Title

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Publication Date

1979-10-01

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ENERGY & ENVIRONMENT DIVISION

Presented at the 2nd International Conference on Energy Use Management, Los Angeles, CA, October 22-26, 1979

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October 1979

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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ABSTRACT

The effects of thermostat control profiles on the energy consumption of the auxiliary heating system in direct-gain passive solar buildings has been studied [1]. The building energy analysis computer program BLAST-2 was used to simulate the thermal performance of high-mass and low-mass direct gain configuration in each of two climatic regions. The results indicate that passive system performance is very sensitive to the manner in which the occupant controls the auxiliary system. Under some control strategies, the performance can actually be degraded by commonly recommended levels of thermal storage mass within the structure.

INTRODUCTION

Past efforts to evaluate and characterize the thermal performance of passive solar systems have dealt primarily with the influence of architectural design parameters of protypical structures. The influences of glazing area, thermal storage mass, etc., have been extensively evaluated in a variety of climates assuming constant thermostat settings [2]. Other studies have investigated the effect of thermostat control strategies, such as night setback, on the performance of conventional construction [3]. The purpose of the work reported here has been to investigate the impact of user control strategies on the auxiliary energy consumption of direct- gain passive solar systems. This study has been performed in conjunction with evaluation of thermal mass in residential construction, which is reported elsewhere [1].

The thermal performance of high- and low-mass direct-gain configurations has been analyzed in both Albuquerque, New Mexico and in Madison, Wisconsin, which have 4348 and 7863 heating degree days, respectively (65^{O}F base). Hourly heating and cooling load calculations were performed for one year using Solmet based Typical Meteorological Year (TMY) weather tapes. The effects of several different constant thermostat setpoints, night setback temperatures, and setback time periods are reported.

*This work was supported by the Passive and Hybrid Systems Branch, Systems Development Division, Office of Solar Applications, U.S. Department of Energy, under Contract No. W-7405-ENG-48.

The buildings simulated are identical to the high-mass and low-mass direct-gain structures used in the thermal mass study reported elsewhere [1], with the exception that an attached shading device is added above the 180 ft^2 of south glazing to reduce cooling loads. In the Albuquerque and Madison simulations, the overhangs are located 1 ft above the 4 ft high window and extend horizontally 3 ft and 2 ft, respectively, from the south wall.

The buildings have identical geometry, orientation, and glazing distribution. Concrete slab floors are assumed; the low-mass building has a gypboard interior finish and the high-mass structure has four inches of concrete in place of the gypboard. In order to focus strictly on the effects of thermal mass and thermostatic controls, the high-mass and low-mass buildings are given equal steady-state conductances for the overall wall construction; this is accomplished by modest adjustments in the insulation levels. A conventional non-massive insulated roof is used. In order to more faithfully reflect regional influences in building design, the wall, roof, and slab insulation level as well as external finishes are different for the two cities studied. These variations and a more complete building specification, including internal thermal loading, appear in Ref. 1.

Infiltration and internal loads (people, lights, equipment) have a profound impact on the thermal loads of the buildings simulated. Setting the infiltration to zero for the high-mass buildings in Madison reduces the heating load by 69%, increases the cooling load by 41%, and reduces the total load by 49%; a similar calculation in Albuquerque reduces the heating load by 89% increases the cooling load by 30%, and reduces the total load by 2%. The combination of moderate annual average temperatures and high internal loads accounts for the net cooling benefits of infiltration; the figures suggest substantial potential for ventilation cooling in both climates. The results are dramatically different when infiltration is set to zero in a building with no internal loads; in Madison the heating, cooling, and total loads are all reduced, by 52%, 26%, and 47%, respectively; in Albuquerque, the corresponding reductions are 66%, 15%, and 29%. Fractional reductions in the heating load are smaller since the auxiliary has to supply energy previously derived from internal sources. In the absence of internal sources, the cooling load derives from solar, conduction, and infiltration gains. In Madison, the reduction in conduction gains resulting from higher insulation levels accounts for the larger percent reduction in cooling load when infiltration is set to zero (26% in Madison vs. 15% in Albuquerque). The values assigned for infiltration and internal loads are not atypical of conditions in a real residence, and any simulation failing to account for these effects must be suspect.

The public domain building energy analysis computer program BLAST* is used to perform hourly dynamic heating and cooling load calculations for each building; heating and cooling system equipment are not simulated. Unlike Ref. 1, the analysis performed for this study does not use thermostat throttling ranges. Considerable effort has been devoted to verification of BLAST by the Passive Solar Group at Lawrence Berkeley Laboratory. Successful comparisons have been made between thermal parameters measured in test rooms (located at Los Alamos Scientific Laboratory) and predictions of the computer program.

RESULTS

Thermostat Setpoints

Constant 24-hour schedules for the heating and cooling thermostat setpoints are defined; within the deadband between the two settings, the interior air temperature is allowed to float freely. Figures 1 and 2 show the influence of raising and lowering the equipment control temperatures on the annual heating and cooling loads in Albuquerque and Madison, respectively. Changes in building loads at the various setpoints have been expressed in reference to the annual load with a 68-78°F deadband. The simulations have indicated that for deadbands greater than about 6°F, there is little interaction between the heating load and cooling thermostat setting (T_c) or the cooling load and heating thermostat setting (T_h). Consequently, the two curves for a city can be treated independently.

In Albuquerque, the cooling load dominates, while in Madison the heating load dominates. Figures 1 and 2 demonstrate that, in the region studied, the dominant load is noticeably less sensitive to changes in thermostat settings and more linear than the smaller of the two loads. However, the absolute sensitivities for the heating and cooling loads in Albuquerque are about equal at 1.8 MBTU/°F, while in Madison, where heating is much more dominant, the heating thermostat sensitivity is 2.4 MBTU/°F, which is nearly twice that of the cooling system control.

Night Setback

Figure 3 shows the effect of a night setback of the heating thermostat on the annual heating load of the high-mass direct-gain structure for both geographic locations and for two daytime settings. The setback occurs during the period from 10:00 p.m. to 8:00 a.m. The figure shows that in Albuquerque, setbacks beyond 8°F are not effective in reducing heating energy consumption. This most likely results from the effect of the mass maintaining the indoor air temperature above the night setting, producing higher inside-to-outside temperature differentials, with consequent higher losses through the envelope. This is in contrast to Madison, where heating energy consumption continues to drop rapidly with increasing setback increment. Although thermal mass can have either a beneficial or a deleterious effect on instantaneous thermal loads, there are no obvious net benefits or net disadvantages to thermal mass when setback strategies are employed in the severe climate of Madison.

According to the above interpretation, one would expect the setback effectiveness to have a relatively stronger dependence on mass in Albuquerque than in Madison. This interpretation is supported by Figures 4 and 5, which show absolute loads calculated by BLAST and the ratio of the heating loads for the high- and low-mass passive solar structures as functions of the setback temperature for Albuquerque and Madison, respectively; results for two daytime thermostat settings are shown. The mass effect is pronounced in Albuquerque and is evident in Madison. Although adding mass to the structure is beneficial in the case of constant thermostat settings, the advantages of the mass diminish with increasing setback. For deep setbacks, thermal mass in the envelope actually has a deleterious effect on the annual heating loads in both climates! This is not surprising when there are higher night losses from the high-mass building

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*Building Loads Analysis and System Thermodynamics. BLAST is copyrighted by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois.

due to the thermal mass maintaining higher interior air temperatures. In this event, the higher losses must be made up by the heating system when the temperature is set up at 8:00 a.m. (before appreciable solar gains are available).

In order to investigate the causes for the decreasing effectiveness of thermal mass with increasing depth of setback, hourly heating loads and air temperatures are plotted in Figures 6 and 7 for Albuquerque and Madison, respectively, for both the high-mass and low-mass buildings with 16°F setbacks. Part (a) of each figure shows the calculated heating load for a 30-hour period beginning at midnight on the noted day in January; part (b) shows the air temperatures with the thermostat setback profile superimposed on the data. In Albuquerque, the air temperature for both mass levels floats downward but does not reach the setback point, so no nighttime heating load occurs. As expected, the high-mass structure moderates the temperature swing. At 8:00 a.m., a large thermal load is realized when the thermostat structure requires that more energy be delivered to the space; the air temperature is at 68°F, so the additional auxiliary energy is being stored in the mass.

After midday, solar gains begin to meet the full building load and the air temperature begins to rise. As expected, the high-mass building moderates the temperature swings in the space. In the evening, auxiliary is again required. Apparently, the low-mass building has higher surface temperatures and convects more of the daytime solar gains to the space, thereby requiring less auxiliary during the evening hours. Alternately, for the high-mass structure, the temperature of the thermal mass is still sufficiently depressed during the evening hours that energy from the auxiliary is again being stored. In other words, the auxiliary and solar gains stored in the mass earlier in the day are not adequate to make up the heat deficiency incurred the night before. When setback occurs, the previous night's behavior is repeated.

A somewhat different behavior occurs in Madison. The more severe climate requires some auxiliary for the low-mass building at night. At setup, the low-mass building produces slightly larger loads during the first hour, probably as a result of the low temperature of the gypboard. The load decreases as the gypboard approaches saturation and solar gains take over; the inside air temperature remains at 68°F during the entire day. The low-mass structure is again more responsive to solar gains and has lower loads. In Madison, auxiliary energy is being used all day to "pump up" the thermal storage of the high-mass structure; this is in contrast to Albuquerque, where the solar contribution around midday is high enough to allow the auxiliary to cut off for a few hours. In either case, the auxiliary energy is being stored in the mass, simply to be lost at night because of a larger inside-to-outside temperature difference; the higher thermal demand of the high-mass structures under setback conditions is thus accounted for.

Finally, Figure 8 shows the annual heating load for a high-mass structure as a function of the time at which the setback period ends. The more nonlinear behavior in Albuquerque [part (a)] as compared to Madison [part (b)] most likely results from the effects of solar gain. In the former location, solar gains can carry substantial fractions of the daytime load. If setup occurs sufficiently late in the morning, the mass is heated by the solar gains rather than by the auxiliary. The effect is apparently far less significant in Madison.

CONCLUSIONS

The effects of occupant use patterns for operating direct-gain buildings have been investigated in two climates. It is shown that these user effects are very large--especially in comparison to variations in the architectural parameters which are described in Ref. 1.

There is noticeable interaction between thermal mass and building operation. For the cases studied, the benefits realized through the use of thermal storage mass are greatly reduced when night setback strategies are employed. In cases where the setbacks are large (but not uncommon or unacceptable), the mass can actually increase the total auxiliary heating energy requirements of a passive building. This conclusion, together with the results of Ref. 1, implies the need for a more comprehensive examination of the role of thermal mass in residential construction.

REFERENCES

(1) B. Curtis et al., "Thermal Mass: Its Role in Residential Construction," presented at the 2nd Int'l Conference on Energy Use Management, 22-26 October 1979, Los Angeles; Lawrence Berkeley Laboratory Report LBL-9318.

(2) J.D. Balcomb and R.D. McFarland, "A Simple Empirical Method for Estimating the Performance of a Passive Solar Heated Building of the Thermal Storage Wall Type," Proceedings, 2nd National Passive Solar Conference, Vol. 2, Philadelphia, March 1978.

(3) L.W. Wall, T. Dey, A.J. Gadgil, A.B. Lilly, A.H. Rosenfeld, "Conservation Options in Residential Energy Use: Studies Using the Computer Program TWOZONE," Lawrence Berkeley Laboratory Report LBL-5271, August 1977.

Fig. 1 EFFECT OF THERMOSTAT SETTINGS IN ALBUQUERQUE

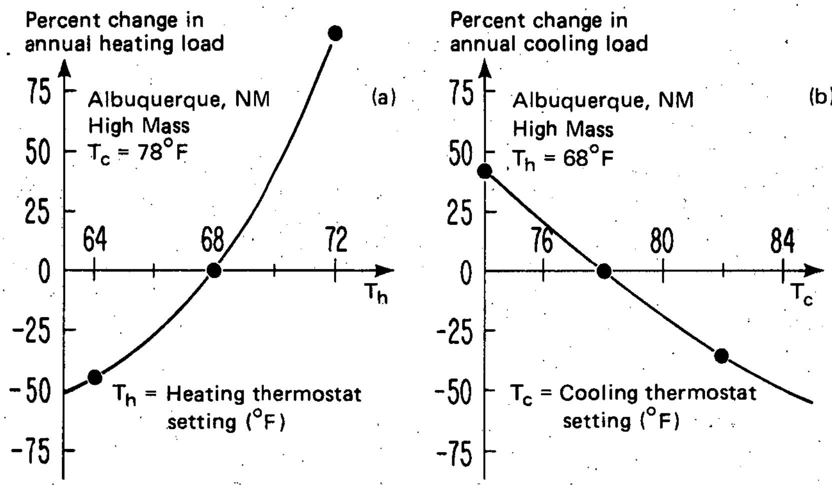


Fig. 2 EFFECT OF THERMOSTAT SETTINGS IN MADISON

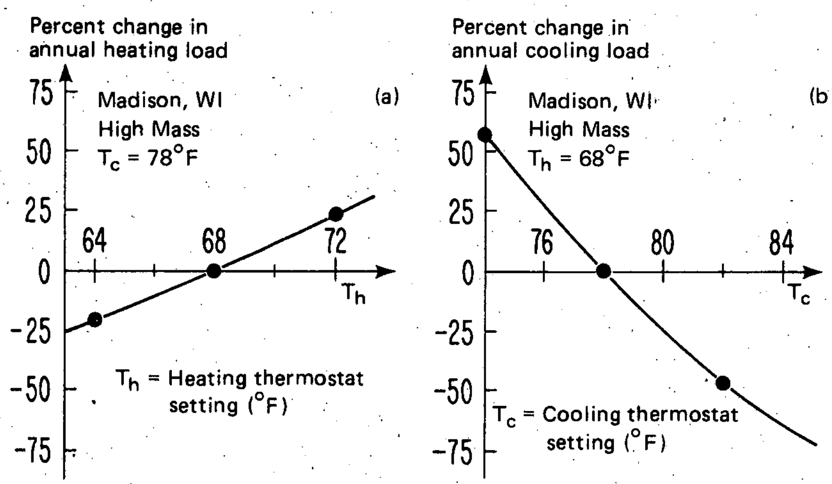
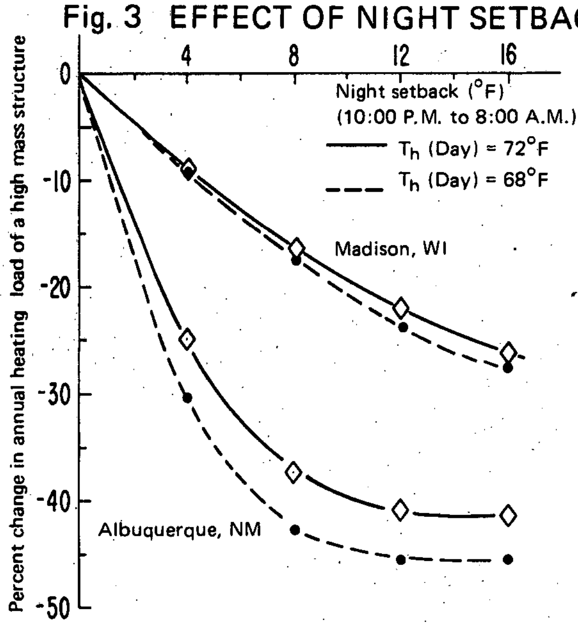
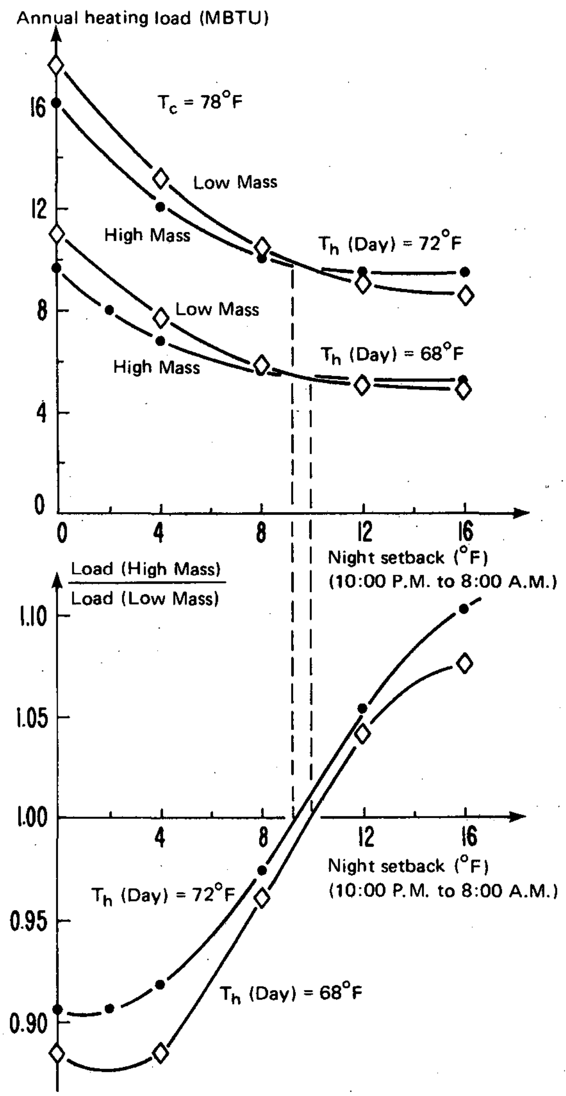


Fig. 3 EFFECT OF NIGHT SETBACK



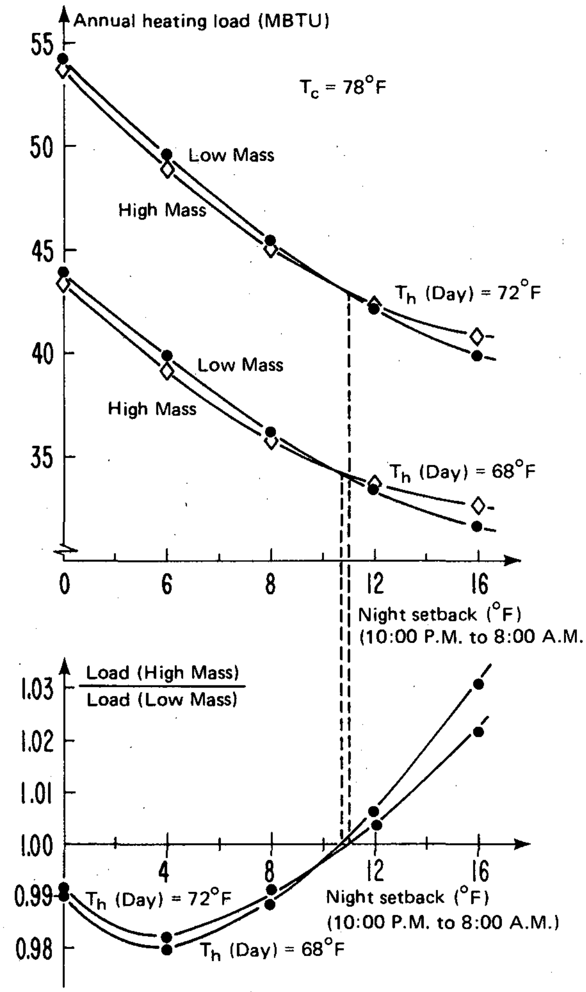
XBL 796 - 1994

Fig. 4 EFFECT OF MASS ON NIGHT SETBACK BENEFITS (ALBUQUERQUE)



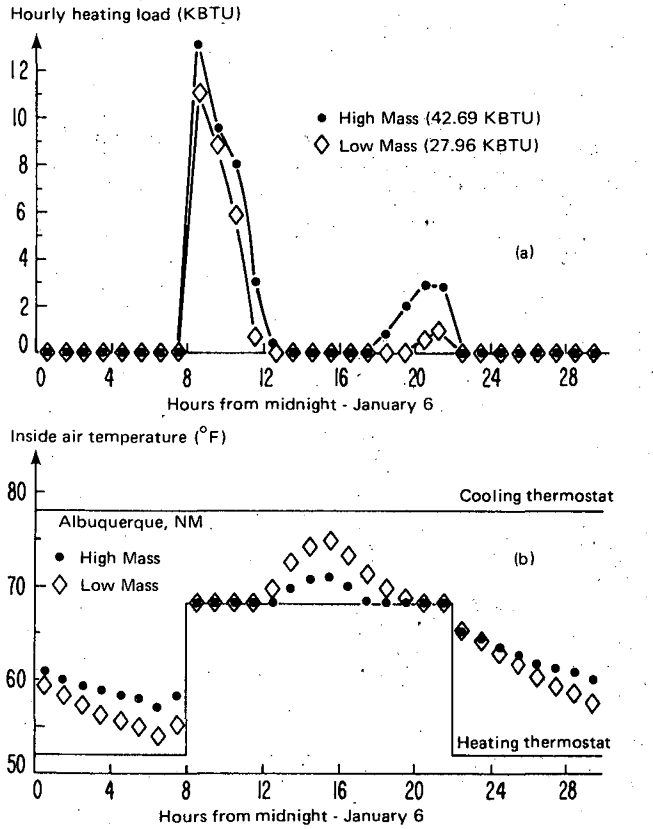
XBL 796 - 1992

Fig. 5 EFFECT OF MASS ON NIGHT SETBACK BENEFITS (MADISON)



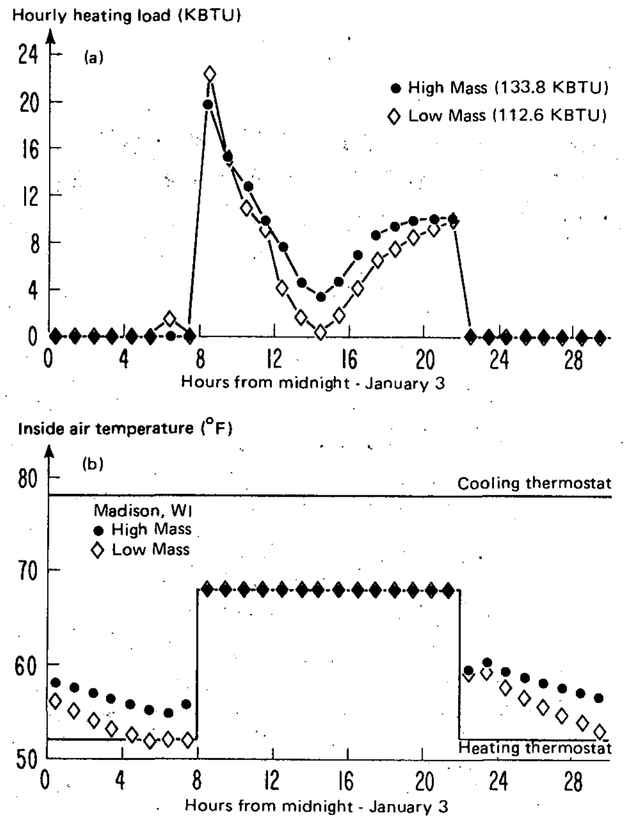
XBL 796 - 1996

Fig. 6 WINTER-DAY LOAD AND TEMPERATURE PROFILES (ALBUQUERQUE)



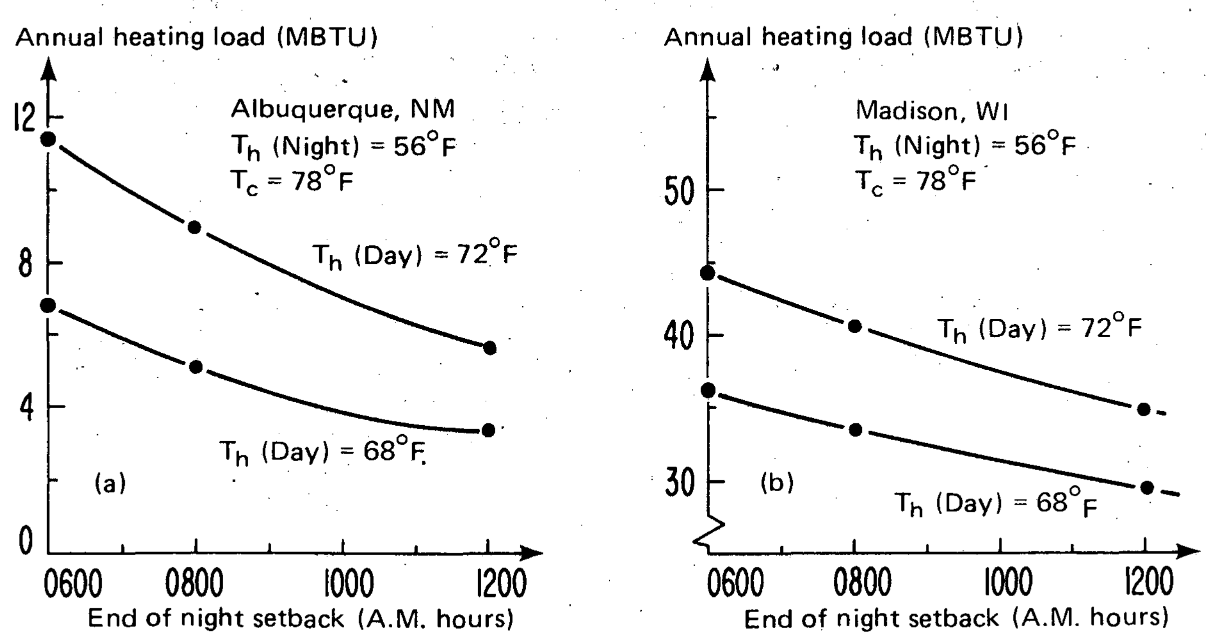
XBL 796 - 1995

Fig. 7 WINTER-DAY LOAD AND TEMPERATURE PROFILES (MADISON)



XBL 796 - 1998

Fig. 8 EFFECT OF NIGHT SETBACK TERMINATION TIME



XBL 796 - 1993