SERI/TP-721-1137
UC CATEGORY: UC-59c
CONF-810509--20

MASTER

# A DAILY RADIATION MODEL FOR USE IN THE SIMULATION OF PASSIVE SOLAR BUILDINGS

S. SILLMAN
D. WORTMAN

APRIL 1981

PRESENTED AT THE
AS/ISES CONFERENCE AND EXPOSITION
26-30 MAY 1981
PHILADELPHIA, PENNSYLVANIA

PREPARED UNDER TASK NO. 1013.00

**Solar Energy Research Institute**
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

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

## DISCLAIMER

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $4.00

# A DAILY RADIATION MODEL FOR USE IN THE SIMULATION OF PASSIVE SOLAR BUILDINGS

Sanford Sillman
David Wortman
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

## ABSTRACT

A model is presented to characterize solar radiation with just three input parameters for each day. This compressed daily radiation data may be used in place of hourly data in simulations of passive solar buildings.

This method is tested with the SUNCAT passive simulation. Global horizontal and direct normal radiation data are input using the compressed daily form instead of by hour. Simulation results are found to be comparable to results based on hourly radiation data.

## 1. INTRODUCTION

Analysis of passive solar buildings is done most accurately with hourly simulations. Although useful to researchers, annual hourly simulations are often inaccessible to designers because they are run on a mainframe computer. Attempts to use an hourly simulation on a minicomputer have been hampered by the need for 17,000 hourly data inputs for global horizontal and direct normal solar radiation.

This paper describes a way to characterize each solar radiation component with just six input parameters for each day—three for global horizontal and three for direct normal radiation. If successful, this method would reduce the number of data inputs needed for yearly solar radiation from 17,000 to 2,300, and make hourly simulation with minicomputers more feasible. This method was tested with the SUNCAT passive simulation. We assume that a SUNCAT program operating on a mini-computer would work by taking the three radiation parameters for each day, calculating 24 hourly radiation values, and finding the building performance for the day. Accuracy is gauged by comparing the results of SUNCAT with daily radiation data to the results with actual hourly data.

## 2. DAILY RADIATION MODELS

Daily radiation is most easily modeled as a sine curve of the form:

$$Q(t) = A \cos \omega t \qquad [1]$$

with t being the hour and solar noon being zero. This equation has two constant parameters, the amplitude A and period ω. The usual method for describing daily radiation is to set ω for each day according to the day length from sunrise to sunset (1). The amplitude is then set to assure that total daily radiation in the sinusoidal model is equal to the actual daily total. The resulting values are:

$$\omega = \pi/t_d \qquad A = (1/2)\omega Q_T \qquad [2]$$

where $t_d$ is the day length and $Q_T$ the total daily radiation.

Figure 1 compares this daily radiation model with actual hourly weather data. As shown in the figure, the model sharply underestimates radiation during the hours of maximum insolation and overestimates radiation during off-peak hours.

An alternative is to set the parameters A and ω based not on day length, but on the maximum radiation for the day. In this method, the amplitude A is chosen to equal the maximum hourly radiation ($Q_m$), so that the maximum hourly radiation in the model will be equal to the actual daily maximum. The period ω is then set so that total radiation equals the actual daily total. Such a method results in the following values for period and amplitude:

$$A = Q_m \quad \text{and} \quad \omega = 2A/Q_T \qquad [3]$$

As shown in Fig. 2, this model is much more accurate than the model based on day length, but it slightly overestimates radiation at midday. A more accurate model would be a combination of these two methods:

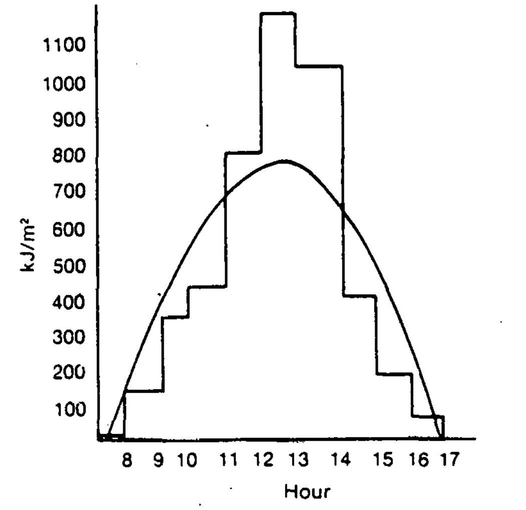



**Fig. 1. Daily Radiation Model Based on Length of Day Compared to Hourly Data**

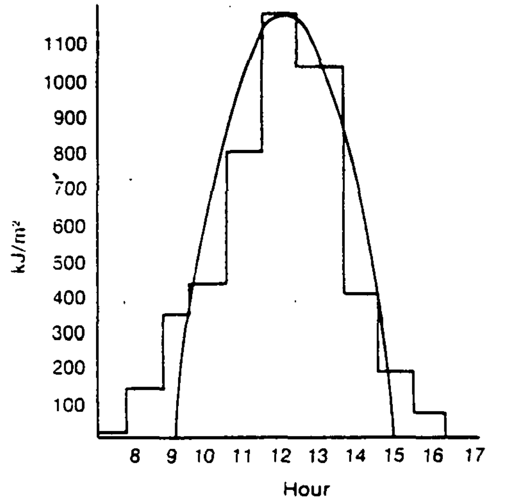



**Fig. 2. Daily Radiation Model Based on Maximum Radiation Compared to Hourly Data**

$$A = f_1(Q_m) + f_2\left[(1/2)\left(\frac{\pi}{t_d}\right)Q_T\right] \text{ and} \quad [4]$$

$$\omega = 2A/Q_T$$

The coefficients $f_1$ and $f_2$ are weighting factors that add to unity. Typical values of $f_1$ and $f_2$ are 0.6 and 0.4, respectively.

A recent study investigated the use of these daily radiation models in simulations of active solar heating systems (2). It concluded that simulations with the daily radiation model using Eq. 3 or 4 yield results comparable to simulations with hourly data.

Using daily radiation models in simulations of passive solar systems is more difficult. The models previously described always record maximum radiation at noontime, whether the actual maximum occurs in the morning, noon, or afternoon. This is adequate for simulation of active systems, since active system performance depends mostly on the magnitude of solar radiation and less on the time of day. Passive system performance, by contrast, is sensitive to the time of day as well as the radiation magnitude. Consequently, the daily radiation model described above will be modified to reflect the time of day.

The modification works as follows. Three inputs are required for each day: total radiation $Q_T$, maximum radiation $Q_m$, and the hour of maximum radiation $t_m$. Hourly radiation values are calculated using the sinusoidal formula. The order of those hourly values is then scrambled so that the maximum radiation occurs at the proper hour. If, for example, the time of maximum radiation occurs in mid-afternoon, the peak radiation values would be shifted to mid-afternoon and the smaller afternoon values would be shifted to morning and midday. The equation used to calculate modified hourly radiation values is

$$Q_H = A \cos \omega[t_H - 12.5 + I_{mod}(t_H, t_m)] \quad [5]$$

where $Q_H$ is the radiation for the hourly period ending at time $t_H$. Both the time $t_H$ and the hour of maximum radiation $t_m$ are expressed here as integers from 1 to 24, with 12 representing noon. $I_{mod}$ is a function of $t_H$ and $t_m$ with values shown in Table 1. Figure 3 shows the results of this modified daily radiation model and compares it with hourly data.

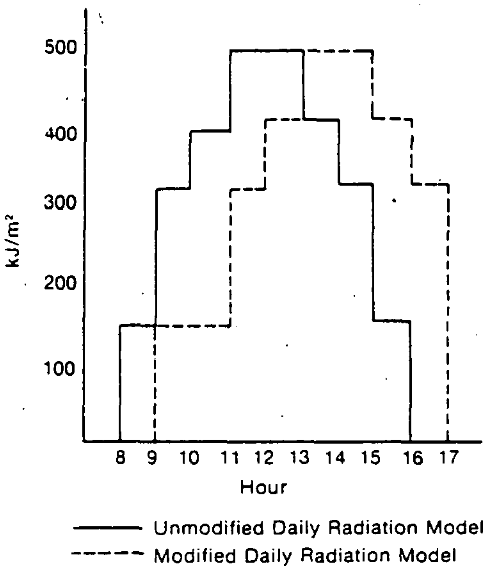
Compressed weather data and the modified daily radiation model will be used with the SUNCAT-2.4 passive computer simulation. Results will be compared with SUNCAT simulation using hourly radiation data.

The daily radiation model is used with the SUNCAT simulation in the following manner. SUNCAT consists of two programs, WCAT1 and WCAT2. WCAT1 is a radiation processing stage that generates transmitted radiation data for specific window configurations. WCAT1 is essentially an algorithm for generating tilted radiation values. Inputs are hourly values for both global horizontal and direct normal radiation. The output is the total hourly transmitted radiation. The second stage, WCAT2, is the actual building simulation, using the hourly transmitted radiation data generated by WCAT1. To be useful, the daily radiation model must be used with each stage of SUNCAT. Consequently, the daily radiation model must meet two criteria: it must model incident solar

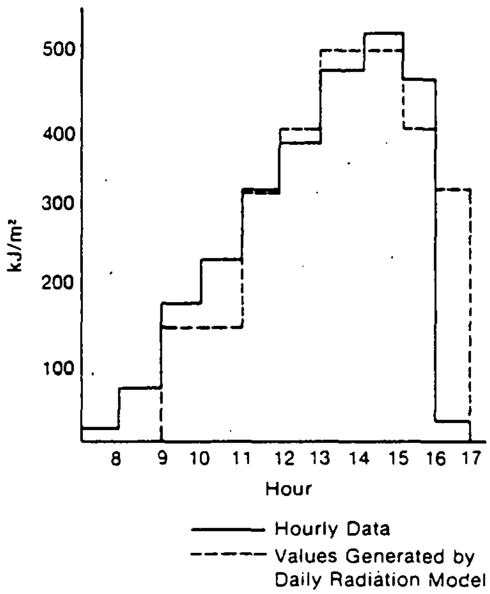
**Table 1. VALUES OF THE TIME-OF-DAY MODIFICATION FACTOR ($I_{mod}$)***

| $t_m$ \ $t_H$ | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 1 | 1 | 0 |
| 10 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 0 |
| 11 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | -1 | -1 | -1 | -1 | -1 | -1 | 0 | 0 |
| 15 | 0 | -1 | -1 | -1 | -2 | -2 | -2 | -2 | -2 | -1 |
| 16 | 0 | -1 | -1 | -2 | -2 | -3 | -3 | -3 | -3 | -3 |

*Values show $I_{MOD}$ as a function of integral hour of the day ($t_H$) and hour of maximum insolation ($t_m$). Both $t_H$ and $t_m$ are presented.




(a) Modification in Daily Radiation Model




(b) Comparison with Hourly Data

**Fig. 3. Daily Radiation Model Modified to Reflect Time of Day Compared to Hourly Data for a Day with Maximum Insolation Occurring in Afternoon**

radiation accurately enough for the passive simulation (WCAT2), and it must also model global horizontal and direct normal radiation with sufficient accuracy to calculate tilted radiation values (WCAT1).

The modified SUNCAT uses compressed weather data to express both global horizontal and direct normal radiation. The WCAT1 stage generates hourly values for global horizontal and direct normal radiation, calculates hourly transmitted radiation values, and outputs the transmitted radiation as daily radiation data. The WCAT2 stage accepts the daily transmitted radiation data and calculates hourly values for simulation. In this way, the SUNCAT program only holds 24 hourly radiation values at one time. The 17,520 radiation data inputs for WCAT1 and 8,760 inputs for WCAT2 are replaced by 2,300 and 1,190 inputs, respectively. The modification adds 15 FORTRAN statements to WCAT1 and 5 statements to WCAT2.

Daily radiation is calculated using Eqs. 1, 4, and 5. The coefficients $f_1$ and $f_2$ in Eq. 4 are set as follows:

For global horizontal radiation $f_1 = 0.6$ and $f_2 = 0.4$.

For direct normal radiation $f_1 = 1$ and $f_2 = 0$.

For incident radiation $f_1 = 0.7$ and $f_2 = 0.3$.

These coefficients are assigned different values because of the changing relative importance of the length of day. Hourly values of the direct normal radiation reflect the hours of bright sunshine rather than the actual day length. Consequently, the weighting factor for day length $f_2$ is set at zero.

The test of the compressed forms of solar radiation data involved running two building models (a high mass case and a low mass case) through the SUNCAT programs. The building models were developed for an ongoing building energy analysis simulation code validation program at SERI. Simulation results based on the compressed radiation data are compared to simulation results with regular hourly data. Typical Meteorological Year (TMY) data from Albuquerque, N. Mex., and Madison, Wis., were chosen, as these cities represent extremes in climatic conditions and provide a good test of the data compression technique. To examine the importance of the time of day on passive simulation, the WCAT2 compressed data case was run twice: once with the modified daily radiation model and once with the original (symmetric) daily radiation model, with maximum radiation always occurring at noon.

## 3. RESULTS

The results of the SUNCAT simulation runs are shown in Table 1 and Figs. 4 and 5. Table 2 shows that yearly heating loads for the compressed data runs are always within 2.2% of the runs using hourly radiation values and yearly cooling loads are within 1.2%. These errors are small compared to

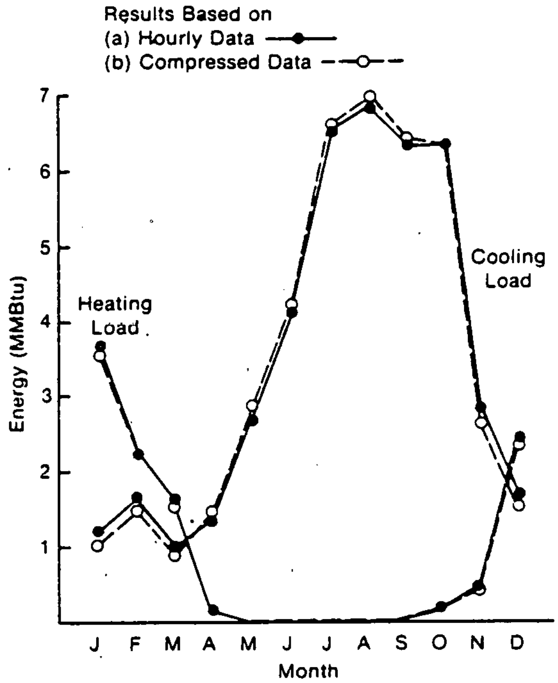



**Fig. 4. Comparison of Monthly Simulation Results: Albuquerque, N. Mex.**

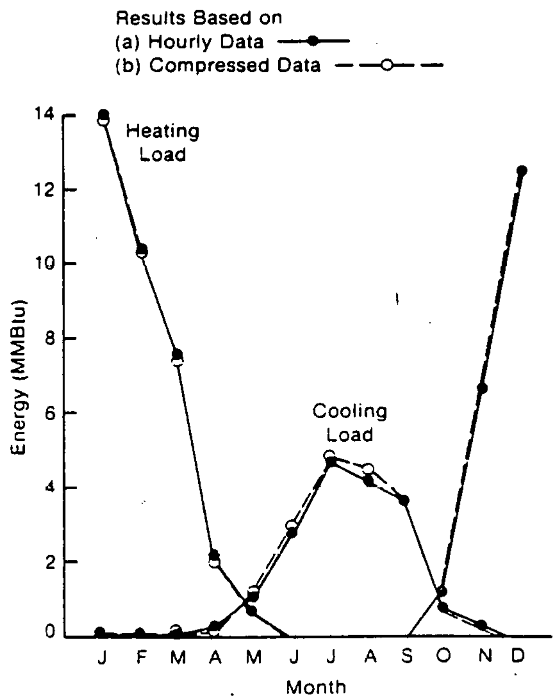



**Fig. 5. Comparison of Monthly Results: Madison, Wis.**

**Table 2. YEARLY LOAD COMPARISONS***

| Data Stations | Building Type | Yearly Loads | Hourly Data Simulation | Compressed Data Simulation | | Monthly RMS Deviation** | |
|---|---|---|---|---|---|---|---|
| | | | | Symmetric | Modified | Symmetric | Modified |
| Albuquerque | High Mass | Heating | 10.76 | 10.57 (-1.8%) | 10.53 (-2.2%) | 3.1% | 3.5% |
| | | Cooling | 42.68 | 42.38 (-0.7%) | 42.34 (-0.8%) | 3.6% | 3.7% |
| Albuquerque | Low Mass | Heating | 39.35 | 39.30 (-0.1%) | 39.15 (-0.5%) | 1.6% | 2.1% |
| | | Cooling | 75.25 | 75.20 (-0.1%) | 75.03 (-0.3%) | 2.6% | 2.8% |
| Madison | High Mass | Heating | 55.41 | 55.18 (-0.4%) | 55.18 (-0.4%) | 0.6% | 0.6% |
| | | Cooling | 17.86 | 18.08 (+1.2%) | 18.08 (+1.2%) | 2.8% | 2.8% |
| Madison | Low Mass | Heating | 75.67 | 75.62 (-0.1%) | 75.60 (-0.1%) | 1.5% | 1.5% |
| | | Cooling | 37.73 | 38.05 (+0.8%) | 38.07 (+0.9%) | 4.2% | 4.1% |

*Loads are all in MMBtu/yr. Percentage deviations between hourly data and compressed data simulations are shown.

**RMS deviation in monthly load values between hourly data and compressed data simulations is expressed here as a percentage of average monthly load.

other errors (such as the characterization of infiltration or ground coupling) inherent in the building energy simulation process. The monthly heating and cooling loads, shown in Figs. 4 and 5, show a greater divergence than the yearly loads. The deviation between compressed data runs and hourly data runs is 10% or less for all but a few months with small heating or cooling loads. The absolute differences for these months are minimal compared to the average monthly loads. Table 2 shows the root-mean-square (RMS) deviation in monthly loads, expressed as a percentage of the average monthly load. The largest RMS deviation is 4.2%.

Table 2 also compares WCAT2 runs, using the symmetric daily radiation model with runs using the modification to reflect time of day. Table 2 shows no significant differences between the symmetric and modified radiation model results. Therefore, we conclude that the time-of-day modification is not necessary in the simulation stage (WCAT2) but only in the radiation processor (WCAT1), which calculates tilted incident radiation values.

Using compressed weather data in the radiation tilting algorithm is very accurate. Calculated incident radiation values based on compressed weather data may be compared with calculated values based on hourly data. The calculated monthly total incident radiation values agree to within 2% or better, and the calculated annual totals agree to within 0.5%.

A trial run was also made using the symmetric radiation model as input to both SUNCAT stages including the radiation processor. Results are less accurate than the assymmetric runs, but of sufficient accuracy to be useful. The error in yearly load calculation is less than 4%, and the error in calculated yearly incident radiation is 2%. We hesitate to recommend use of the symmetric model in the WCAT1 stage because its accuracy may depend on the building window configuration. Further research is necessary to determine whether the tilting algorithm in the WCAT1 stage can be run accurately with the global horizontal and direct normal radiation inputs compressed in symmetric form.

## 4. CONCLUSION

Although further investigation is needed, the daily radiation model presented here appears to be sufficiently accurate to be used in simulations of passive solar buildings. Furthermore, the daily radiation model may be used as input to an algorithm that generates tilted radiation data. We believe that use of daily radiation models can facilitate the development of passive solar design tools that may be run without the aid of a main-frame computer.

## 5. ACKNOWLEDGMENT

This research has been supported by the Office of Advance Conservation Technologies of the U.S. Department of Energy.

## 6. REFERENCES

(1) Barley, C. D. "Passive Solar Modeling with Daily Weather Data," Proceedings of the Fourth National Passive Solar Conference, Kansas City, MO (3-5 October 1979).

(2) Sillman, S. Investigation of Simple Daily Radiation Models Suitable for Use in the Design of Solar Heating Systems, SERI/RR-721-675, Solar Energy Research Institute, Golden, CO.

(3) Palmiter, L. "SUNCAT Version 2.4 User Notes."