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Analysis of Thermal Comfort in A Passive Solar Heated Residence

U.S. DEPARTMENT COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Washington, DC 20234

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

An analytical investigation was conducted on the thermal comfort conditions in a passive solar heated residence of the popular Trombe Wall configuration. The National Bureau of Standards Load Determination Program (NBSLD) was used to simulate the indoor thermal environment of an actual passive solar residence, using the Typical Meteorological Year(TMY) weather data tape as input at three locations of different climatic conditions. The relevant thermal comfort parameters such as the space air temperature, mean radiant temperatures, operative temperatures, radiant temperature asymmetry, and temperature drifts of the occupied zone, were computed for a prime heating month, a transition month, and a prime cooling month of a typical weather year at the three locations. These parameters were analyzed in accordance with the criteria specified in the recently revised ASHRAE Comfort Standard 55-81. It was found that for the specific passive solar residence analyzed, the upper boundary of the comfort envelope can be exceeded (overheating) during a typical clear day in the transition month of April unless a change of clothing to summer wear is made during the daytime high solar radiation hours. The upper boundary will be exceeded during a typical clear day in the prime cooling month of August for a person in typical summer clothing at all three locations unless the average air movement in the occupied zone is increased above the level of natural circulation, or the thermostat setting is reduced to a lower level, or both.

KeyWords: ASHRAE Standard; asymmetric heating; collector/storage wall; comfort envelope; comfort zone; mean radiant temperature; operative temperature; passive solar; temperature drifts; thermal comfort condition; Trombe Wall

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1. INTRODUCTION

Over the past several years, the national concern with the increasing cost of conventional energy and on energy conservation has placed great emphasis on the utilization of solar energy for the heating and cooling of buildings. Specifically, the design of residential buildings with passive solar heating features has received increasing attention from both the U.S. Department of Energy (DoE) and the general public because of the potential for large energy savings at lower cost than for many active solar heating systems. In a passive system, solar energy which impinges on the building is collected and stored by the architectural elements of the building such as heavy mass walls, floor, or roof, and is distributed by natural means such as conduction, convection, and radiation without the use of solar collectors and conventional mechanical equipment. However, the acceptance and growth in the number of passive solar heated buildings will depend to a large extent on occupant comfort in such buildings. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 55-81, "Thermal Environmental Conditions for Human Occupancy," [1]*, which defines the condition for thermal comfort in a building, has recently been revised to include adjustments for extending the comfort zone due to the effect of air movement. The revisions also set limits on the amount of temperature drift within the occupied zone, and on the non-uniformity of vertical temperature distribution, radiant asymmetry, and floor temperature. All these have a direct bearing on the level of thermal comfort existing in passive solar buildings.

This report describes an investigation of the thermal comfort condition in a collector/storage wall (Trombe Wall) residence which is one of the more popular configurations in passive solar heated buildings. The National Bureau of Standards (NBS) Load Determination Program, NBSLD [2], which is expanded to include a subroutine for the simulation of the thermal interaction between the living space and the collector/storage wall assembly, was used to simulate the indoor thermal environment of an actual passive solar residence. The thermal comfort parameters such as the space and surface temperatures, space mean radiant temperatures, relative humidity, and operative temperatures were computed on a dynamic, hour-by-hour basis for the heating, cooling, and transition seasons of a typical year at three geographical locations of different climatic conditions. The Typical Meteorological Year (TMY) weather tape [3] developed by the Sandia Laboratories for the Department of Energy and prepared by the U. S. Environmental Data Service, National Climatic Center, were used as the weather data input to the computer program. The indoor thermal comfort conditions for the three seasons and three locations were analyzed and discussed on the basis of the criteria established in the ASHRAE Standard 55-81 (1981).

The thermal simulation computer program, the indoor physical environment settings and the passive solar feature of the residence modeled, the weather data, and the analysis of the thermal comfort conditions, are described in the following sections.

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* See references at end of text.

2. ASHRAE STANDARD 55-81

The standard specifying the thermal environmental conditions in a building for the comfort of healthy people is ASHRAE Standard 55-81, "Thermal Environmental Conditions for Human Occupancy" [1], revised in 1981. It states in part that at the center of, and 0.6 m (2 ft) from each exposed wall, and at the center of the room, the following standards should be met at all times:

1. The operative temperature, T_o, measured within the occupied zone shall be on the boundary or within the "comfort envelope". The operative temperature is defined as the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. The comfort envelope is defined as a quadrangle with the following corner coordinates when plotted on the psychrometric chart:

   Winter: T_o = 19.5-23 °C (67.1-73.4 °F) at 16.7 °C (62 °F) dew-point temperature (DP), and
   T_o = 20.2-24.6 °C (68.4-76.35 °F) at 1.7 °C (35 °F) DP.

   Summer: T_o = 22.6-26 °C (72.7-78.8 °F) at 16.7 °C DP
   and
   T_o = 23.3-27.2 °C (74-80.9 °F) at 1.7 °C DP.

2. The humidity as described in terms of dew-point temperature (DP) shall not be less than 1.7 °C (35 °F) or greater than 16.7 °C (62 °F).

3. The average air movement in the occupied zone shall not exceed 0.15 m/s (30 fpm) in winter and 0.25 m/s (50 fpm) in summer. However, the comfort zone can be extended above 26 °C (79 °F) if the average air movement is increased 0.275 m/s for each degree C (30 fpm for each °F) of increased temperature to a maximum temperature of 28 °C (82.5 °F) and 0.8 m/s (160 fpm).

4. When the mean radiant temperature (defined as the uniform surface temperature of a radiant black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space) differs from the air temperature in the occupied zone, the air temperature shall be adjusted to keep the operative temperature within the appropriate comfort zone. For low air movement, T_o is approximately the average of the air temperature and the mean radiant temperature.

5. Monotonic, steady, non-cyclical temperature changes (drifts) shall not extend beyond the comfort zone by more than 0.6 °C (1 °F) and for longer than one hour.

6. The radiant temperature asymmetry for a plane element 0.6 m (2 ft) above the floor, shall be less than 5 °C (9 °F) in the vertical direction and less than 10 °C (18 °F) in the horizontal direction.

The above criteria are specified for persons clothed in typical summer or winter ter clothing, at light, mainly sedentary, activity. The insulating value of clothing is defined in units of Clo, where 1 Clo = 0.155 $m^2 \cdot K/W$ (0.88 $ft^2 \cdot h \cdot F/Btu$). An example of typical winter clothing is given in Std. 55-81 as consisting of heavy slacks, long sleeved shirt and sweater, with an overall insulating value of 0.9 Clo, and for summer clothing, light slacks and short sleeve shirt (0.5 Clo). In addition to the above criteria, Standard 55-81 also states the conditions for temperature cycling, nonuniformity in vertical air temperature and floor temperature, for sedentary but nontypical clothing, and for active persons. Details of these are contained in Reference [1].

For the present study, the occupants were assumed to be in typical winter or summer clothing, at sedentary or light activity level, with normal indoor thermostat and humidity settings, so that only the criteria 1 to 6 above are applied in the analysis.

3. THE THERMAL SIMULATION PROGRAM

The program NBSLD [2] is a research oriented computer program developed by T. Kusuda of the NBS for the dynamic simulation of the building indoor thermal environment when the building is subject to hour-by-hour randomly fluctuating outdoor climatic conditions. The program computes, on an hourly basis, the heat loss and heat gain within and through the building envelope, the indoor air temperature, and all the inside surfaces temperatures required for the computation of the mean radiant temperature. Details of this program are given in reference [2].

The program NBSLD as described in reference [2] does not simulate the interaction between two zones on a simultaneous basis. For a passive solar heated building with the Trombe wall assembly as an integral part of the building, strong thermal interaction exists between the Trombe wall assembly and the living space, so that dynamic simulation of the two zones simultaneously becomes a necessity. For the present study, a new subroutine called "TROMBE" was developed and integrated into the program NBSLD to accomplish this purpose. Subroutine "TROMBE" used the same solution method and algorithm as used for the simulation of the living space in NBSLD. The narrow space between the glazing and the mass thermal storage wall in the Trombe wall assembly was treated as a two-surface mini-zone. The air and surface temperatures of this mini-zone were computed on an hour-by-hour basis simultaneously with those of the living space, where output of one zone were used as input to the other zone, and vice-versa. In its present form, the subroutine "TROMBE" can simulate a Trombe assembly with one or two-glazing layers, with or without thermal circulation flow between the Trombe wall space and the living space, with or without nighttime insulation, and vented or unvented Trombe wall space in the summertime. A listing of the program code for subroutine "TROMBE" is given in appendix A for reference.

4. WEATHER DATA

The Typical Meteorlogical Year (TMY) weather data tape was developed by the Sandia Laboratories under the sponsorship of DoE, and prepared for distribution by the U.S. National Climatic Center, Asheville, N.C. [3]. It contains a composite year's data of solar radiation and surface meteorological data (temperatures, barometric pressure, wind, cloud cover) for 26 locations in the United States.

For each location, data for each calendar month are selected from among 23 years (1953-1975) of data as the most representative, or typical, for the month, using a statistical technique developed by Sandia Laboratories. Detailed information on the tape is contained in reference [3]. For the present study, three geographical locations, covering three types of climatic conditions, are selected. The three locations are:

1. Albuquerque, NM - 2383 °C - days (4290 °F - days) for heating, arid climate
2. Madison, WI - 4290 °C - days (7730 °F - days) for heating, northern climate
3. Washington, DC - 2339 °C - days (4210 °F - days) for heating, warm and moist summer climate

The reason for the selection of Albuquerque, N.M., and Washington, D.C. which have almost identical heating degree-days, is that they have different summer time climate. Albuquerque has an arid climate while Washington, D.C. normally has a warm and moist climate in summer. The effect of humidity on the indoor thermal comfort condition can be studied with results from these two locations.

5. DESCRIPTION OF BUILDING MODELED

The building selected for the simulation study is the Bruce Hunn residence [4] located at White Rock, New Mexico. It is extensively instrumented and monitored by the Los Alamos National Laboratory (LANL) to assess the thermal performance of a collector/storage-wall (Trombe wall) passive system under actual occupancy conditions. The portion of the house containing the Trombe wall is a two storey structure with the south-facing Trombe wall extending from the ground up to the roof overhang. Figure 1 shows the floor plans of the building. Detailed construction data are in reference [4]. The Trombe wall is constructed of 0.3 m (1 ft) thick open slump block completely filled with concrete. A 5 cm (2 in) air space separates the mass storage wall from the double glazing. The wall is equipped with operable vents for summertime venting of the wall with roof chimney vents serving as exhaust ports. The double glazings are standard 9 mm (3/8 in) thick plate glass spaced 2.5 cm (1 in) apart. The dimension of the Trombe wall are 3.7 m (12 ft) wide by 7.2 m (23.5 ft) high. The outer surface of the wall is stained a dark brown color with a measured solar absorptivity of 0.91. No vent openings are provided for thermal circulation flow between the Trombe wall space and the living space. The heating of the living space by the Trombe wall is by radiation and convection from the inner surface of the thermal storage wall. All rooms of the two storey section are open in order to provide free natural circulation paths. A description of the building variables and the thermal physical properties of the construction materials taken from reference [4] are given in the appendix B for reference.

For the present study, only the section of the building containing the Trombe wall was simulated. The indoor thermostat and humidity settings for the simulation are as follows:

a. Space Air Temperature:

20-25.6 °C (68-78 °F). Auxiliary heating is supplied to maintain 20 °C (68 °F) minimum space air temperature. Natural cooling (if feasible, by ventilation) or air conditioning is used to maintain 25.6 °C (78 °F) maximum space air temperature. These temperature limits are chosen so that the space temperature, when not under the influence of the thermal storage wall surface temperature, will stay within the comfort zone boundaries of ASHRAE Standard 55-81.

b. Indoor Relative Humidity: 20-50 percent

The 24-hour daily internal heat gain data (lighting, appliance, and occupants) which contribute to the indoor temperature variations were taken from reference [5] and are given here in appendix B for reference.

6. VERIFICATION OF THE COMPUTER PROGRAM

The computer program NBSLD has been verified by experimental work on two separate research projects at NBS [6,7]. However, the expanded program for a building with an attached mini-zone (Trombe wall) has not been verified before. Therefore, the expanded program was checked for its ability to predict the temperature variations in the Trombe wall assembly. The Hunn residence was simulated for a two-week period in January using the actual measured weather and solar radiation data reported in reference [4]. The resulting computed inside and outside thermal mass wall surface temperatures for a cloudless 48-hour period were compared with the actual measured surface temperatures reported in reference [4]. The results of the comparison are shown in figure 2. The agreement is shown to be very good, especially during the period of high solar heat gain. Since the thermal storage wall inner surface temperature is the main driving force for the variation in the mean radiant temperature for storage wall type passive solar heated house, the computer program is considered to be verified for use in the simulation of indoor physical environment for thermal comfort study.

7. SIMULATION RESULTS AND DISCUSSIONS

The living area of the Hunn residence containing the Trombe wall section was simulated with the expanded program NBSLD, using the TMY weather data as input, for the prime heating month of January, the transition month of April, and the prime cooling month of August, for the three locations described in section 4 of this report. The air temperature and the surface temperatures of all interior surfaces were computed on an hour-by-hour basis, and the thermal comfort parameters such as the mean radiant temperature, the operative temperature, the radiant asymmetry, and the operative temperature drifts were computed from these temperature data and evaluated on the basis of ASHRAE Std. 55-81 as discussed below. Since the effect of solar radiation on the passive solar residence will be most pronounced during a clear day, all the results to be shown were for a clear day chosen from the first two weeks of each of the three months mentioned previously. The solar radiation data for the first two weeks of each month for the three locations are shown in figures 3 to 5 where the selected days are shaded.

7.1 Operative Temperature at Center of the Room

The hourly variations of the outdoor temperature T_{amb}, the indoor space temperature T_a, and the operative temperature T_o for a typical clear day in each of the three months for each of the three locations are shown in figures 6 through 14. The operative temperature T_o was computed as the average of the space air temperature and the mean radiant temperature at the center of the living space, 0.6 m (2 ft) above the floor. The mean radiant temperature, T_{mrt}, was computed from the inside surface temperatures and the associated angle factors as given by ASHRAE Std. 55-81. In equation form, the mean radiant temperature is written as, approximately [1],

$$T_{mrt} = F_{P-1}\, T_1 + F_{P-2}\, T_2 + \dots + F_{P-N}\, T_N \tag{1}$$

where T_N = temperature of surface N,

F_{P-N} = angle factor from person at location P to surface N,

N = total number of surfaces.

For the purpose of discussion, the thermal comfort zone boundaries for a person clothed in typical winter and/or summer clothing at light activity specified in the comfort envelope of the ASHRAE Std. 55-81 are also shown in figures 6 through 14. Figures 6, 7, and 8 show the variation of the operative temperature, T_o, for a typical clear day in January in the three locations. It is seen that, except in Madison, T_o stays within or close to the lower comfort boundary of ASHRAE Std. 55-81 for a person in typical winter clothing (Clo = 0.9) during the nonsleeping hours. The low operative temperature in Madison was caused mainly by the low outside temperature which caused the not well insulated Trombe wall surface temperature to drop below the space air temperature. The upper comfort boundary will not be exceeded in Albuquerque if a change of clothing to summer wear (Clo = 0.5) is made during the high solar radiation daytime hours.

The high operative temperature in Albuquerque is caused mainly by the higher outdoor temperature in the daytime hours. Figures 9, 10, 11 show the results for a typical clear day in April. For all three locations, the operative temperature stays within the comfort boundaries if a change of clothing from winter to summer wear is made during the daytime hours.

Figures 12, 13, and 14 show the results for a typical clear day in August. The comfort boundaries for Albuquerque were based on a 1.7 °C (35 °F) dew point (DP) temperature due to its arid climate, while the boundaries for Madison and Washington, DC were based on 16.7 °C (62 °F) DP (50 percent relative humidity). It is seen that the operative temperature exceeded the upper comfort boundary for all 3 locations by the amount of 0.6 °C (1 °F) in Albuquerque to near 1.7 °C (3 °F) in Madison, WI and Washington, DC.

7.2 Operative Temperature Near the Thermal Storage Wall

The occupied zone is defined in ASHRAE Std. 55-81 as the region within a space between the floor and 1.8 m (6 ft) above the floor, and more than 0.6 m (2 ft) from the walls. Since the higher operative temperature was caused by the higher surface temperature of the Trombe wall, the operative temperature for a person 0.6 m (2 ft) away from the Trombe wall and 0.6 m above the floor level was also computed. The results are shown in figures 15, 16, and 17 where, for comparison, the operative temperatures at the center of the space are also shown. It is seen that for all three geographical locations, the maximum difference in operative temperature between the two locations was less than 0.6 °C (1 °F) during the period when the comfort boundary was exceeded, with the location near the Trombe wall having the higher value most of the time as expected.

7.3 Temperature Drifts

As stated in section 2 of this report, the ASHRAE Std. 55-81 specifies that the drift of the operative temperature shall not extend beyond the comfort zone by more than 0.6 °C (1 °F) and for longer than one hour. It is seen from figures 6 through 17 that the excursion of the operative temperature over the upper comfort boundary for Madison and Washington, DC lasted over a period of more than 10 hours and exceeded the boundary by nearly 1.7 °C (3 °F) at the center of the room, and by nearly 2.2 °C (4 °F) at a point 0.6 m (2 ft) from the Trombe wall.

7.4 Radiant Temperature Asymmetry

The plane radiant temperature for an environment, T_{Pr}, is defined as the uniform temperature of an enclosure in which the incident radiant flux on one side of a small plane element within the enclosure is the same as in the existing environment. In equation form, it can be written approximately as [1]:

$$T_{Pr} = F_{e-1}\, T_1 + F_{e-2}\, T_2 + \ldots + F_{e-N}\, T_N \tag{2}$$

where T_N is the temperature of surface N. F_{e-N} is the angle factor from the plane element to surface N, where the N surfaces form a hemisphere or open box enclosing the element. The values of F_{e-N} are given in Reference [1]. The radiant temperature asymmetry in the horizontal (vertical) direction is the difference in plane radiant temperatures in opposite directions with respect to a small vertical (horizontal) plane element 0.6 m (2 ft) above the floor. It is an indication of the asymmetric radiant heating from surfaces with different temperatures. In equation form, it is defined as [1]:

$$\Delta T_{Pr} = T_{Pr1} - T_{Pr2} \quad .$$

For the present study, ΔT_{Pr} in the horizontal direction for a vertical plane element 0.6 m (2 ft) from the Trombe wall was computed. The maximum values of ΔT_{pr} attained during a typical clear day are shown below:

LOCATION	MAX. ΔT_{Pr}, °C		
	JAN	APR	AUG
Albuquerque, NM	4.5	3.0	2.5
Washington, DC	2.0	2.2	2.4
Madison, WI	1.0	2.8	2.8

The above table shows that the maximum values of ΔT_{Pr} reached were far below the 10 °C maximum allowable value specified in the Std. 55-81.

7.5 Effects of Nontypical Conditions

1. Air movement: In the present study, natural circulation was assumed to exist within the living space where the air movement in the occupied zone was less than 0.15 m/s (30 fpm). ASHRAE Std. 55-81 specifies that the upper boundary of the comfot zone can be extended to above 26 °C (79 °F) if the average air movement is increased 0.275 m/s for each 1 °C of increased temperature (30 fpm for each 1 °F) to a maximum temperature of 28 °C (82.5 °F) and air movement of 0.8 m/s (160 fpm). Therefore, if some mechanical means were used to increase the air movement to 0.8 m/s during high operative temperature periods, the occupied zone would stay within the extended upper comfort boundary.

2. Thermostat setting: The simulation was run for a normal thermostat setting of 20 °C - 25.6 °C (68 °F - 78 °F) as described in section 5. Since the operative temperature is approximately the average of the air temperature and the mean radiant temperature, and a decrease of 1 to 2 °C of the air temperature is not expected to materially affect the value of the mean radiant temperature which is a function of the wall surface temperatures, the operative temperature could be reduced to within the comfort zone boundary for most of the time if the upper thermostat setting was reduced

to a lower setting of 24 °C (75 °F). This would, however, increase the mechanical cooling energy requirement.

3. Nontypical clothing: ASHRAE Std. 55-81 specifies that for each 0.1 decrease or increase in Clo value, the comfort zone boundary operative temperature can be increased or decreased respectively by 0.6 °C. With a minimal clothing of 0.05 Clo, the upper boundary can be extended to 29 °C (84 °F). Therefore, if the occupants would adjust (reduce) the clothing to below the typical summer clothing's value of 0.5 Clo during the high operative temperature period of the day, the length of the time period when the comfort criteria was exceeded would be reduced or eliminated.

4. Active Persons: The comfort zone boundary values stated in section 2 are for a sedentary or slightly active person. If the activity level of the occupants are increased, the standard requires a decrease in the upper boundary value. For example, for a person doing domestic work (medium activity) and wearing clothes with a Clo value of 0.35, the reduction in the upper boundary temperature would be by 3.2 °C (5.8 °F). This would cause the operative temperature at the center to exceed the allowable boundary value by 3.8 °C (6.8 °F) in Albuquerque and by 5 °C (9 °F) in Madison and Washington, DC.

8. CONCLUSIONS

Based on the preliminary study described in this report, the following conclusions can be drawn:

1. The occupied zone of a collector/storage wall (Trombe wall) type, well insulated residence will stay close to or within the recently revised ASHRAE thermal comfort standard (Std. 55-81) during the prime heating months without overheating if a change of clothing from winter to summer wear, when necessary, is made during the high solar radiation hours. The exception is in a northern climate zone where the lower boundary of the comfort zone specified in Std. 55-81 will be exceeded. This is caused by the low outside temperature which reduces the poorly insulated Trombe wall surface temperature to the uncomfortable region. Night time insulation of the Trombe wall should help in alleviating this condition.

2. The occupied zone will stay within the comfort zone during the transition months (in-between heating and cooling season) for all three climatic regions studied, if a change of clothing to summer wear is made during the daytime high solar radiation hours.

3. The operative temperature in the occupied zone will exceed the upper comfort boundary for all three climatic regions studied during the prime cooling months. However, an increase in the average air movement within the occupied zone by some means, a reduction of clothing below the typical summer wear's value of 0.5 Clo, or a reduction of the thermostat setting to a lower value, will reduce or eliminate the period of time when overheating occurs. Shading of the Trombe wall from outside by additional or longer overhang projections should also help in reducing the overheating problem.

A note of caution should be made about applying these results. The results of this report apply in detail only to the building modeled here along with the operating assumptions (e.g., internal heat gain schedules, summer venting and overhang size, no convective flow between the Trombe wall space and the living space, etc.). While the results should apply in general to similar buildings, additional study on the variations of the building design and operating conditions on indoor comfort conditions, through computer simulation as is done in the present study and through analysis of data from actual thermal performance test results, is also indicated and recommended.

9. ACKNOWLEDGMENT

The author wishes to acknowledge the advice of Dr. T. Kusuda of NBS in the development of the computer subroutine TROMBE for the predicting of the thermal performance of the Trome-wall space. J. Barnett of NBS provided great help in the coding and de-bugging stage of the development. The author also would like to express his appreciation to Dr. Larry Berglund of the Pierce Foundation Laboratory of the Yale University for his suggestions and comments on this project.

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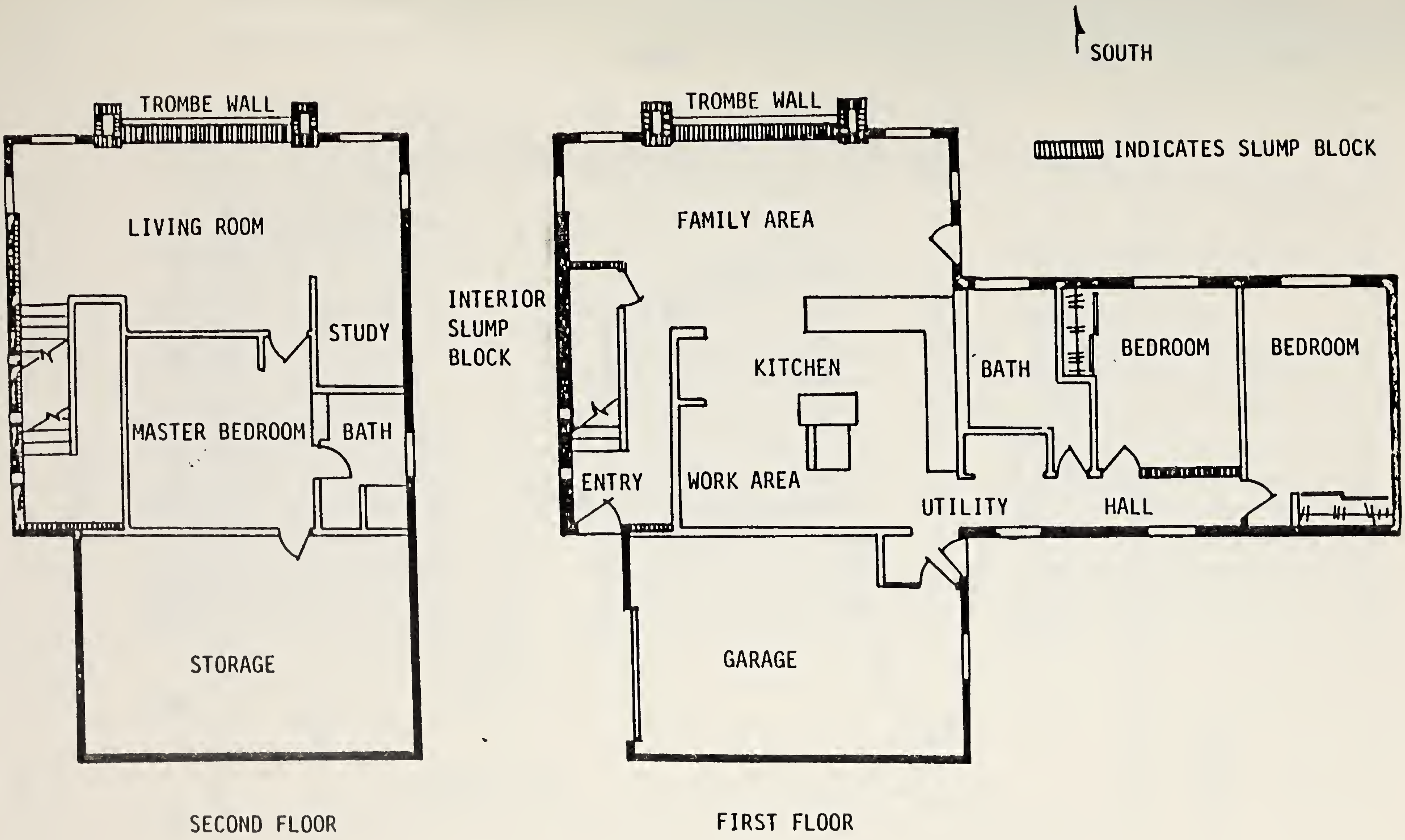

Figure 1. Floor Plan of the Passive Solar (Trombe Wall) House

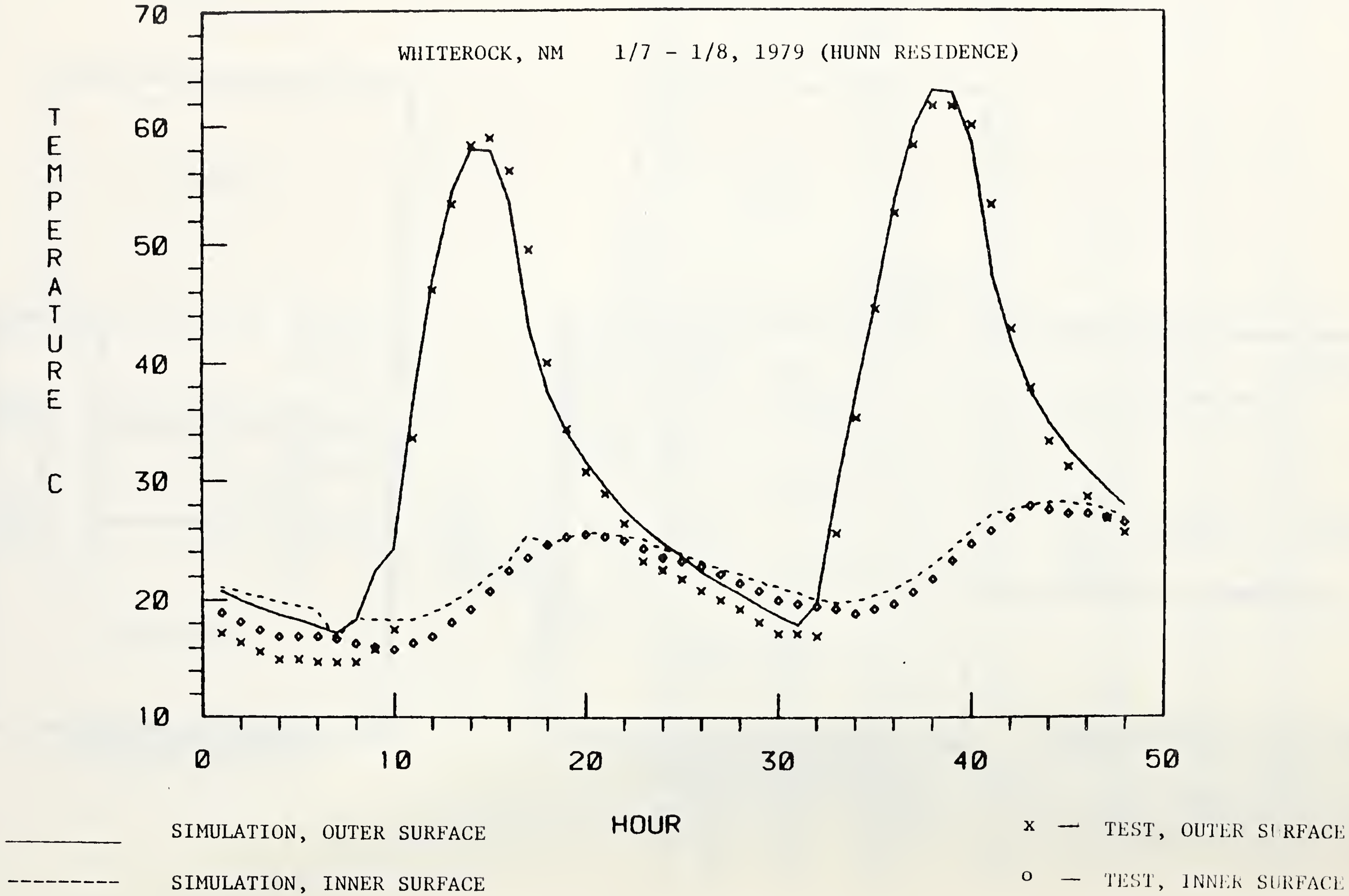

Figure 2. Comparison of Experimental and Simulation Results on the

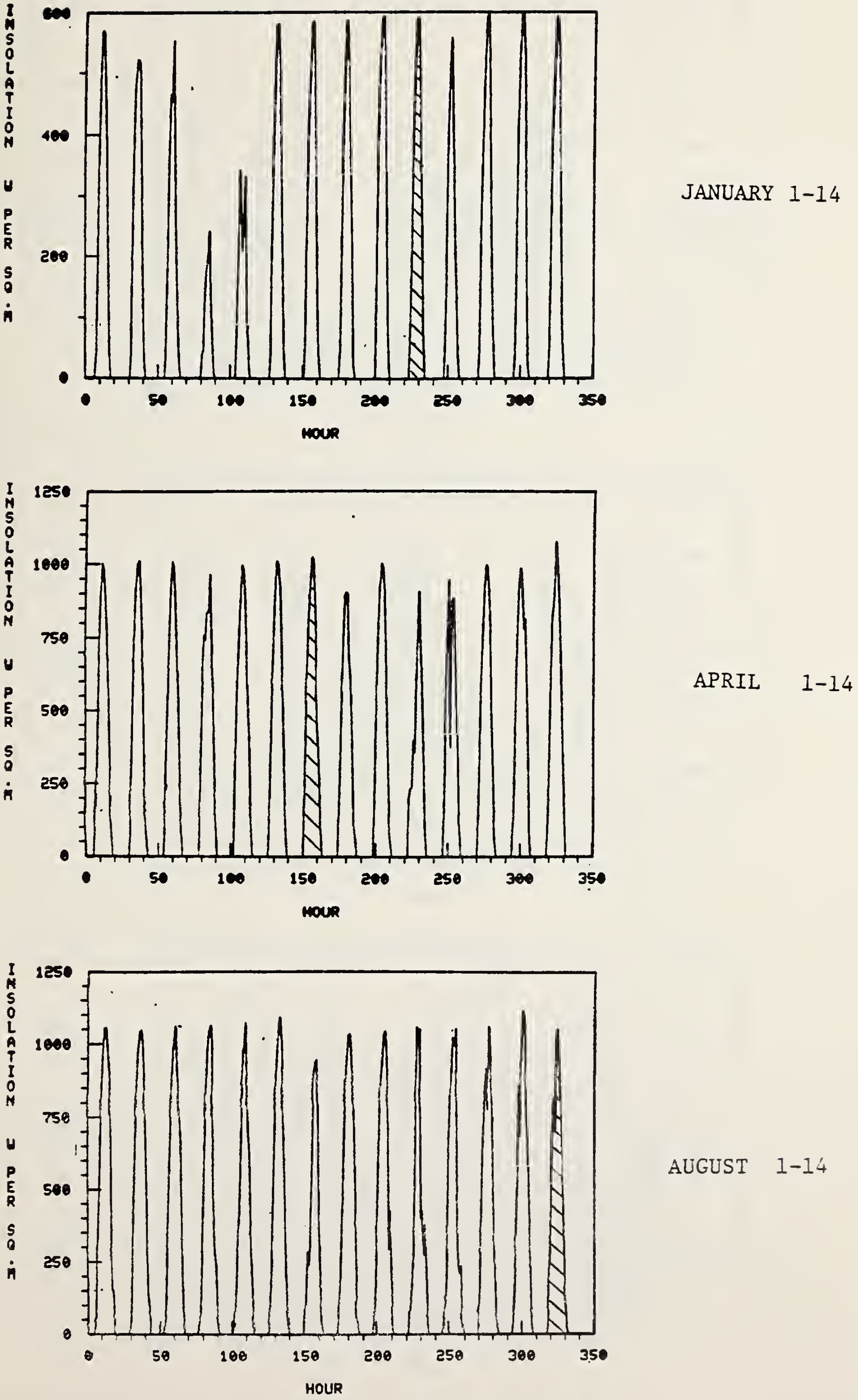

Figure 3. Hourly Solar Radiation on a Horizontal Surface, Albuquerque, NM.

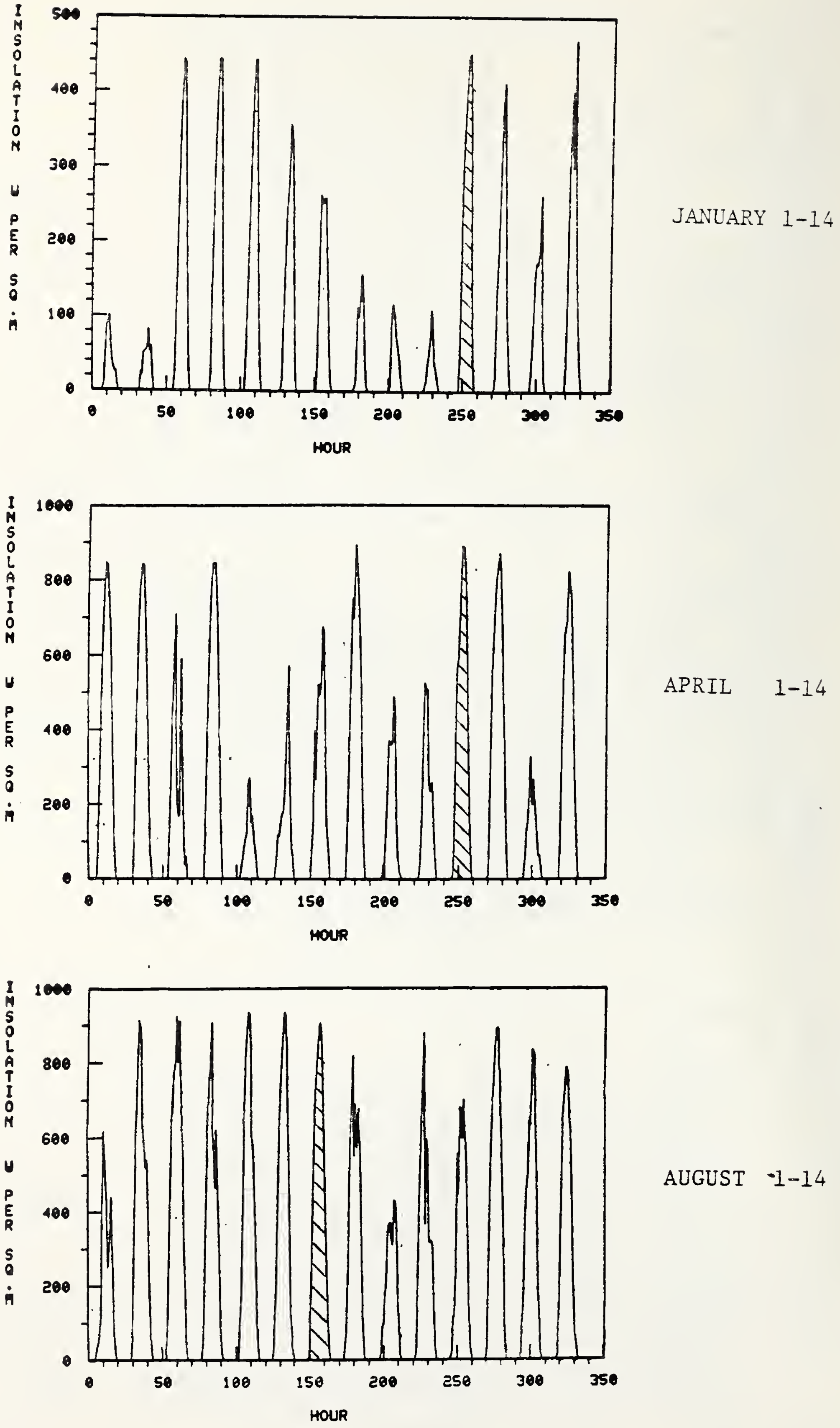

Figure 4. Hourly Solar Radiation on a Horizontal Surface, Washington, DC.

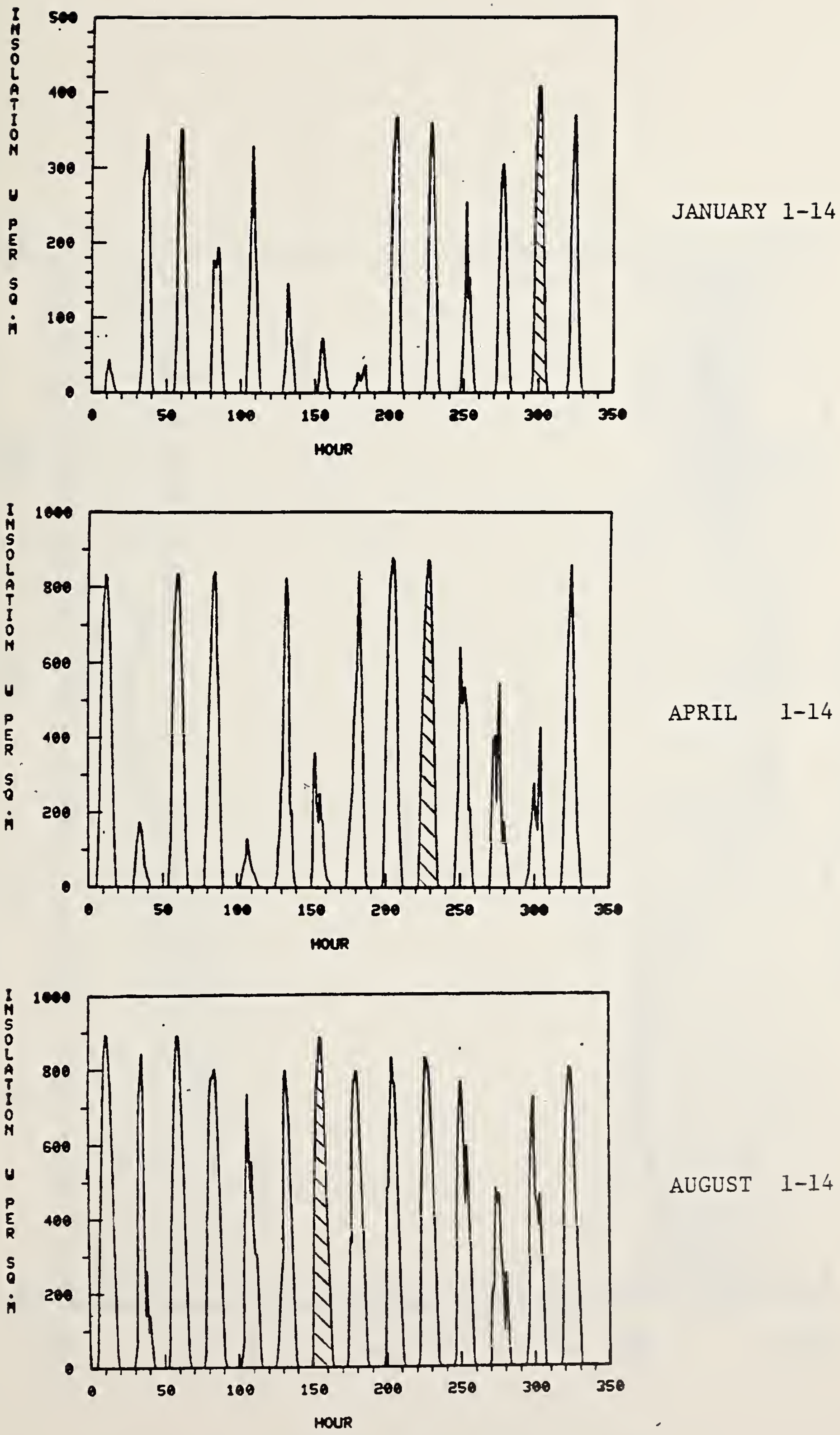

Figure 5. Hourly Solar Radiation on a Horizontal Surface, Madison, WI.

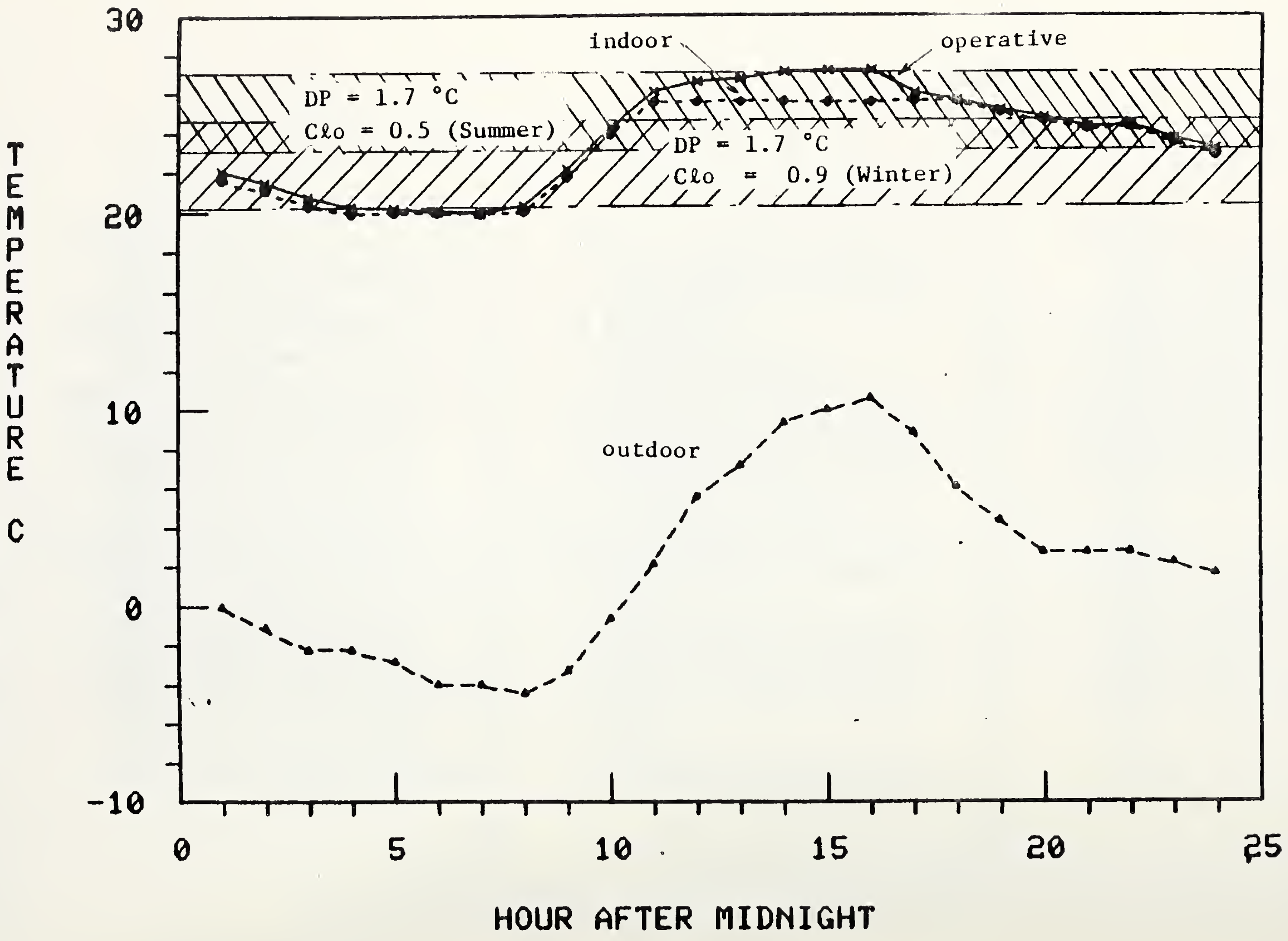

Figure 6. Operative and Air Temperature at Center of Room on a Clear Day in January (Albuquerque, NM).

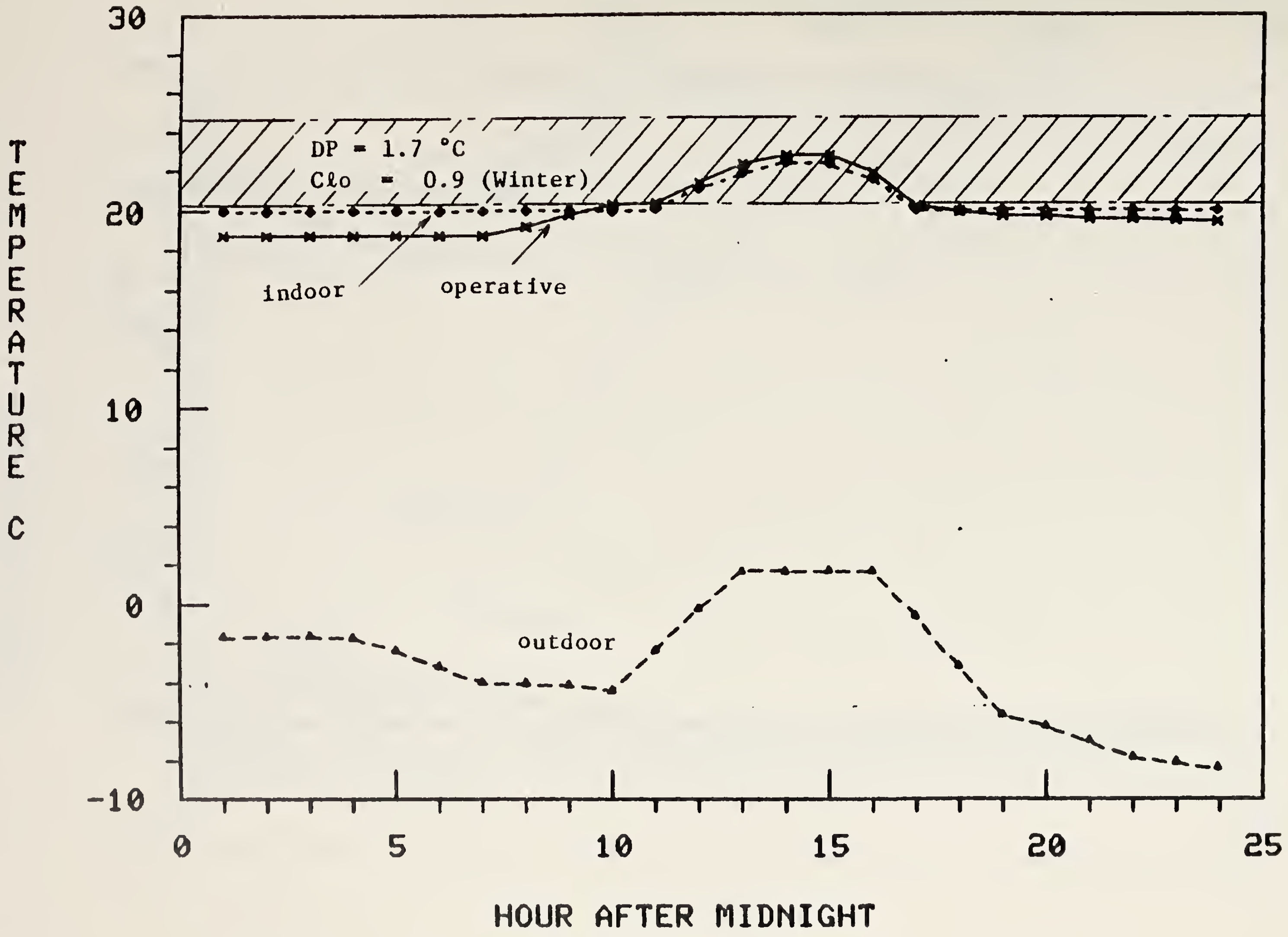

Figure 7. Operative and Air Temperature at Center of Room on a Clear Day in January (Washington, DC).

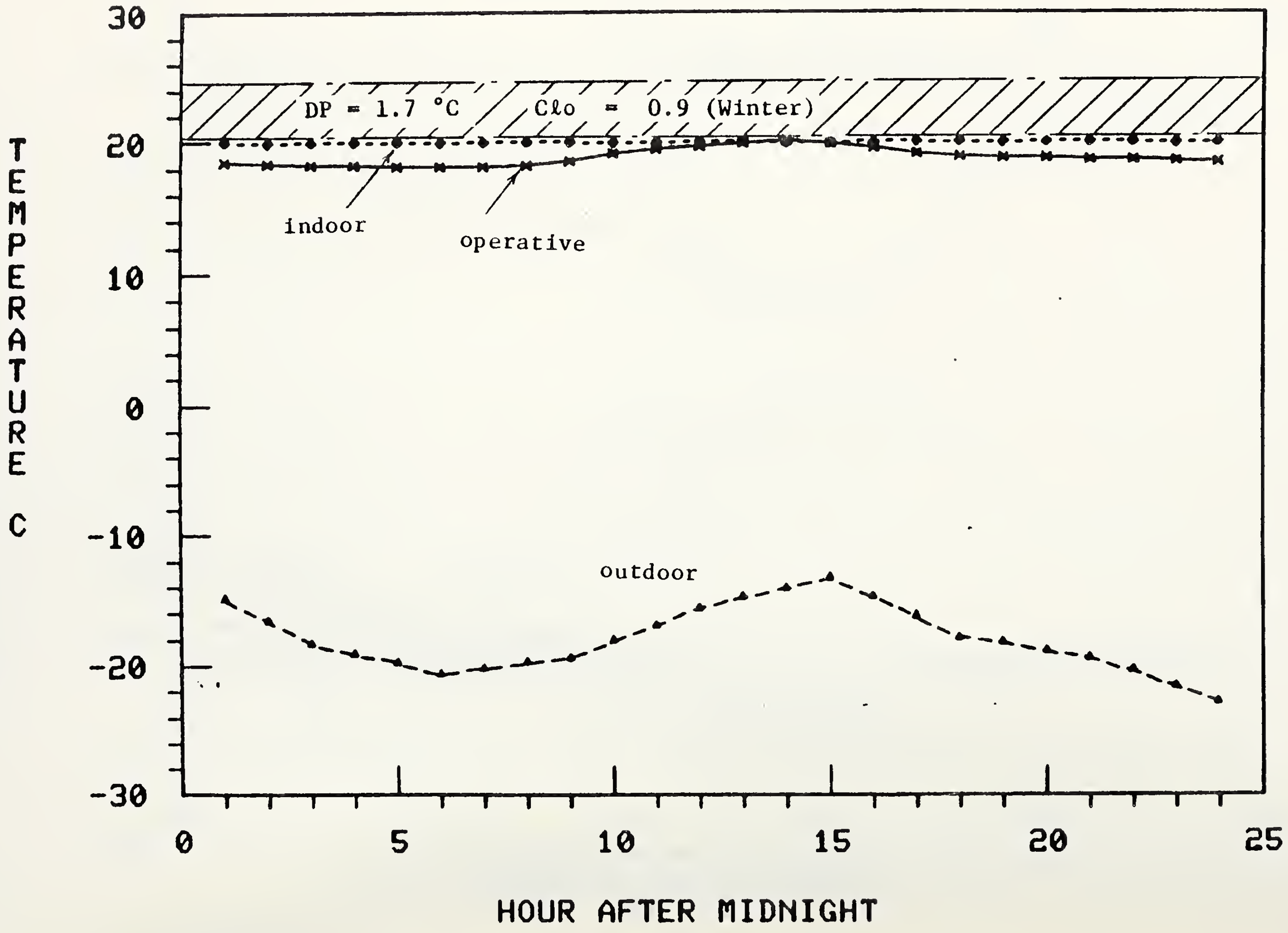

Figure 8. Operative and Air Temperature at Center of Room on a Clear Day in January (Madison, WI).

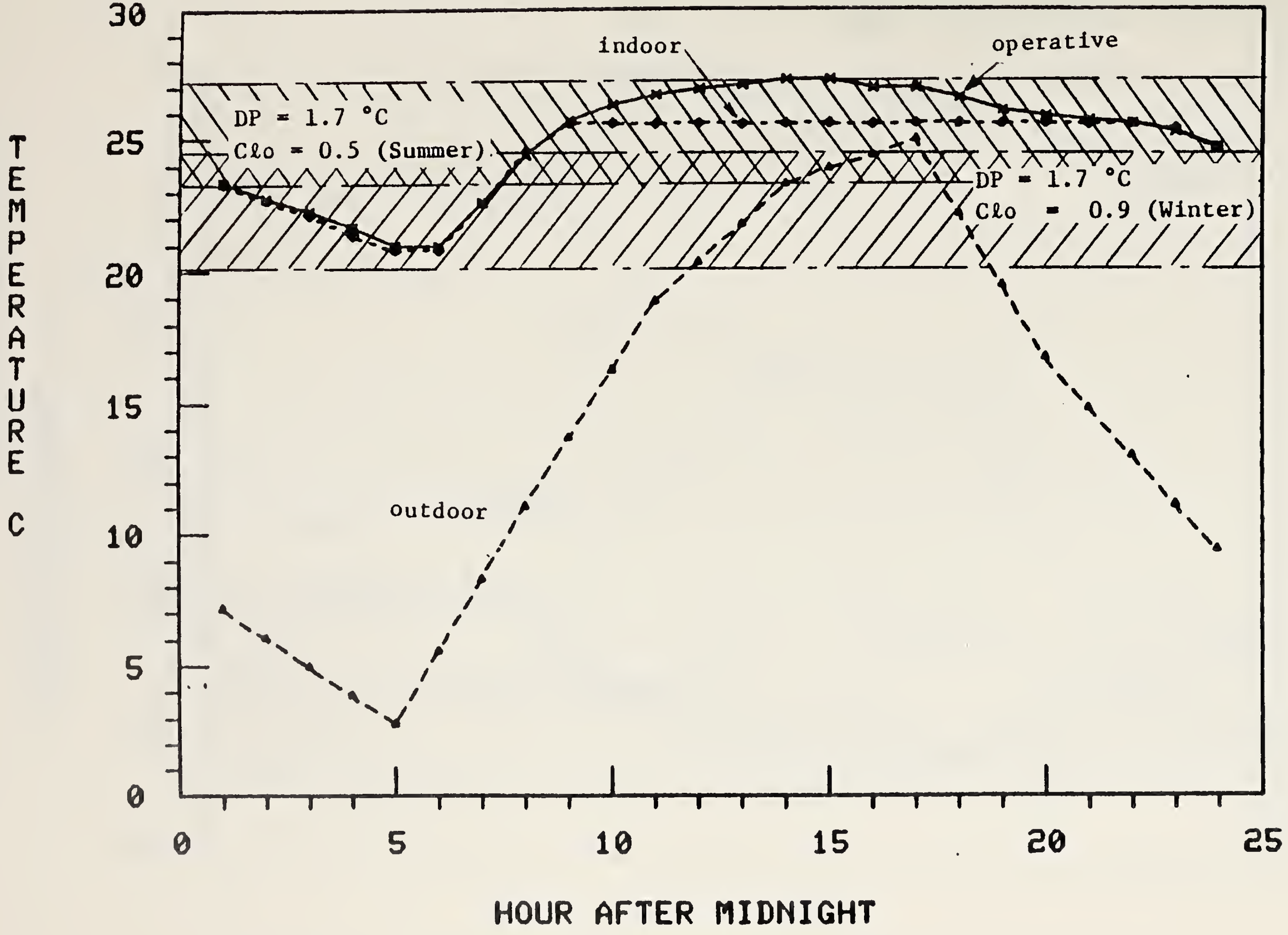

Figure 9. Operative and Air Temperature at Center of Room on a Clear Day in April (Albuquerque, NM).

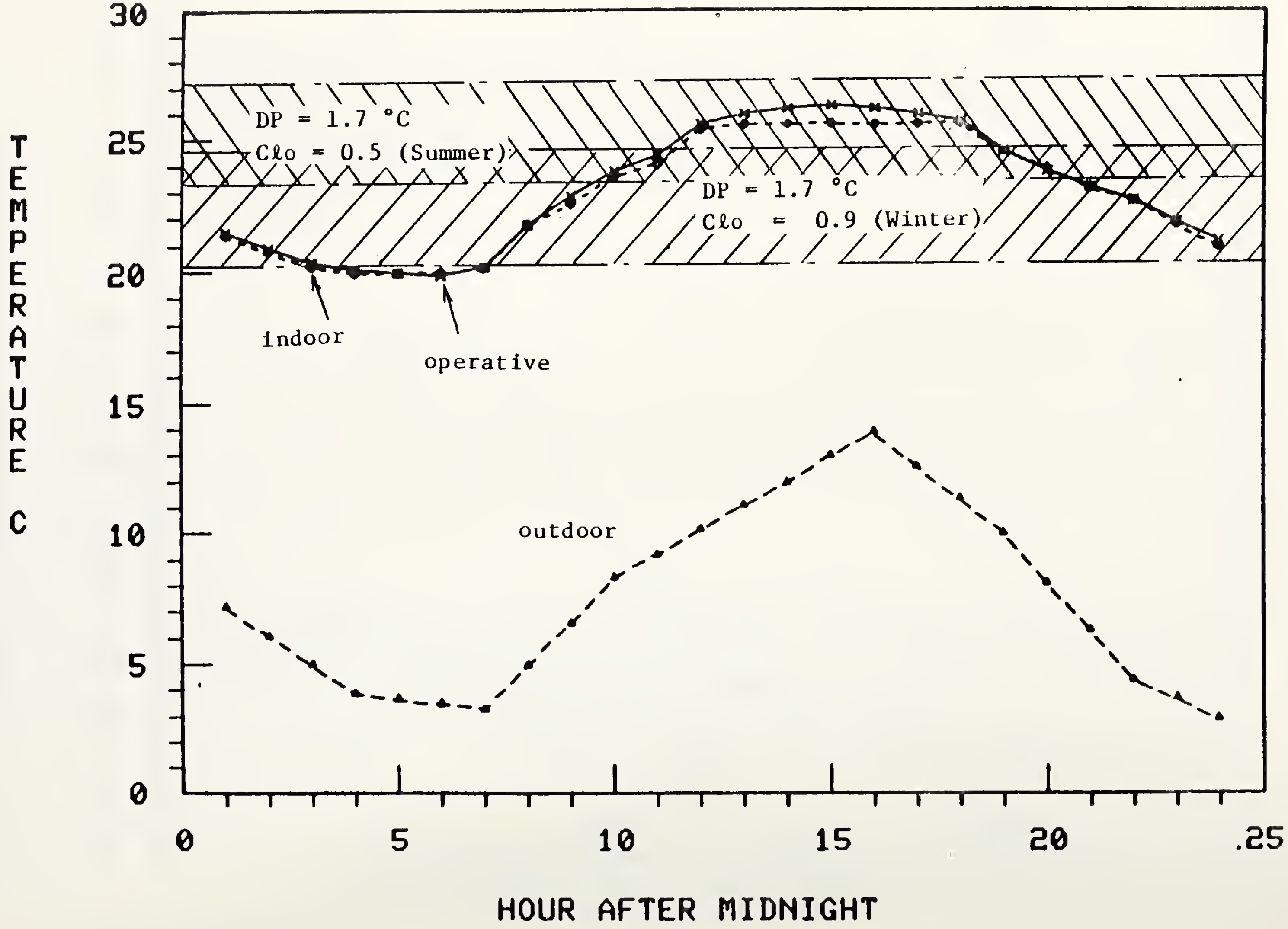

Figure 10. Operative and Air Temperature at Center of Room on a Clear Day in April (Washington, DC).

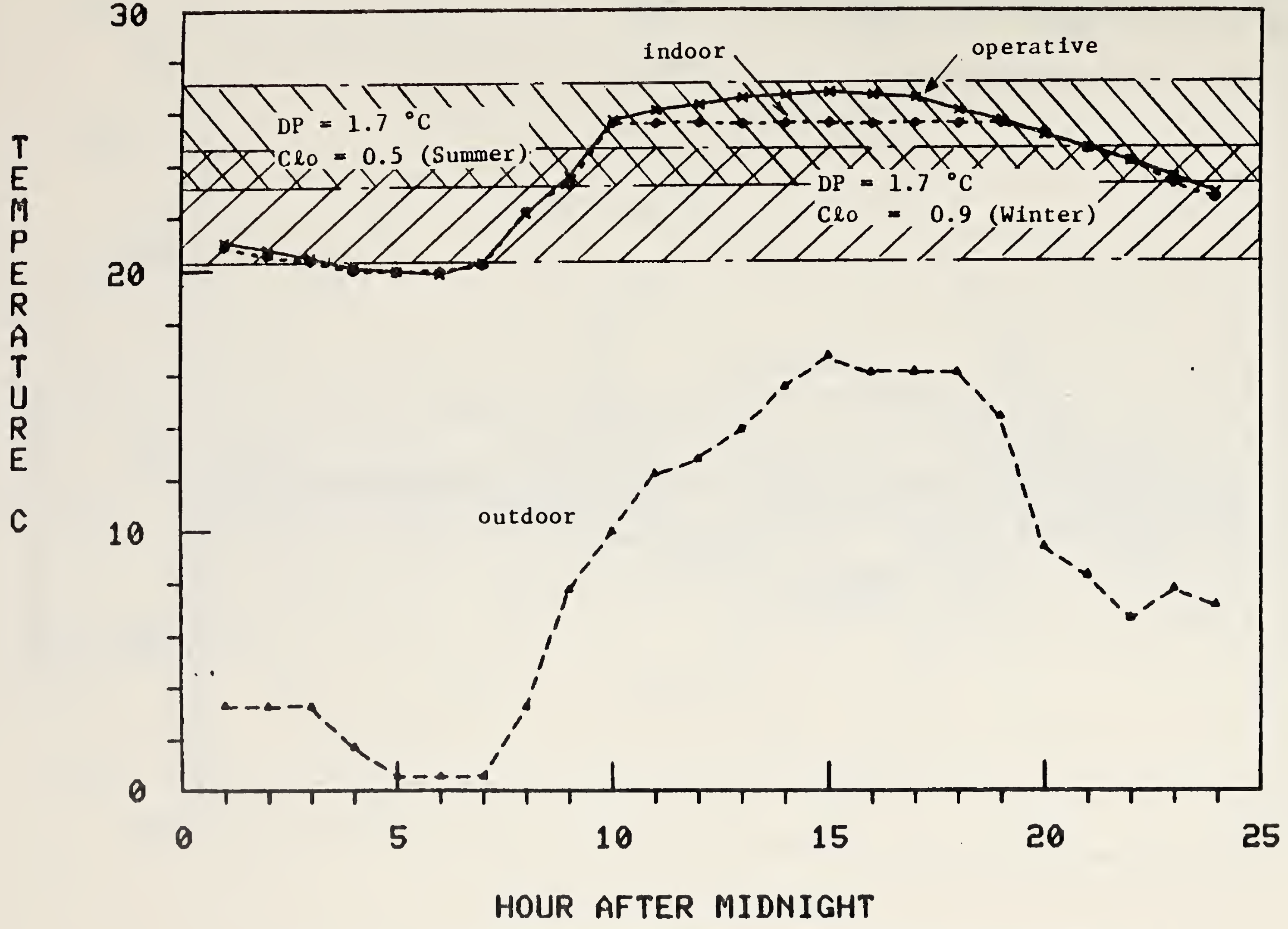

Figure 11. Operative and Air Temperature at Center of Room on a Clear Day in April (Madison, WI).

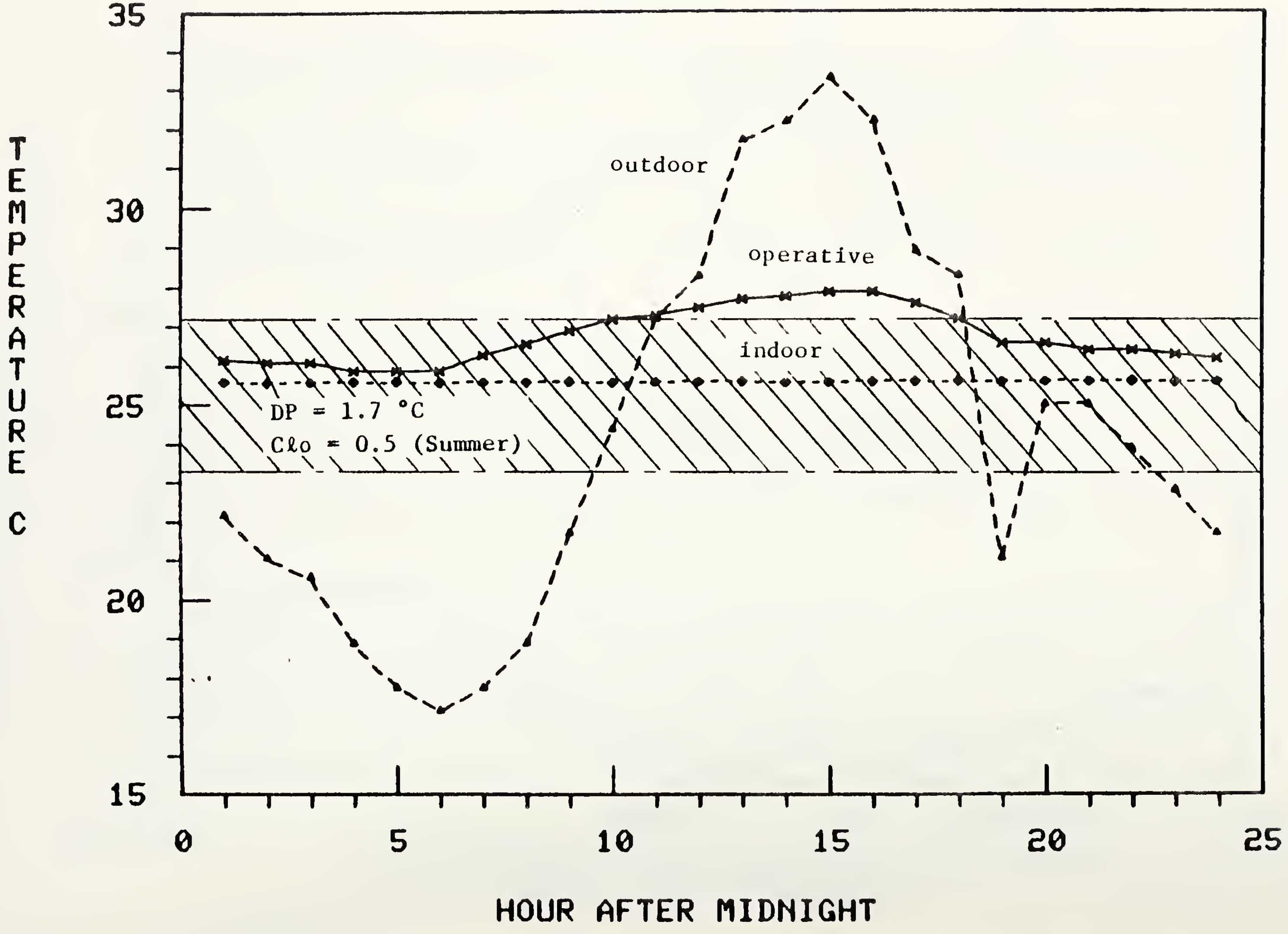

Figure 12. Operative and Air Temperature at Center of Room on a Clear Day in August (Albuquerque, NM).

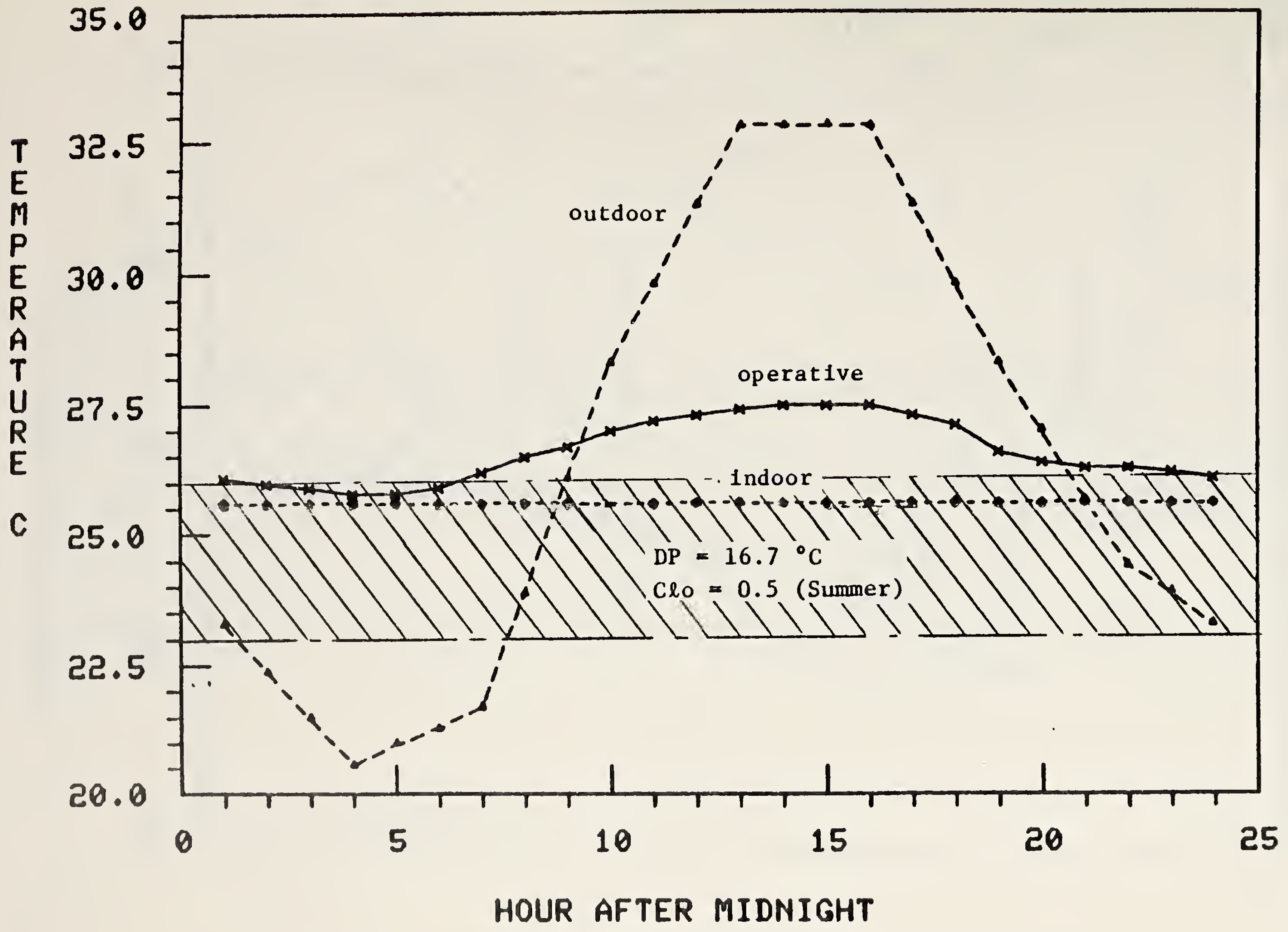

Figure 13. Operative and Air Temperature at Center of Room on a Clear Day in August (Washington, DC).

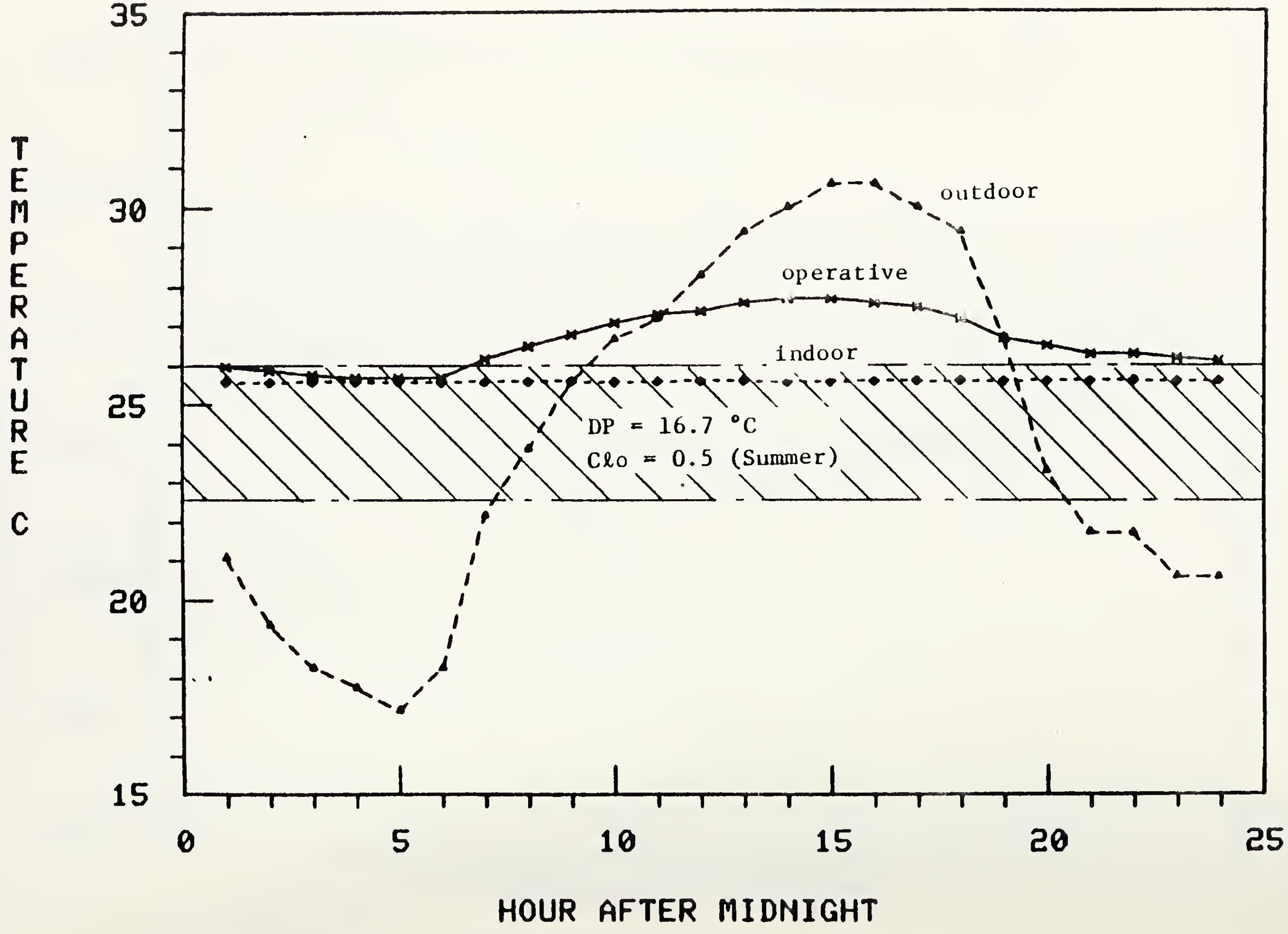

Figure 14. Operative and Air Temperature at Center of Room on a Clear Day in August (Madison, WI).

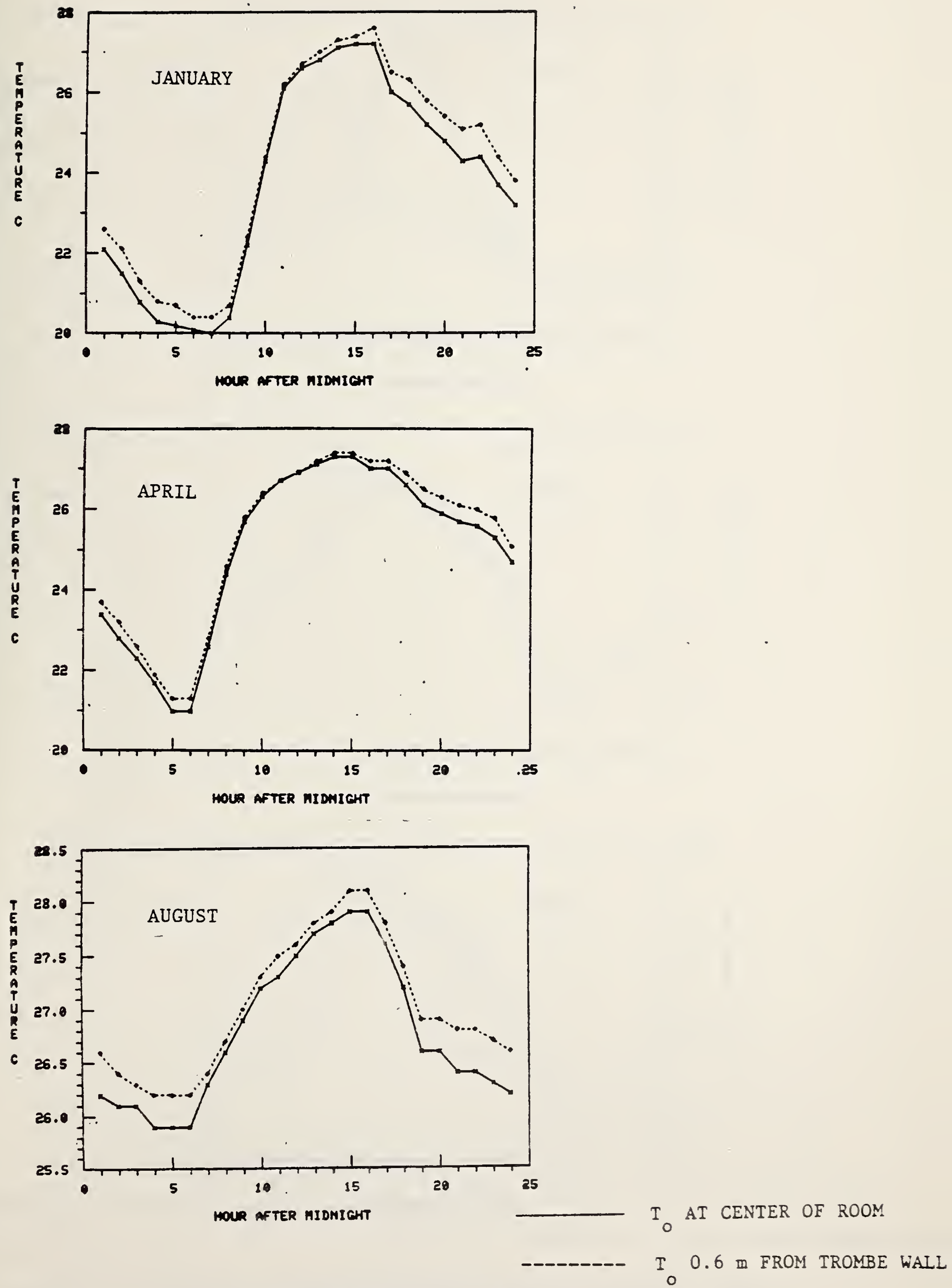

Figure 15. Variation of Operative Temperature in the Occupied Zone (Albuquerque, NM).

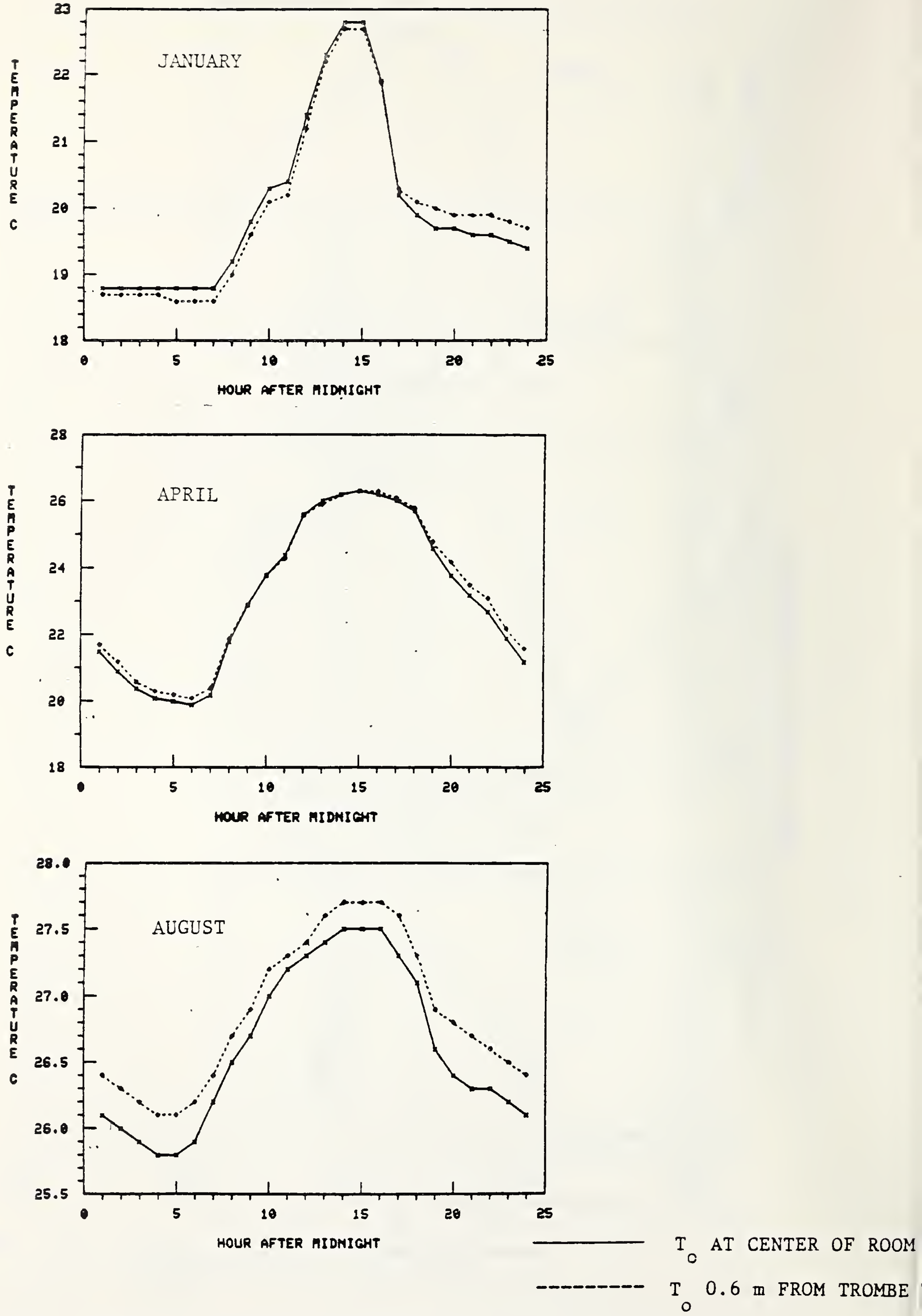

Figure 16. Variation of Operative Temperature in the Occupied Zone (Washington, DC).

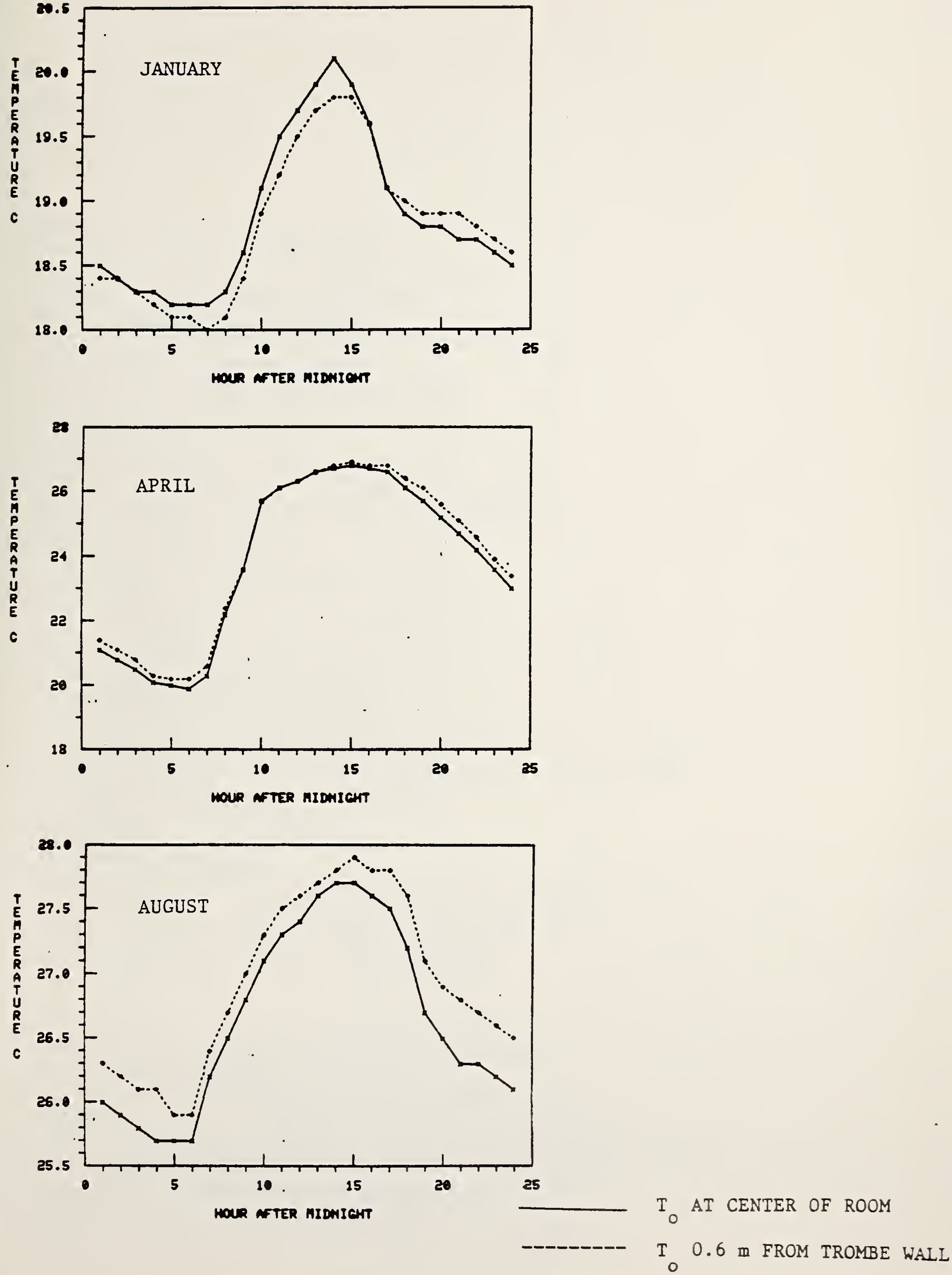

Figure 17. Variation of Operative Temperature in the Occupied Zone (Madison, WI).

APPENDIX A. LISTING OF SUBROUTINE "TROMBE"

The following list defines the input and output variables in the Subroutine TROMBE:

Inputs:

X,Y,Z - Response factors for the mass storage wall
CR - Response factors common ratio
NT - Number of terms of the response factors
UT - U-value of the Trombe wall assembly
DAT(1) - Solar absorptivity of glazing
DAT(2) - Solar absorptivity of mass wall outer surface
DAT(3) - Emissivity of glazing surface
DAT(4) - Emissivity of mass wall outer surface
DAT(5) - Number of glazing layers
DAT(6) - Glazing area
DAT(7) - Mass wall surface area
DAT(8) - Thermal circulation vents area (inlet=outlet)
DAT(9) - Cross-sectional area of summer vent opening
DAT(10) - Height of Trombe wall
DAT(11) - Width of Trombe wall
DAT(12) - Trombe wall space gap width
DAT(13) - Vent opening indicator
    = 0 - no opening
    = 1 - with opening
DAT(14) - Night-time insulation indicator
    = 0 no night-time insulation
    = 1 with night-time insulation
DAT(15) - Therma resistance value (R-value) of the night-time insulation
TI - Surface temperature of mass wall facing the living space
TA - Air temperature of the living space
TIM - A reference temperature
DB - Outside dry bulb temperature
PB - Barometric pressure
FO - Coefficient of heat transfer for surface facing outside
SO - Total insolation normal to Trombe wall surface
SHGW - Solar heat gain through Trombe wall glazings
QLS - Sensible (hourly) load of the building

Outputs:

QO - Convective heat transferred between Trombe wall air space and mass wall outer surface
QI - Convective heat transferred between room air and mass wall inner surface
QC - Heat transferred by thermal circulation from Trombe wall air space to living space through vents
TO - Temperature of mass wall outer surface
TWA - Trombe wall air space temperature
TG - Average temperature of the Trombe wall glazings

```
LIU*NBSLD(1).TROMBE1(0)
              SUBROUTINE TROMBE(X,Y,Z,CR,NT,UT,DAT,QO,QI,QC,TO,TI,TWA,TG,TA,TIM,
             1                  DB,PB,FO,SO,SHGW,MONTH,NHOUR,QLS)
              DIMENSION DAT(15),X(48),Y(48),Z(48),TWO(48),TWI(48),TI(48),TO(48)
              DIMENSION A(31,31),B(31),T(31)
              IDAY=DAY
              IHOUR=HOURQ
              IF(IDAY.LE.5.OR.IDAY.GE.14) GO TO 1
              IF(MOD(IDAY,2).EQ.0.AND.IHOUR.EQ.24)WRITE(6,71)
      1       CONTINUE
              ABSG=DAT(1)
              ABST=DAT(2)
              EG=DAT(3)
              ET=DAT(4)
              PANES=DAT(5)
              AG=DAT(6)
              AT=DAT(7)
              AV=DAT(8)
              ACROSS=DAT(9)
              HT=DAT(10)
              WT=DAT(11)
              GAP=DAT(12)
              IVT=DAT(13)
              NBEAD=DAT(14)
              RBEAD=DAT(15)
              HRC=4.*0.1714/((1./EG)+(1./ET)-1.)
              TWO1=TO(1)+TIM
              DO 5 I=2,NT
      5       TWO(I)=TO(I-1)
              DO 10 I=1,NT
              TWI(I)=TI(I)
      10      CONTINUE
              SX=X(1)*TWI(1)
              SY=Y(1)*TWI(1)
              SZ=0.
              SXY=0.
              DO 20 J=2,NT
              SX=SX+X(J)*TWI(J)
              SY=SY+Y(J)*TWI(J)
              SZ=SZ+Z(J)*TWO(J)
              SXY=SXY+Y(J)*TWO(J)
      20      CONTINUE
              QOX=SY-SZ+CR*QO
      30      CONTINUE
              NP=PANES
              IF(NP.EQ.2) GO TO 80
              DTOA=ABS(TWO1-TWA)
              DTGA=ABS(TG-TWA)
              HOTW=0.19*(ABS(TWO1-TWA))**0.333
              IF(DTOA.LE.0.1) HOTW=0.088
              HG=0.19*(ABS(TG-TWA))**0.333
              IF(DTGA.LE.0.1) HG=0.088
              TAVG=460.+(TG+TWO1)/2.
              HR=HRC*((TAVG/100.)**3)/100.
              IF(DB.GT.TA) GO TO 45
              IF(IVT.EQ.0) GO TO 40
```

```
      IF(TWA.LE.TA) GO TO 40
      VOL=0.8*20420.*SQRT(HT*(TWA-TA)/(TWA+460.))*AV
C     COMPUTE MASS FLOW FROM VOLUME FLOW
      FLOW=(1.3265*PB/(TWA+460.))*VOL
      GO TO 50
40    FLOW=0.
      GO TO 50
45    IF(DB.GT.TWA) GO TO 46
      AVV=ACROSS
      VOLV=0.8*20420.*SQRT(HT*(TWA-DB)/(TWA+460.))*AVV
      FLOWV=(1.3265*PB/(TWA+460.))*VOLV
      FLOW=FLOWV
      GO TO 50
46    FLOWV=0.
      FLOW=FLOWV
50    CONTINUE
      A(1,1)=HOTW+HR+Z(1)
      A(1,2)=-HR
      A(1,3)=-HOTW
      A(2,1)=-HR
      A(2,2)=FO+HR+HG
      A(2,3)=-HG
      A(3,1)=-HOTW*AT/AG
      A(3,2)=-HG
      A(3,3)=HG+HOTW*(AT/AG)+0.24*FLOW/AG
      B(1)=QOX+SHGW*ABST+Z(1)*TIM
      B(2)=SO*ABSG+FO*DB
      B(3)=0.24*TA*FLOW/AG
C     SOLVP IS A SUBROUTINE TO SOLVE N SIMULTANEOUS LINEAR ALGEBRAIC
C     EQUATIONS WITH COEFFICIENT MATRIX A, UNKNOWN VECTOR T, AND
C     CONSTANT VECTOR B.
      CALL SOLVP(3,4,A,B,T,31)
      TWO(1)=T(1)-TIM
      TG=T(2)
      TWA=T(3)
      GO TO 200
80    IF(IDAY.EQ.0.AND.IHOUR.EQ.0) GO TO 90
      GO TO 100
90    TGI=DB
      TGO=DB
100   CONTINUE
      RSPACE=1.15
      HSPACE=1./RSPACE
      TAV=460.+(TWO1+TGI)/2.
      HR=HRC*((TAV/100.)**3)/100.
      DTOA=ABS(TWO1-TWA)
      DTGA=ABS(TGI-TWA)
      HOTW=0.19*(DTOA**0.333)
      HG=0.19*(DTGA**0.333)
      IF(DTOA.LE.0.1) HOTW=0.088
      IF(DTGA.LE.0.1) HG=0.088
C     IF(DTOA.GT.0.) HOTW=0.56
C     IF(DTGA.GT.0.) HG=0.56
      IF(DB.GT.TA) GO TO 145
      IF(IVT.EQ.0) GO TO 140
C     VOLUME FLOW RATE THRU TROMBE WALL CHANNEL BASED ON EQUATION USED
C     IN THE PROGRAM PASOLE OF LASL
      IF(TWA.LE.TA) GO TO 140
```

```
      VOL=0.8*20420.*SQRT(HT*(TWA-TA)/(TWA+460.))*AV
C     COMPUTE MASS FLOW
      FLOW=(1.3265*PB/(TWA+460.))*VOL
      GO TO 150
140   FLOW=0.
      GO TO 150
145   IF(DB.GT.TWA) GO TO 146
      AVV=ACROSS
      VOLV=0.8*20420.*SQRT(HT*(TWA-DB)/(TWA+460.))*AVV
      FLOWV=(1.3265*PB/(TWA+460.))*VOLV
      FLOW=FLOWV
      GO TO 150
146   FLOWV=0.
      FLOW=FLOWV
150   CONTINUE
      A(1,1)=HOTW+HR+Z(1)
      A(1,2)=-HR
      A(1,3)=-HOTW
      A(1,4)=0.
      A(2,1)=-HR
      A(2,2)=HG+HR+HSPACE
      A(2,3)=-HG
      A(2,4)=-HSPACE
      A(3,1)=-HOTW*AT/AG
      A(3,2)=-HG
      A(3,3)=HG+HOTW*AT/AG+0.24*FLOW/AG
      A(3,4)=0.
      A(4,1)=0.
      A(4,2)=-HSPACE
      A(4,3)=0.
      A(4,4)=FO+HSPACE
      B(1)=QOX+SHGW*ABST+Z(1)*TIM
      B(2)=SO*(1.-ABSG)*ABSG
      B(3)=0.24*FLOW*TA/AG
      B(4)=SO*ABSG+FO*DB
      IF(NBEAD.EQ.0) GO TO 190
      UBEAD=1./RBEAD
      IF(MONTH.GE.6.AND.MONTH.LE.9) GO TO 180
      IF(NHOUR.GE.7.AND.NHOUR.LE.17) GO TO 190
      GO TO 170
180   IF(NHOUR.LT.7.OR.NHOUR.GT.17) GO TO 190
170   CONTINUE
      A(2,2)=HG+HR+UBEAD
      A(2,4)=-UBEAD
      A(4,2)=-UBEAD
      A(4,4)=FO+UBEAD
      B(1)=QOX+Z(1)*TIM
      B(2)=0.
      B(4)=0.9*SO+FO*DB
190   CONTINUE
      CALL SOLVP(4,5,A,B,T,31)
      TWO(1)=T(1)-TIM
      TGI=T(2)
      TWA=T(3)
      TGO=T(4)
      TG=(TGI+TGO)/2.
```

```
              TO(J)=TWO(J)
      60      CONTINUE
              QO=QOX-Z(1)*TWO(1)
              FLOW=0.0
              IF(DB.GT.TA) GO TO 61
              IF(TWA.LT.TA.OR.IVT.EQ.0)GO TO 61
              VOL=0.8*20420.*SQRT(HT*(TWA-TA)/(TWA+460.))*AV
              FLOW=(1.3265*PB/(TWA+460.))*VOL
      61      QC=0.24*FLOW*(TWA-TA)
              IF(HOURQ.EQ.24.)HOURQ=0.0
              IF(HOURQ.EQ.0.0)DAY=DAY+1
              HOURQ=HOURQ+1
              TWO1=TWO(1)+TIM
              TWI1=TWI(1)+TIM
              QLSFT=QLS/AG
              QTCWL=(-QI*AT+QC)/AG
              IYR=78
              MDAY=NDAY
              IF(MONTH.EQ.3) MDAY=NDAY+14
              NDAY=DAY
      C       IF(NDAY.LE.6.OR.NDAY.GE.15) GO TO 300
              IF(NP.EQ.2) GO TO 75
              WRITE(6.70)DAY,HOURQ,SHGW,DB,TG,TWA,TWO1,TWI1,TA,QO,QI,QC
              GO TO 300
      75      WRITE(6,70) DAY,HOURQ,SHGW,DB,TGO,TGI,TWA,TWO1,TWI1,TA,QO,QI,QC
      C       WRITE(11,72) MONTH,MDAY,IYR,NHOUR,TA,TWI1,TWO1,TGO,TGI,QLSFT,QTCWL
      72      FORMAT(3I2,I4,7F10.2)
      70      FORMAT(13F10.1)
      71      FORMAT(1H1)
      300     RETURN
              END
  END PRT

@LOOK
```

Appendix B. Selected House Physical Data Used in the Study

A. Building Variables

1) Interior Dimensions:	Refer to construction drawings [4]
2) Glazing Area: (Values include wood framing Glazing thickness is 1/4 in. except for 3/8 in. thick glazing of Trombe Wall)	South - 9.58m^2 (103.2 ft^2) Direct Gain 24.04m^2 (258.8 ft^2) Trombe Wall. North - 0.66m^2 (7.1 ft^2) East - 3.51m^2 (37.7 ft^2) West - 2.79m^2 (30 ft^2) Skylights - 1.5m^2(16 ft^2) 45° South Tilt 0.9m^2(9.6ft^2) 20° North Tilt
3) Glazing Transmittance:	0.87 * (Per 3/16 in. pane)
4) Glazing U-value:	2.84 w/m^2°C (0.50 BTUH/ft^2°F)* double pane glass with 2.54 cm air space.
5) Total Mass:	16,600KG (36,660 lbs) Trombe wall directly behind glazing 2,710KG (5,980 lbs) Bedroom #2
6) Estimated Mass Heat Capacity:	3865 whr/°C (7330 BTU/°F) Trombe wall directly behind glazing 633 whr/°C (1200 BTU/°F) bedroom #2
7) Mass Surface Area:	26.2m^2 (282 ft^2) Trombe wall directly behind glazing 6.4m^2 (69 ft^2) Bedroom #2
8) Solar Absorptance of Mass:	0.91 Trombe wall, measured
9) Building Heat Load Factor:	40.9 whr/m^2•Cday(7.2 BTU/ft^2/°Fday) standard ASHRAE methods using 0.5 air exchange per hour
10) Infiltration:	0.4 - 0.5 air exchange per hour. Estimated using measured data for June 1979 of 0.26 air exchange per hour. in closed condition.
11) Ventilation:	Operable windows only

*Standard values taken from ASHRAE "Handbook of Fundamentals," 1977 manual.

B. THERMAL PROPERTIES OF EXTERIOR SURFACES

MATERIAL	THICKNESS CM (IN.)	RESISTANCE $M^2HR°C/KJ$ $(FT^2HR°F/BTU)$	DENSITY KG/M^3 (lb/FT^3)	SPECIFIC HEAT KJ/KG°C (BTU/lb°F)
GYPSUM BOARD	1.27 (½)	0.02 (0.45)	801 (50)	0.84 (0.20)
FIBERGLASS BATT INSULATION	8.89 (3½)	0.55 (11.00)	24 (1.5)	0.75 (0.18)
	13.97 (5½)	0.95 (19.00)	24 (1.5)	0.75 (0.18)
INSULATING SHEATHING	1.27 (½)	0.09 (2.00)	29 (1.8)	1.21 (0.29)
PLYWOOD	1.27 (½)	0.03 (0.62)	545 (34)	1.21 (0.29)
	1.59 (5/8)	0.04 (0.78)	545 (34)	1.21 (0.29)
15 # FELT	0.64 (¼)	0.01 (0.12)	N/A	N/A
235 # ASPHALT SHINGLES	0.64 (¼)	0.02 (0.44)	1121 (70)	1.47 (0.35)
STUCCO	1.91 (3/4)	0.01 (0.15)	1858 (116)	0.84 (0.20)
CARPET	---	0.06 (1.23)	N/A	1.42 (0.34)

C. Internal Heat Gain Data

Lighting:

24-Hour Profile

1.	0.0	7.	1.0	13.	0.023	19.	0.023
2.	0.0	8.	1.0	14.	0.023	20.	0.5
3.	0.0	9.	0.023	15.	0.023	21.	0.5
4.	0.0	10.	0.023	16.	0.023	22.	1.0
5.	0.0	11.	0.023	17.	0.023	23.	0.0
6.	0.0	12.	0.023	18.	0.023	24.	0.0

Normalization Factor = 0.38 watts/sq. ft

Equipment/Appliance:

24-Hour Profile

1.	0.25	7.	0.33	13.	0.42	19.	0.92
2.	0.25	8.	0.46	14.	0.25	20.	0.68
3.	0.25	9.	0.63	15.	0.25	21.	0.68
4.	0.25	10.	0.88	16.	0.58	22.	0.68
5.	0.25	11.	0.35	17.	0.58	23.	0.51
6.	0.25	12.	0.88	18.	1.0	24.	0.23

Normalization Factor = 0.75 watts/sq. ft

Occupants:

24-Hour Profile

1.	1.0	7.	1.0	13.	0.4	19.	1.0
2.	1.0	8.	1.0	14.	0.4	20.	1.0
3.	1.0	9.	0.4	15.	0.4	21.	1.0
4.	1.0	10.	0.4	16.	0.69	22.	1.0
5.	1.0	11.	0.4	17.	0.69	23.	1.0
6.	1.0	12.	0.4	18.	1.0	24.	1.0

Normalization Factor = 2 adults and 2 children

NBS-114A (REV. 2-80)

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5. AUTHOR(S)

S. Liu

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

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Office of Solar Heat Technologies
Washington, DC 20545

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

An analytical investigation was conducted on the thermal comfort conditions in a passive solar heated residence of the popular Trombe Wall configuration. The National Bureau of Standards Load Determination Program (NBSLD) was used to simulate the indoor thermal environment of an actual passive solar residence, using the Typical Meteorological Year (TMY) weather data tape as input at three locations of different climatic conditions. The relevant thermal comfort parameters such as the space air temperature, mean radiant temperatures, operative temperatures, radiant temperature asymmetry, and temperature drifts of the occupied zone, were computed for a prime heating month, a transition month, and a prime cooling month of a typical weather year at the three locations. These parameters were analyzed in accordance with the criteria specified in the recently revised ASHRAE Comfort Standard 55-81. It was found that for the specific passive solar residence analyzed, the upper boundary of the comfort envelope can be exceeded (overheating) during a typical clear day in the transition month of April unless a change of clothing to summer wear is made during the daytime high solar radiation house. The upper boundary will be exceeded during a typical clear day in the prime cooling month of August for a person in typical summer clothing at all three locations unless the average air movement in the occupied zone is increased above the level of natural circulation, or the thermostat setting is reduced to a lower level, or both.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

ASHRAE Standard; asymmetric heating; collector/storage wall; comfort envelope; comfort zone; mean radiant temperature; operative temperature; passive solar; temperature drifts; thermal comfort condition; Trombe Wall

13. AVAILABILITY

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