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EVALUATION OF HOURLY BUILDING ENERGY PROGRAMS FOR PASSIVE SOLAR RESIDENTIAL CONSTRUCTION

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ABSTRACT

The accuracy of three computer programs, DOE-2.1b, TARP84, and EMPS 2.1, for predicting the hourly energy use of passive solar residential buildings was investigated. Measured energy use and interior space temperatures from passive solar test buildings were compared with the results obtained from computer analyses of those buildings. The data base was composed of available data from unoccupied buildings that had passive solar components and had detailed, accurate measurements over a well-defined test period. The results indicate that TARP84 and EMPS-2.1 can accurately model most passive solar features, whereas DOE-2.1b is not as accurate for some high mass structures. Structures with partial shading of the high mass component were more accurately modeled by TARP84 and by EMPS-2.1 than by DOE-2.1b.

INTRODUCTION

Computer simulation programs that perform hourly building energy analysis are potentially powerful tools for predicting the performance of houses that incorporate various conservation and solar alternatives. Compared with experimental testing, such programs offer the means to investigate many different passive solar options at reduced cost and in a shorter period of time. However, in order for these programs to be useful and accepted, it must be demonstrated that they can accurately predict the hourly load profile of the building. This is a much more stringent requirement than accurate prediction of the seasonal and/or design energy consumption, particularly where large amounts of insolation are experienced or where massive construction alters the thermal response of the building.

The accuracy of hourly building energy simulation computer codes in evaluating high mass and passive solar features has been of interest to many in the solar energy community. Hunn (1982) describes the SERI Class A solar building monitoring programs and the data that are expected to be available from this program. In a later paper (1983), Hunn provides a description of the completeness and suitability of the Class A data sets for use in evaluation and validation of passive solar computer codes. The later paper also provides a preliminary comparison of the measured data with predictions from DOE-2 computer programs. Judkoff (1985) investigated the input/output consistency between various international building energy simulation codes, using one of the National Research Council of Canada passive solar test buildings. Wortman, Judkoff, and Burch (1983) report a preliminary comparison of measured and predicted energy use from the SERI Class A test house in Golden, Colorado. In a related project, Robertson and Christian (1985) undertook a study of the difference in energy use between high mass and frame construction. To isolate high mass effects, the buildings used in the study had various frame and high mass envelopes but had no windows or other passive solar features. In addition, four building energy simulation codes were used as a consistency check of the data. In most cases the predicted energy consumption and interior temperatures were in

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good agreement with the measurements. Although the comparison with the codes was not intended as a validation study, it does have some aspects of such an investigation. Bowman and Lomas (1986) investigated the accuracy of a large number of building energy computer programs, including in the investigation some buildings with passive solar features. Much of the work described above deals with seasonal or annual energy use, rather than the hourly energy use profiles investigated here.

This paper describes an investigation of the accuracy of three computer programs, DOE-2.1b, EMPS 2.1, and TARP84, in predicting the hourly energy use of residential structures that incorporate large quantities of thermal mass, glazing, or both. The work builds on an investigation of these programs described in a previous paper by Sorrell et al. (1985). All three programs have been used by various organizations to predict energy consumption of passive solar designs. DOE-2.1b is a public domain code developed under contract to the U.S. Department of Energy. DOE-2 was used in the present work with custom weighting factors and with the optical properties of the glass input to the BDL. EMPS 2.1, the Methodology for Preferred Residential Systems, was designed specifically to evaluate solar and other alternative energy technologies. TARP84, the Thermal Analysis Research Program from the National Bureau of Standards (NBS), calculates loads only and does not include a system simulation.

The system simulations available in DOE-2.1b and EMPS 2.1 were not used to any appreciable extent. The evaluation was concerned with the accuracy of the codes in predicting thermal loads in residential buildings with typical passive solar features, such as high mass components and increased glazing. Of particular interest was the accurate prediction of the thermal load when it is changed or reduced by insolation stored or released from high mass structures. SERIRES was not evaluated because at the time of this work it required 64-bit hardware, to which we did not have convenient access. BLAST was not included because the thermal loads portion of the code is similar to TARP84, and the project did not deal with the system simulation in the code. The decision not to include SERIRES and BLAST was made as a matter of convenience to reduce the scope of the work and was not based on any prior evaluation of either code.

A high level of detail and quality was required in the measured data used for validation. A description of these requirements is given in the section entitled "Measured Data Base." The data selected for this project were from three National Research Council of Canada (NRCC) buildings, three houses from the passive solar project at Pala, California, and four test cells from the SERI Class A test at the National Bureau of Standards (NBS) site.

Using the three selected computer programs, each of these sites was modeled over a period of time that included the weeks during which the detailed measurements were taken. Three to four days were allowed for the building to reach equilibrium with the weather cycle, and the measured and computed values of the hourly energy consumption and indoor temperature were then compared. In the case of the Pala houses, only summer data were examined, while winter data were used for the other two sites. Two weeks of data were examined for the NRCC houses, ten weeks for the Pala houses, and one month for the NBS test cells.

The measured and computed quantities are compared in the "Results" section. This comparison includes not only energy use but also selected indoor temperature profiles. Results are presented graphically for several of the cases and in a statistical summary for all cases.

MEASURED DATA BASE

The measured data base consisted of previously conducted tests where enough data to model the building accurately were measured or otherwise known. For a project to be considered for the data base, the following requirements were set.

1. Weather must be measured on site.
2. The building must be unoccupied and have a known internal load.
3. Internal temperatures must be measured.
4. Either the actual performance of the HVAC system must be measured or the coil loads must be measured directly. It was desirable that both be measured.

A description of each of the projects that supplied measured data is provided below.

In a Canadian project, tests were conducted on three buildings of various construction in Ottawa, Ontario. The project, described in detail by Barakat (1984), includes four two-room "houses" and four single-room units. For this validation work, data were used from three of the two-room houses: a conventional frame house, a "medium mass" house with extra layers of gypsum board on the walls and ceiling, and a "high mass" house where all of the walls are finished with cement brick on the interior. In each of the buildings, the floor is frame construction over a separately heated basement. An insulated partition wall separates each house into a north room and a south room; only data taken while the connecting doors between the north and south rooms were closed were used in the validation work. The rooms were slightly pressurized to eliminate outdoor air infiltration.

As part of the Class A monitoring program, a passive solar test facility was constructed at the NBS site in Gaithersburg, Maryland. The single-story structure, described in Mahajan (1984), is divided into four long narrow test cells that each measure 27 ft (8.23 m) by 12 ft (3.66 m). All cells have a concrete floor slab and a clerestory window facing south. Cell 1 is used for instrumentation; Cell 2 contains a 8-in (20-mm) thick concrete masonry Trombe wall across the entire south wall; Cell 3 is a "control" cell with a 14.4-ft^2 (1.34-m^2) south-facing window; Cell 4 has direct gain glazing across the entire south wall, a patch of high-density concrete in the floor where incident solar radiation falls, and additional concrete masonry thermal storage on the interior of the north wall.

In a project funded by two California utilities, eight 256-ft^2 (24-m^2) test houses were constructed at Pala, California, to investigate the performance of various passive solar features. This project has been described in detail by Clinton (1985) and Fralik (1984.) Three of these houses were modeled for the validation: a conventional frame structure with a concrete slab floor, a "high mass" structure where the walls are solid concrete as well, and a Trombe wall design. Because the data appeared inconsistent when the chilled water cooling loop was operating, the validation was performed against data taken when the cooling system was not operating and the temperatures were allowed to float.

A detailed description of the buildings mentioned above, the physical properties that were measured, and the data that were taken in each test is given in the references for each test. Table 1 gives a brief description of the physical characteristics of each building to provide a quick summary of these buildings that were modeled.

Input decks were prepared by Sorrell, Childers, and Vanhoy in a joint effort; that is, all three authors prepared or checked the input decks for all three codes. Measured values of thermal conductivity and density were used in most of the cases. In cases where the parameters were not measured, values from <u>ASHRAE Fundamentals</u> were used. However, care was taken to ensure that the values used, measured or estimated, were the same for each of the three codes. No attempt was made to "force" the results to agree with measured energy or temperatures. However, if the output was in substantial disagreement with the measurements, the input deck was re-checked for errors. Several errors, usually geometric, were found this way.

Both the NBS and the Pala buildings had slab-on-grade floors. For the NBS cells, the floor mass, thermal conductivity, and the ground temperature were measured. As the ground temperature was virtually constant over the simulation period, it was a simple matter to input this heat loss and mass in the codes. The Pala building was handled the same way. However, the floor mass and conductivity were not measured but were <u>Handbook</u> values for the material used. The ground temperature was not measured, and thus was estimated from the local weather. Because the estimated ground temperature was very close to the interior temperatures, the heat loss through the floor is quite small relative to the overall head balance. Thus a reasonable change in estimated temperature did not make an appreciable difference in the results. Of course, the floor properties and ground temperature were the same for each code.

<u>RESULTS</u>

A complete statistical summary of the results is given in Table 2 for all three building energy simulation codes used in this study. This table summarizes the building simulation runs that were made and provides the statistical accuracy of each simulation. The Canadian and the Pala buildings were divided into a north and a south room, the data given in Table 2 are for the south room; since the focus of the study was on accuracy in modeling passive solar features. However, simulations were run for both rooms. While statistical data are useful, graphical representation often provides a more detailed perspective of the results and of the accuracy or failure of the simulation. The eight graphs included here illustrate typical results or show differences in the ability of each code to accurately model the building energy use profile. A discussion of the results for each test location follows.

NRCC Test Buildings. The Canadian buildings are small unoccupied buildings with separate north and south rooms. The south rooms each have a glazing area larger than is typically found in residential structures. The data used in the validation work were taken when the door between the north and the south rooms was closed. Data taken with the door open and a fan helping to circulate air between the rooms are also available, but modeling the resulting combined forced and natural convection did not appear as straightforward as the situation with the door closed. Data were available for three types of wall construction: conventional wood frame, medium mass, and high mass. All floors are constructed of wooden joists and particleboard over a separately heated basement.

Simulations were conducted for all three types of construction, using each of the three computer codes. The agreement between the measured and computed results is indicated in Table 2. Because the work focuses on high mass construction, graphical results are given only for the high mass unit. Figure 1 plots the measured and computed energy consumption for the north room. This room required heating at all times, and therefore the temperature remained at the thermostat setpoint, within the accuracy of the control system. The results shown in Figure 1 are typical for the north room for all three building constructions and are taken to indicate satisfactory results from the computer models. Figure 2 gives the measured and computed energy for the south room with high mass walls. Although the outdoor dry bulb temperature is quite low, this room receives sufficient solar gain that the room temperature can rise above the thermostat set point and auxiliary heating is not always required. Generally, the measured energy consumption and the computed energy consumption are in good agreement, but the computer programs tend to predict slightly longer periods when no heating is required than were measured. The temperatures in the south room are shown in Figure 3. The times when the room temperature "floats" (the temperature rises above the set point without additional heating) are in good agreement; however, the calculated floating temperatures are always lower than the measured floating temperatures. These two factors--longer calculated float time and lower calculated floating temperatures--indicate that the computer models may tend to predict that more solar energy is absorbed by the building mass during the daytime than is actually the case. However, the computer models also predict that slightly more energy is required to heat the building at night than was measured, which is obviously not consistent.

The standard or RMS error for the calculated values is computed by taking the difference between the measured and calculated values each hour of the simulation period. The standard error generally indicates a larger error than would be expected from looking at the graphical results or than is given by the percent error. The percent error may indicate a smaller error because predictions of higher-than-measured energy during some periods may be canceled by predictions of lower-than-measured energy during other periods. On the other hand, the standard error tends to indicate a larger error. This is particulary true when there is cycling of the HVAC system, as is evident in Figure 4. Thus the percent error is usually an optimistic estimate and the standard error is a conservative estimate of how well the computer simulation predicts the building energy use.

NBS Test Cells. The NBS test cells are long narrow cells housed in a single building located in Gaithersburg, Maryland. Three types of construction are represented: a conventional cell, a direct gain cell with high mass walls, and a Trombe wall cell. The accuracy in modeling the conventional cell is given in Table 2. Results from modeling the Trombe wall were mixed, and all codes had some difficulty in modeling the direct gain cell. Because of this, and also because the focus of this work is on passive solar features, the following discussion is centered on the Trombe wall and the direct gain cells.

A summary of the error between measured and computed energy consumption in the cell with the Trombe wall is given in Table 2. Both EMPS and DOE have a Trombe wall subroutine, and it is relatively easy to model Trombe wall construction with these two codes. TARP, however, does not have a Trombe wall subroutine, and the Trombe wall must be "built." That is, the correct glass, air space, high mass wall, and living space must be put separately into the input deck to model or "build" the Trombe wall. DOE gave excellent results in modeling the Trombe wall. Both EMPS and TARP gave reasonable results, and other than the additional time required to model the wall, there was no particular disadvantage in using TARP for a building with a Trombe wall. On the other hand, for the Pala house discussed below, different results were obtained.

As can be seen from Table 2, TARP and EMPS underpredict the required energy consumption for the direct gain cell by 20%-30%, whereas the difference between the energy consumption predicted by DOE and the measured consumption is 50%. In addition, as evident from Figure 4, both TARP and DOE predicted longer floating times than actually occurred. In some cases (Days 27, 28, and 29 in Figure 4,) DOE predicted the cell would not require heating energy throughout an entire day, while the measurements show substantial heating energy required at night. The floating internal temperature profiles from TARP and EMPS, shown in Figure 5, are in reasonable agreement with the measured temperatures; however, DOE substantially overpredicts the internal temperature rise due to solar heating. All the simulations appear to be overpredicting the amount of energy stored in the high mass floor of the building, giving too much credit for thermal mass. This error is believed to be due to the long narrow geometry of the cell, where the high mass floor is never completely covered by incident radiation. Only part of the slab is in the sun at any one time. If this explanation is correct, DOE is giving more credit for thermal storage than is TARP or EMPS and much more credit than is indicated by the measurements.

The reason that DOE is less accurate than the other two codes is believed to be due to the different ways the three codes model incoming solar radiation. Both EMPS and TARP have an optional ray-tracing technique (which was used in all simulations) to compute the amount of solar radiation coming through the window and stored by the structure. DOE-2.1b allocates the amount of solar energy transmitted through the window to various building components by a fractional or percentage method. As would be expected, this method is not as accurate as the ray tracing technique, and DOE apparently predicts more energy storage in the floor than actually occurs.

<u>Pala Passive Solar Houses</u>. As described in the section on the data base, this project included eight small structures incorporating various passive solar design elements. Summer cooling energy use data and floating temperatures (the interior temperatures experienced when no cooling was used) were obtained for three of the buildings: the conventional, high mass, and Trombe wall houses. It should be noted that the conventional house had a 4-in (10-cm) thick concrete floor and, thus, for a small building had more than average thermal storage capacity. The high mass house had an identical slab floor but high mass concrete masonry walls. Because there appeared to be some problems with the data when the cooling system was operating, the only data used for the present validation work were data taken when the cooling system was inoperative and the temperatures were allowed to float. Measured and simulated floating temperatures are therefore compared rather than measured and simulated energy use.

The comparison of measured and floating temperatures for the south room of the conventional building is given in Figure 6, and similar results for the north room are shown in Figure 7. Since the door between the two rooms was always open, there is not much difference in temperature between the two rooms. Both EMPS and TARP modeled the floating temperatures with good accuracy, but DOE tended to underpredict the floating temperature swings. This is believed to be due to the high mass floor and the problems associated with modeling it, described above in the discussion of the NBS direct gain cell. The temperature is not predicted to rise as high during the day as is measured, because DOE predicts that more energy is absorbed by the mass storage; the temperature is not predicted to fall as low at night as it does, because the excess energy assigned to the mass must be released. A simulation using EMPS but suppressing the detailed ray-tracing analysis gave results similar to those from DOE.

Since percent error in mean temperatures has little value when floating temperatures are compared, a different approach is needed to present the statistical results. Instead, the standard (root mean squared) error between computed and measured temperature is used as the measure of accuracy for these cases. Standard error is probably best compared to the maximum difference between the measured daily high and the measured daily low temperatures; that is, the root mean squared (RMS) error in temperature can be compared to the temperature range. These results are given in Table 2. Because the measured floating temperature curve is relatively smooth, the standard error probably gives a good picture of the accuracy of the simulation.

Figure 8 shows the measured and predicted floating temperatures for the south room of the Trombe wall house at Pala. Again, the Trombe wall subroutines in EMPS and DOE were used to model this house, but the Trombe wall had to be "built" when using TARP. Surprisingly, TARP gave the most accurate results. Both EMPS and DOE underpredicted the temperature swing for this building, although the mean temperature predicted by EMPS is reasonably close to the measured value. DOE not only underpredicted the temperature swing but also calculated more solar energy transferred into the room than is actually the case. Floating temperatures from

TARP are in good agreement with the measured values. A summary of the RMS errors in floating temperatures for this case are given in Table 2.

Simulation of the high mass building gave a more accurate prediction of the floating temperatures as indicated by the lower RMS error in Table 2. However, the floating temperature range is also smaller because of the increased mass, so the percent error remains approximately the same. This building did not have the large south-facing window of the NBS direct gain cell, but it did have high mass walls. The lower solar gain, together with the fact that the code did not have to differentiate between a floor that was high mass and walls that were not, is probably the reason that predicted temperatures were in much better agreement with the measured values. The floating temperatures predicted by DOE for this building were in good agreement with the measured data and with the other two codes. All three codes were therefore deemed to have given acceptable results.

CONCLUSIONS

1. All three codes (EMPS 2.1, DOE-2.1b, and TARP84) accurately model passive solar features as long as there are no high mass structures in which only a part of the high mass component receives solar radiation.

2. In structures with high mass components, particularly high mass floors, where only a part of the high mass area receives solar radiation, EMPS 2.1 and TARP84 gave good results. The results from DOE-2.1b are generally not as accurate. The increased accuracy of EMPS 2.1 and TARP84 is believed to be due to the ray tracing algorithm in each.

3. Residential buildings with a Trombe wall were modeled reasonably accurately by both EMPS 2.1 and TARP84. However, in one case, DOE-2.1b gave accurate results, while in another case it did not.

REFERENCES

Barakat, S. A. 1984. NRCC Passive Solar Test Facility Description and Data Reduction. Building Research Note 214, National Research Council of Canada.

Bowman, N. T., and Lomas, K. J. 1986. Empirical validation of dynamic thermal computer models of buildings. Building Services Engineering Research and Technology, (In Press).

Clinton, J. R. 1985. Pala passive solar project final report, Volume I. Solar Energy Analysis Laboratory, San Diego, CA.

Hunn, B. D.; Turk, W. V.; and Wray, W. O. 1982., "Validation of passive solar analysis/design tools using Class A performance evaluation data." Progress in passive solar energy systems, American Solar Energy Society, p. 177.

Hunn, B. D. 1983, Analysis of validation Data Sets in The Class A Performance Evaluation program.

Fralik, S. 1984. "The Pala passive solar project" Solar Age, December.

Judkoff, R. 1985. International energy agency building simulation comparison and validation study. Proceedings of the DOE Building Energy Simulation Conference, August 22, 1985, Seattle, WA.

Mahajan, B. M. 1984. National Bureau of Standards passive solar test facility - Instrumentation and site handbook. NBSIR 84-2911.

Robertson, D. K., and Christian, J. E. 1985. "Comparisons of four computer models with experimental data from test buildings in northern New Mexico." ASHRAE Transactions, Vol. 91, Part 2B, p. 591.

Sorrell, F. Y.; Luckenback, T. S.; and Phelps, T. L., 1985. "Validation of hourly building energy models for residential buildings." ASHRAE Transactions, Vol. 91, Part 2B, p. 701.

Wortman, D. N.; Judkoff, R.; and Burch, J. D. 1983. "Measured vs. predicted performance of the SERI test house: A validation study." Proceedings of the National Heat Transfer Conference, June, Seattle, WA.

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TABLE 1
Building Properties

BUILDINGS	Total Floor Area, ft^2	Glass Area in ft^2		Floor Construction in lb/ft^2	Wall Construction in lb/ft^2
		Total	South-Facing		
NRCC				(2x12 Frame)	(Frame)
Conventional	321.6	38.77	27.98		6.14
Medium Mass					12.39
High Mass				9.91	*44.56
NBS				(5 1/2" Slab on Gravel)	
Conventional	355.0	26.80	18.05	61.21	6.58
Trombe Wall	352.7	117.12	108.37	61.21	#Trombe Wall
Direct Gain	352.7	88.75	80.00	62.73	Glass
PALA				(4" Slab on Grade)	
Conventional	276.0	35.56	9.50		12.24
Trombe Wall		89.93	63.87	36.70	+Trombe Wall
High Mass		35.56	9.50		4" Slab

* Frame wall backed by a 4 in concrete brick wall
\# 7.625 in CMU wall 110 lb/ft^3
\+ One-foot-thick CMU wall 110 lb/ft^3

TABLE 2

tatistical Summary --- Building Energy Use

Average Hourly Energy (kWh)	DOE-2.1b		EMPS 2.1		TARP84	
	% Error Total Energy	Standard Error (kWh)	% Error Total Energy	Standard Error (kWh)	% Error Total Energy	Standard Error (kWh)
271 771 42	-11.1 -7.5 -1.3	0.295 0.187 0.083	-0.4 -2.7 4.3	0.202 0.149 0.059	-5.1 -3.9 0.2	0.253 0.161 0.085
	-20.1 1.9 -53.9	0.121 0.152 0.476	6.4 20.6 -20.7	0.124 0.161 0.253	16.2 13.8 -30.7	0.113 0.214 0.277
	Standard Error (degrees F)		Standard Error (degrees F)		Standard Error (degrees F)	
	4.26 4.15 1.44		1.69 1.71 1.01		1.91 1.16 1.56	

ys NBS-18 days Pala-7 days

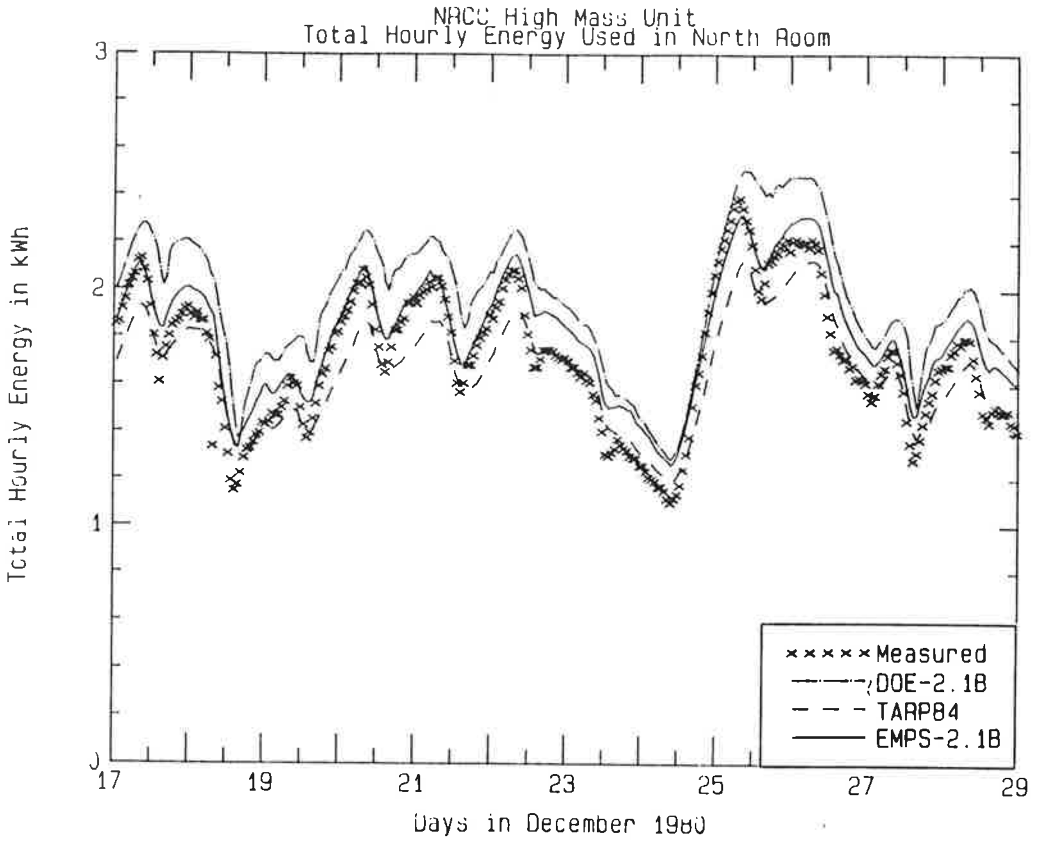

Figure 1. Measured and computed energy for the north room of the NRCC high mass passive solar test building

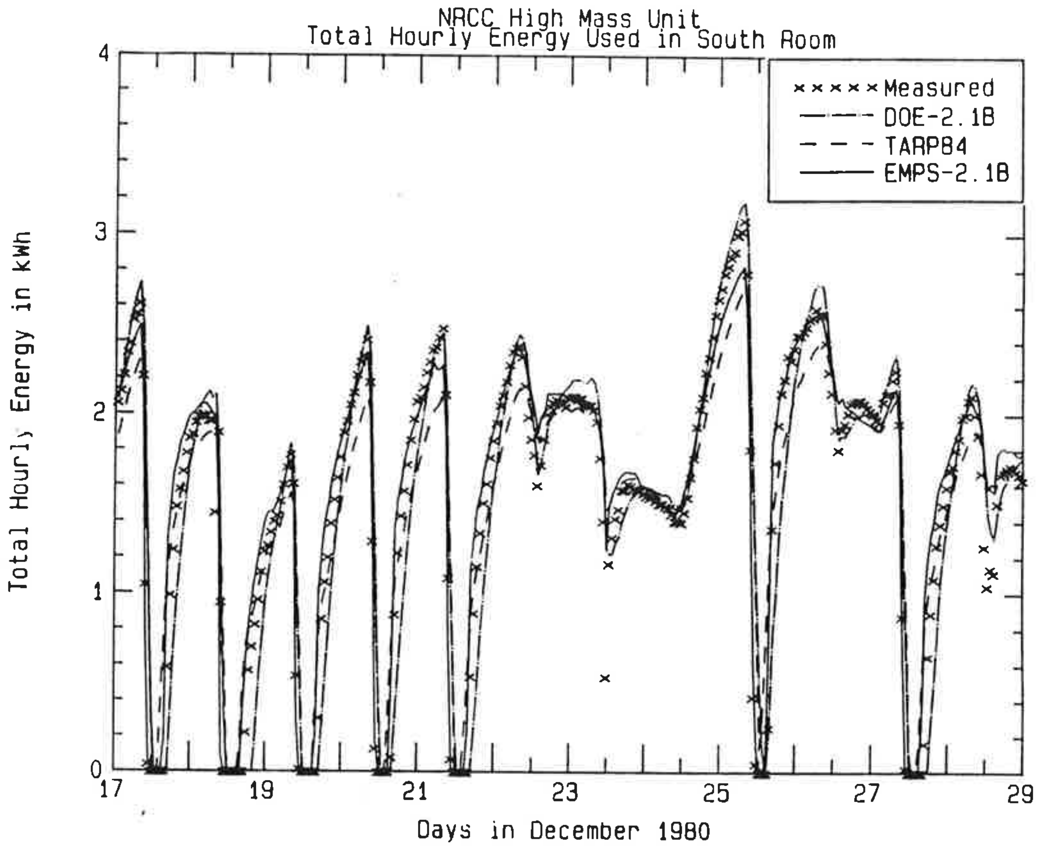

Figure 2. Measured and computed energy for the south room of the NRCC high mass passive solar test building

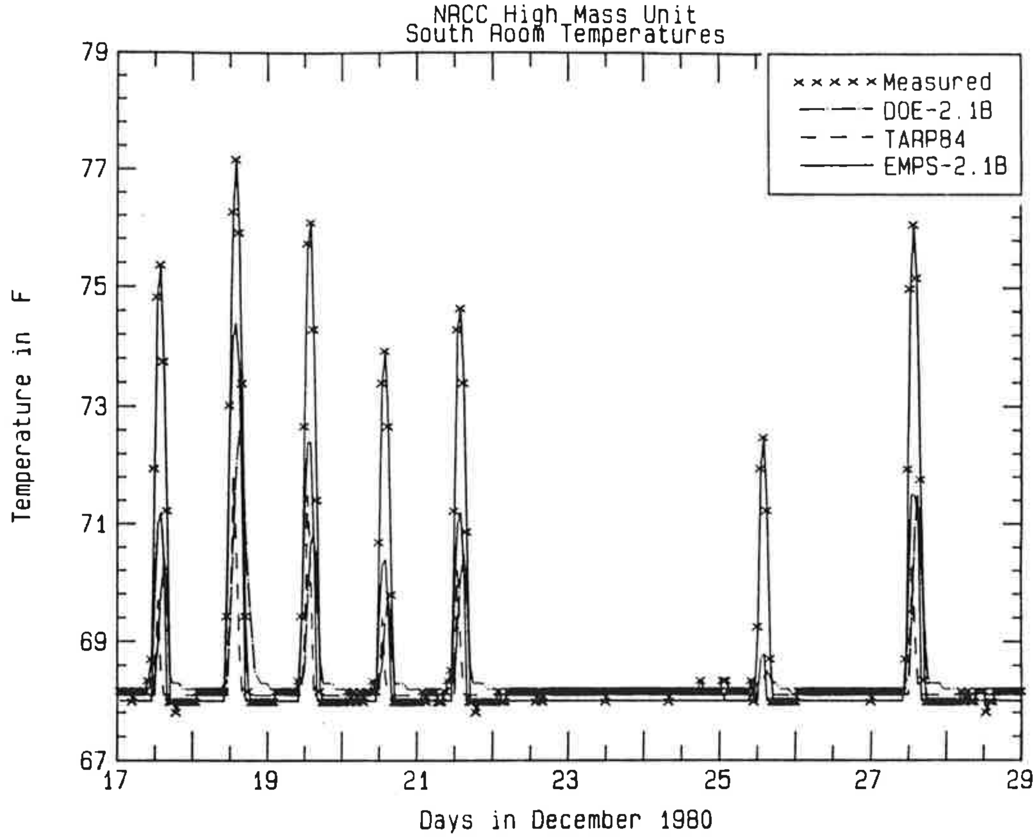

Figure 3. Measured and computed internal floating temperatures for the south room of the NRCC high mass passive solar test building

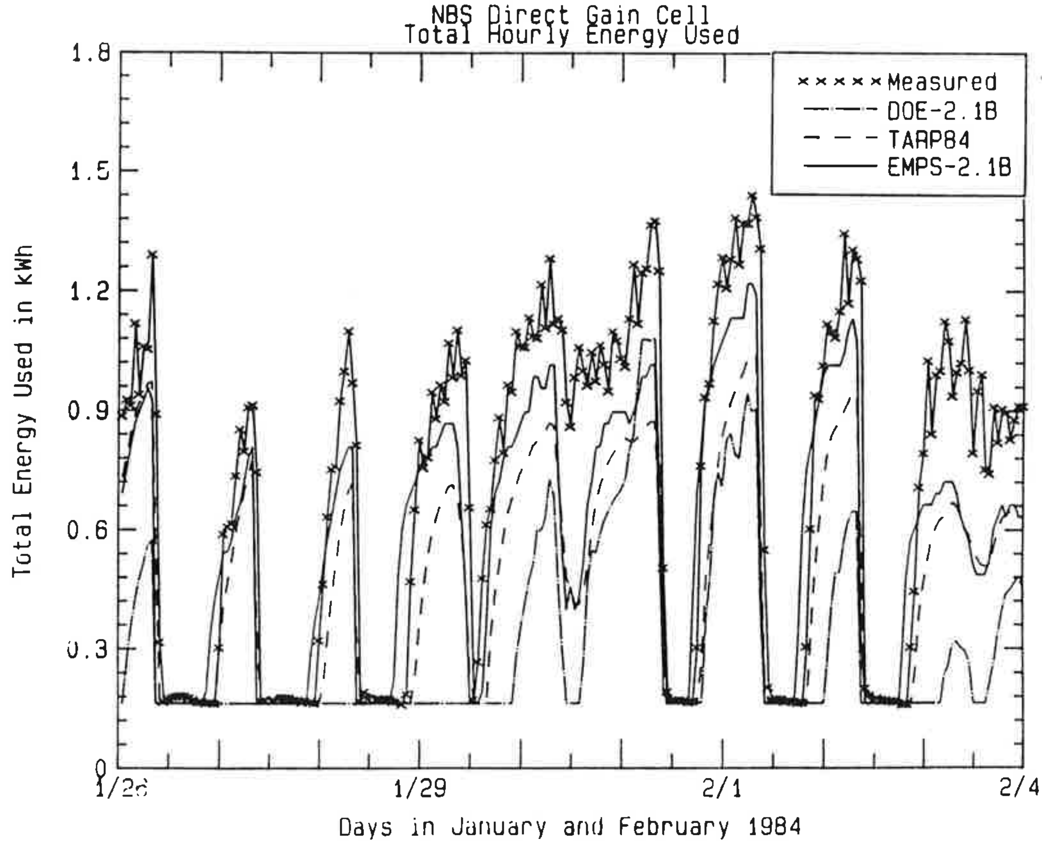

Figure 4. Measured and computed energy use for the NBS direct gain cell

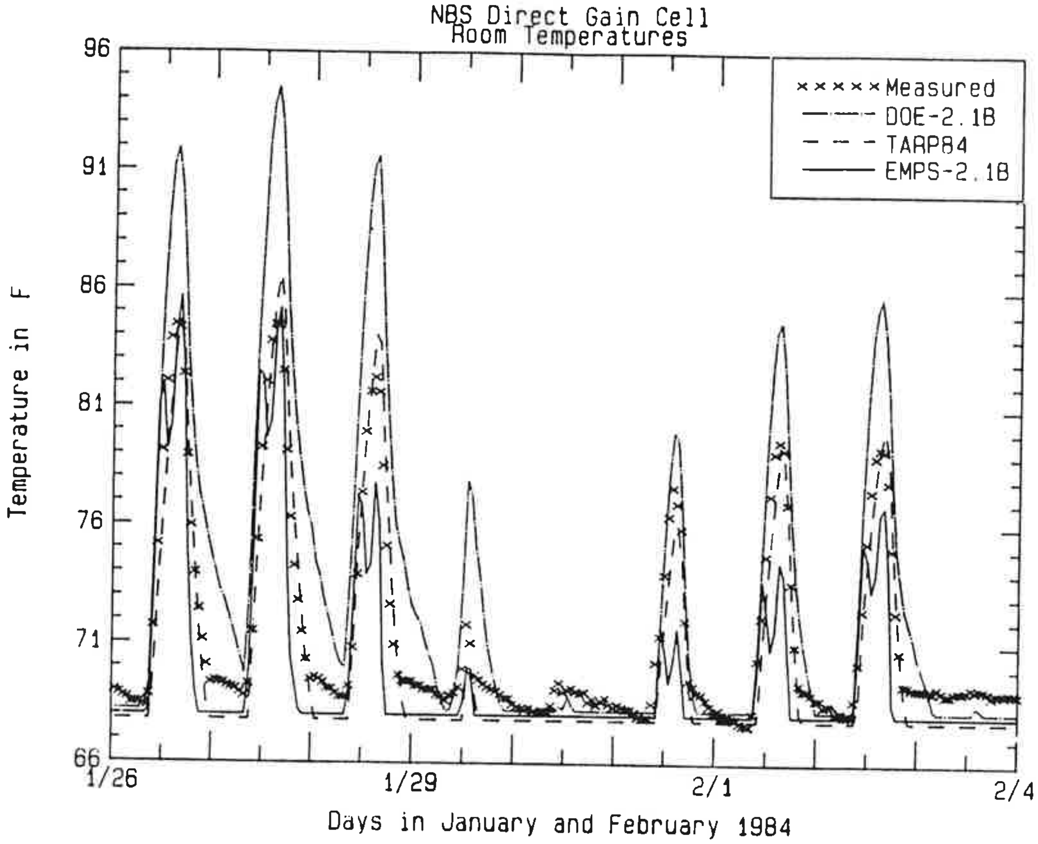

Figure 5. Measured and computed interior temperatures for the NBS direct gain cell

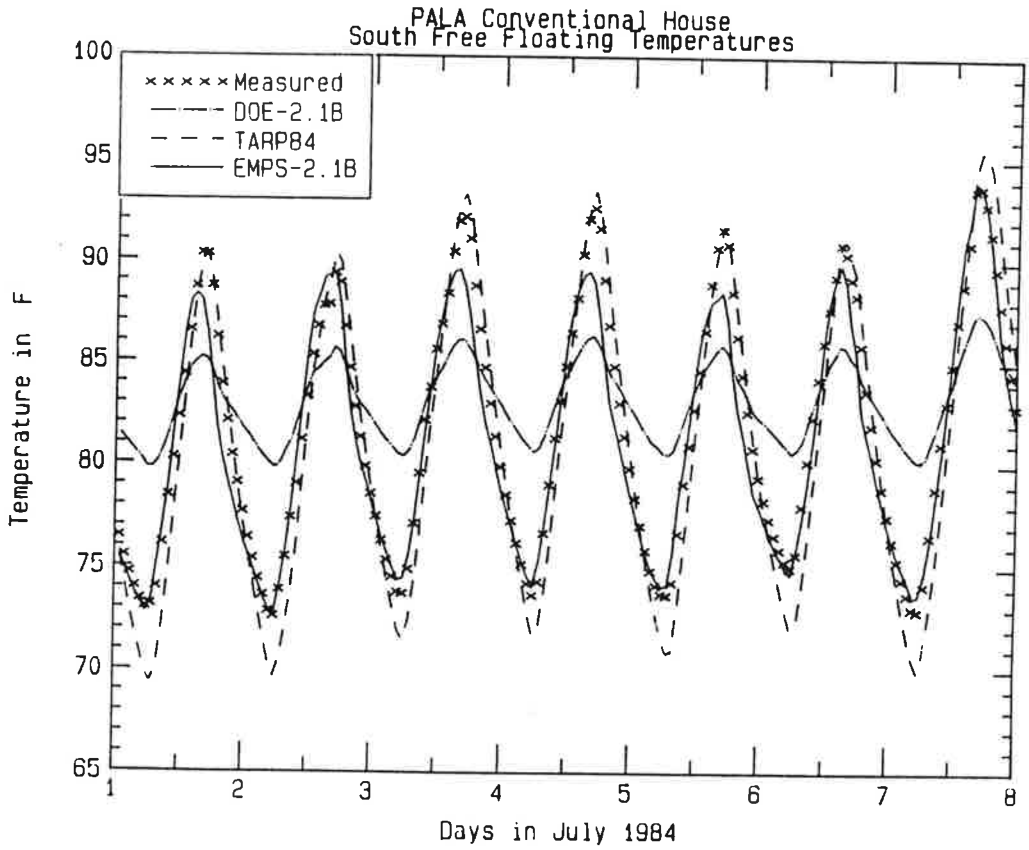

Figure 6. Measured and computed floating temperatures for the south room of the pala conventional house

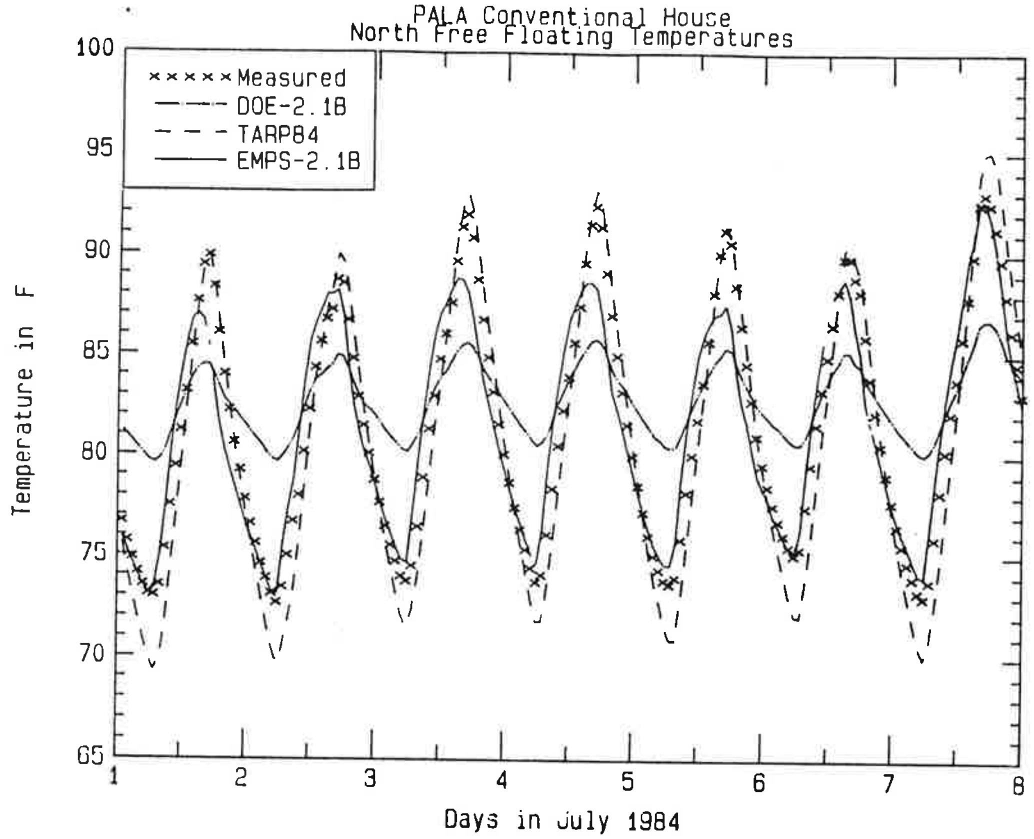

Figure 7. Measured and computed floating temperatures for the north room of the pala conventional house

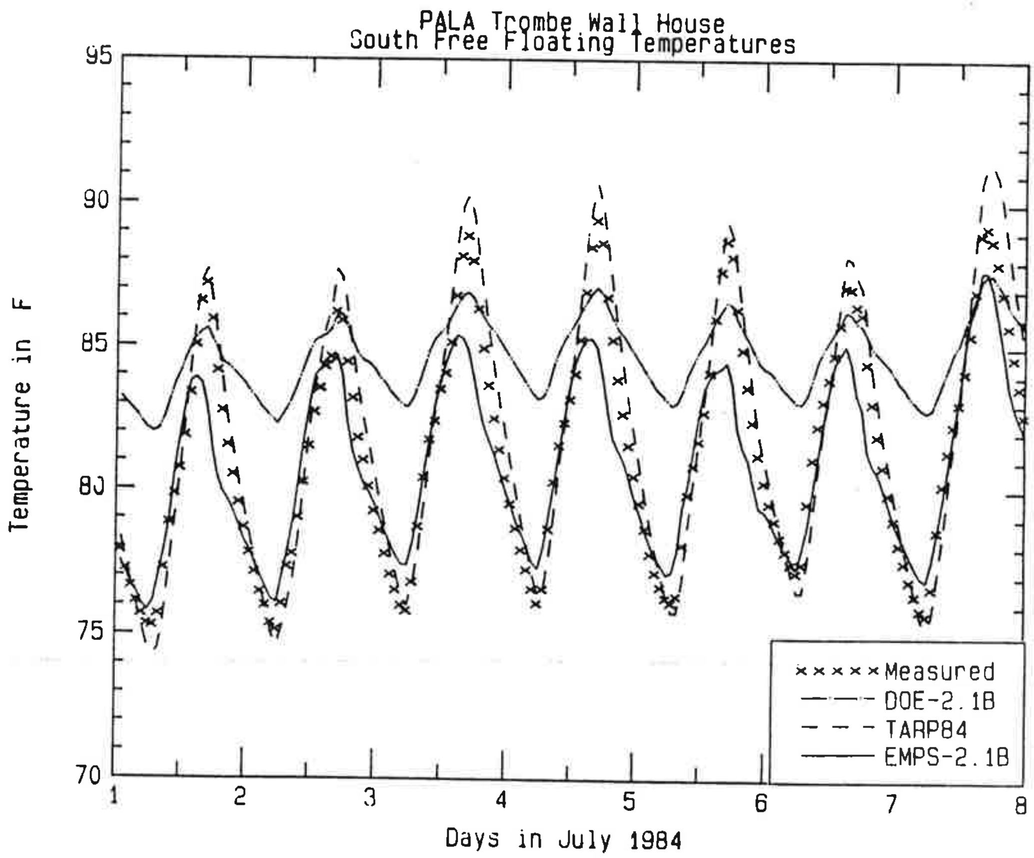

Figure 8. Measured and computed floating temperatures for the south room of the pala trombe wall house