simulation analyses indicated a need for an intelligent controller, a microprocessor-based control system was specified and installed. The controller is quite flexible, allowing for the study of different control strategies. The use of this controller during the 1980-81 winter illuminated a number of problem areas pertaining to microprocessor control of advanced heating systems; the specific problems with which we dealt were sensor failure, system response to power failures, and improving operator interface.

Performance Analysis

The system was operated in different control modes during the experimental period. The specific results of the effect of control strategy are not complete; however, the system used considerably more electrical heating energy than expected. Temperature measurements in the ground and floor slab were used to calculate heat flow into the heated enclosure; the heating system was activated on November 27, 1980. The monthly performance of the system from December 1980 through April 1981 is summarized in Table IV. The total of heating degree-days for October through April was 5504 degree-days.

We observed that only 50% of the electrical energy used is delivered to the heated enclosure. The losses are thus far greater than expected. Heat-flow calculations for the soil below the electrical mats indicate that 8% of the heat is lost downward. This loss is well within the limit for economical operation, as found in the simulation analyses. However, an additional 42% of the heat appears to be lost peripherally, and this loss leads to poor system performance.

Average enclosure temperatures are summarized in Table V. The control system was set to control the interior temperature at 70°F.

| Table IV |
|-------------------|-------------------|-------------------|-------------------|-------------------|
| Month  | Solar (Direct + Trombe Wall) Energy (kwh) | Electrical Heating Energy (kwh) | Floor Heating Energy (kwh) | Heating Degree-Days | Heating System Efficiency (%) |
| Dec.  | 47.7 | 23.7 | 12.3 | 913 | 51.9 |
| Jan.  | 46.7 | 27.5 | 11.7 | 1012 | 42.5 |
| Feb.  | 51.6 | 36.9 | 17.2 | 800 | 49.3 |
| Mar.  | 24.0 | 40.3 | 22.4 | 871 | 55.6 |
| Apr.  | 20.6 | 22.0 | 16.0 | 391 | 45.5 |
| Seasonal  | 42.0 | 29.6 | 14.7 | 3693 | 50.0 |

| Table V |
|-------------------|-------------------|-------------------|-------------------|
| Month  | Avg Room °F | Avg High Room °F | Avg Low Room °F | Ambient °F |
| Oct.  | 74.8 | 81.4 | 69.0 | 46.9 |
| Nov.  | 69.9 | 75.6 | 64.8 | 35.1 |
| Dec.  | 71.5 | 77.2 | 66.9 | 33.3 |
| Jan.  | 69.9 | 75.1 | 65.7 | 32.4 |
| Feb.  | 69.9 | 75.6 | 65.2 | 36.2 |
| Mar.  | 67.8 | 71.6 | 64.1 | 36.9 |
| Apr.  | 71.9 | 75.5 | 68.6 | 52.0 |
| Unheated  | 57.0 | 63.0 | 50.0 | 30.0 |

Conclusion

A breakdown of heating cost--adjusted for the off-peak rate differential--compared to the heating cost for a conventional system--also adjusted for the off-peak rate differential--has not yet been made. The low system-heating efficiency of 50% suggests, however, that the comparison will
probably not be favorable. The control system performed reasonably well; it appears that the normal passive heating system overheating problem was not aggravated, and the nominal interior temperatures were kept near the desired setpoint. The house was unoccupied a great deal of the time so that normal interior heat loads were not present, and normal operation would not require the 70°F setpoint. These factors increased the heat load. The question of whether this system can be made to operate economically is being examined. In order that a passive ground-storage system be functional beyond question, a great deal of care must be taken during construction to isolate thermally the ground storage reservoir. Specifically, sufficient rigid insulation should be extended to a depth of at least two ft below the electrical-mat level.

IX. SUPPORT TO DOE HEADQUARTERS (J. E. Perry, W. O. Wray)

Los Alamos technical support work consists of four general aspects: (1) responses to specific requests for information from the DOE Passive Solar Division, (2) the intercomparison of passive solar network computer calculations, (3) participation in meetings for the generation of a multiyear plan for data acquisition in Class A monitored passive buildings, and (4) monitoring of the University of California at San Diego (UCSD) contract on the "Impact of Controls in the Passive Heating of Buildings.”

In the first category, multiyear passive solar plans for passive solar heating and cooling and passive solar products were read and extensive reviews were provided.

As the second aspect of our support work, we direct the activities of national and international working groups on passive solar simulation analysis. Simulation exercises are defined by Los Alamos and distributed to working group members. Results are later submitted to the Laboratory, where a comparative analysis is conducted. The results of the comparative analysis are reported at periodic meetings of the two working groups. The NATO-sponsored Committee on the Challenges of Modern Society (SS/EA) working group that last met on December 10, 1980, in Nice, France, to discuss results. The next meeting is planned for August 22 in Brighton, England.

The System Simulation and Economic Analysis (SS/EA) working group was organized by DOE and functions at the national level. The SS/EA group last met in Philadelphia on May 27, 1981, during the AS/ISES conference. Another meeting is tentatively planned to coincide with the 6th National Passive Solar Energy Conference in Portland, Oregon, September 8-12, 1981.

Considerable time has been spent discussing with members of the Energy Center of UCSD their passive controls work; we have also studied their papers. We are monitoring this excellent work for the Chicag Operation Office of DOE, which funds passive contracts.

REFERENCES


PASSIVE PAPERS PUBLISHED DURING FY-81


J. D. Balcomb, "Passive Solar or Superinsulation?" A. T. Times, National Center for Appropriate Technology, Butte, MT, April, 1981. (LA-UR-81-1133)