O. M. Burch
DIV-742 Ext. -6433
Pages 32

NBSIR 86-3458

The Effect of Wall Mass on the Peak Sensible Heating and Cooling Loads of A Single-Family Residence

D.M. Burch
G.N. Walton
B.A. Licitra
K. Cavanaugh
M.D. Klein

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Gaithersburg, MD 20899

October 1986

Prepared for:
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

NBSIR 86-3458

THE EFFECT OF WALL MASS ON THE PEAK SENSIBLE HEATING AND COOLING LOADS OF A SINGLE-FAMILY RESIDENCE

D.M. Burch
G.N. Walton
B.A. Licitra
K. Cavanaugh
M.D. Klein

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Gaithersburg, MD 20899

October 1986

Prepared for:
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

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

Contents

THE EFFECT OF WALL MASS ON THE PEAK SENSIBLE HEATING AND COOLING LOADS OF A SINGLE-FAMILY RESIDENCE

by D. M. Burch, G. N. Walton, B. A. Licitra, K. Cavanaugh, and M. D. Klein

ABSTRACT

The effect of wall mass on the peak sensible heating and cooling loads of a single-family residence was investigated using a sophisticated computer program called the Thermal Analysis Research Program (TARP). The computer simulation accuracy was verified by comparing its predicted sensible heating and cooling loads to measured values for six test buildings each having different wall constructions at the National Bureau of Standards. Good agreement was obtained for the load comparisons. The computer program subsequently was used to simulate the performance of identical houses each having the following three insulated wall constructions: wood frame, conventional masonry (outside wall mass), and innovative masonry (inside wall mass).

When the house was operated with fixed thermostat settings, the effect of wall mass on the peak sensible heating and cooling loads was found to be less than 11% for the climatic regions analyzed. Operating the typical house with a 10°F (5.6°C) night temperature setback during an 8-hour night period caused the daily peak sensible heating loads to be approximately twice those without setback.

Keywords: night temperature setback; peak sensible heating loads; peak sensible cooling loads; thermal mass; and whole house performance.

1. INTRODUCTION

Electric utilities are interested in identifying and promoting building construction techniques and building operating procedures that reduce and delay peak space heating and cooling loads of residences. The magnitude of the peak electric loads determines the required capacity of electric generating equipment. In response to this interest, the Electric Power Research Institute, a research association representing the electric utilities, funded the National Bureau of Standards to analyze the effects of wall mass and building operation strategies on the peak sensible heating and cooling loads of a single-family residence.

The present study consists of two parts. The first part uses a sophisticated computer program, called the Thermal Analysis Research Program (TARP), to extend the field measurements of peak sensible loads for six test buildings to a typical house. The second part analyzes the daily peak sensible heating and cooling loads for six test buildings previously used for thermal mass research studies at the National Bureau of Standards [1-4]. The peak load results for the test buildings were found not to be directly applicable to residences, because the wall heat transfer was a considerably larger part of the overall envelope heat transfer as compared to that for a typical house. For this reason, the peak load results for the test buildings are presented in an appendix.

The individual loads of a large number of houses combine to produce the component of the electric utility load attributable to space heating and cooling of residences. In this paper, the computer-predicted "hourly" sensible heating or cooling load of a typical house is used to assess the impact of wall mass on reductions and delays in this electric utility load component. A peak load based upon a smaller time period (e.g., 15 minutes) would approach the installed HVAC equipment capacities and would therefore not be meaningful in view of load diversification.

2. DESCRIPTION OF COMPUTER PROGRAM

TARP is a sophisticated computer program that predicts sensible heating and cooling loads of a building under a dynamic set of boundary conditions. TARP uses a detailed heat-balance method for the calculation of the energy requirements. The computer algorithms are partly based on subroutines from the Building Loads Analysis and System Thermodynamics (BLAST) Computer Program. In using TARP, the user specifies a detailed description of the building including the heat-transfer parameters for all materials comprising the building envelope, an operation schedule for the building, and hourly outdoor climatic data. Further information about TARP may be found in ref. [5].

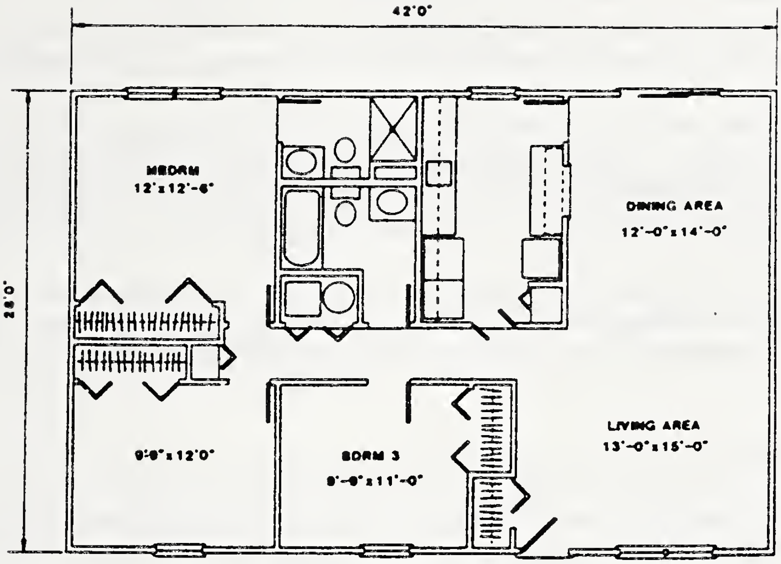
Sensible heating and cooling loads predicted by TARP were compared to corresponding measured sensible heating and cooling loads for the six thermal mass test buidings with good agreement in refs. [6,7]. Comparisons were carried out during a 3-day winter heating period, a 5-day spring heating period, and a 3-day summer cooling period. In these comparisons, TARP predictions followed accurately the general trends of the measured data. TARP predicted peak sensible heating and cooling loads within 15% and 18%, respectively. Good agreement was also observed for special tests with a partition wall and interior furnishings installed in the uninsulated test buildings [7]. This level of agreement was considered to be reasonable in view of the uncertainty associated with the heat-transfer properties of the building materials specified as input to the program and the simplifying approximations in the computer algorithms. The level of agreement is comparable and in most cases better then that for other similar computer programs cited in the literature [8-11]. A strong case for the valididy of the TARP program relative to the thermal mass studies [1-3] is that during climatic periods when a thermal mass effect was experimentally observed, the TARP Program predicted the correct relative cumulative sensible heating or cooling loads. That is, the ranking of the test cells and the relative magnitudes of the predicted thermal mass effects were the same as those for the actual test buildings.

3. HOUSE SIMULATION

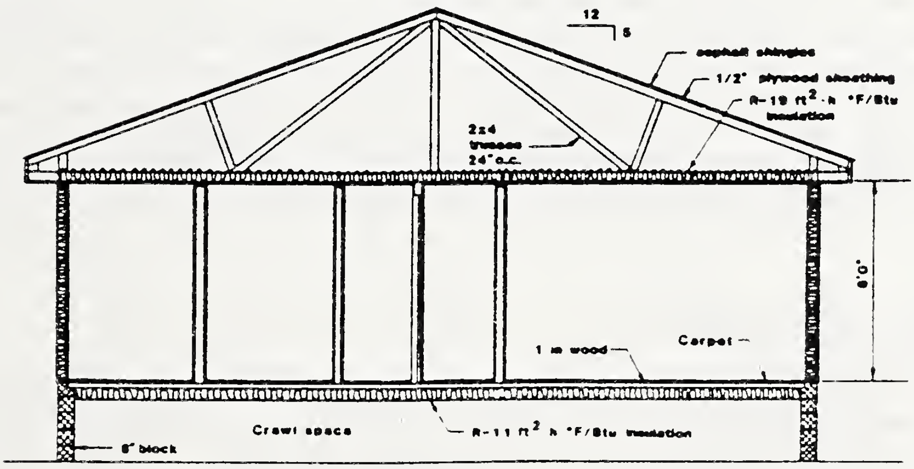
3.1. House Description

A modified version of the Hastings' ranch house [12] was used as a typical residence for the simulations. A floor plan and an elevation for this house are given in figure 1. The construction was selected to have high thermal resistance in its building envelope, in order to be consistent with current energy conservation practice. The house is described below.

The house was a wood-frame rambler having a floor area of 1180 ft^2 (110 m^2). It had a pitched roof and ventilated attic with R-19 $h\cdot ft^2\cdot °F/Btu$ (3.3 $m^2\cdot K/W$) ceiling insulation. The wall constructions analyzed included: insulated wood



A. Floor plan



B. Elevation

Figure 1. Floor plan and elevation for the house used in the analysis

frame; insulated masonry with outside mass; and insulated masonry with inside mass. A description of the wall constructions is given in Table 1. The walls were the same as those for the test buildings (see Table A-1 of the appendix), except that the overall thermal resistances were made to be identical to each other by adjusting the thermal conductivity of the wall insulation.

The windows were double-glazed and had a surface area of 141 ft^2 (13.1 m^2), or 12% of the floor area. For each wall orientation, the ratio of window area to gross wall area was constant. The floor consisted of 1 in (2.5 cm) wood and R-11 $h \cdot ft^2 \cdot °F/Btu$ (1.9 $m^2 \cdot K/W$) insulation placed over a ventilated crawlspace.

Steady-state heat-transfer parameters of the components comprising the building envelope are summarized in Table 2. Note that the heat transfer through the walls comprises only 19% of the overall envelope heat-transfer coefficient.

3.2. House Modeling

The house was simulated as a single zone with partition walls and interior furnishings included as surfaces within the building enclosure. The air temperature within this zone was assumed to be uniform.

The partition walls were modeled as two surfaces within the zone. Each surface consisted of 2 x 4 in (50 x 100 mm) framing with 1/2 in (13 mm) gypsum board attached at opposite sides. The surface area of these two surfaces was equal to that for the Hastings' ranch house. Interior furnishings were modeled as a 2-in-thick (50 mm) slab of wood. The total weight of interior furnishings was 7000 lb (3200 kg), and its specific heat was taken to be 0.29 Btu/lb·°F (1200 J/kg·K).

For space heating and cooling with fixed thermostat settings, the thermostat was set at 68°F (20°C) for space heating and 76°F (24°C) for space cooling. Within the deadband between the setpoints, space conditioning was not provided. A constant internal load of 0.75 W/ft^2 of floor (8.1 W per m^2) was used to simulate the heat release associated with lighting, equipment, and occupants. For the analysis, the rate of air infiltration was assumed to be constant at one volume change per hour. Winter space heating with a 10°F (5.6°C) night temperature setback during an 8-hour period from 11:00 p.m. to 7:00 a.m. was also analyzed.

4. REDUCTION IN PEAK LOADS

The TARP computer program was used to predict the hourly sensible heating and cooling loads in identical houses with the three wall constructions. Weather data from WYEC* magnetic computer tapes was used.

4.1. Summer Space Cooling with Fixed Thermostat Settings

Daily peak sensible cooling loads were correlated with maximum outdoor temperatures using least-squares fitting. The procedure is illustrated in figure 2 for the house with wood-frame wall construction exposed to

---

* Weather Year for Energy Calculations [13].

Table 1. Description of Wall Constructions

Insulated Wood Frame

0.5-in. gypsum board
0.002-in. polyethelene film
2x4 in. studs placed 16 in. o.c. with R-11 blanket insulation installed between the studs
5/8-in. exterior plywood

Insulated Masonry (Outside Mass)

0.5-in. gypsum board
0.002-in. polyethylene film
2-in.-thick extruded polystyrene insulation placed 24 in. o.c.
1/4-in air space
4-in., 2-core, concrete block
4-in. face brick

Insulated Masonry (Inside Mass)

0.5-in. plaster
8-in., 2 core, concrete block
3-1/2-in. perlite cavity insulation
4-in. face brick

Table 2. Heat-transfer Parameters for the House

Component	Surface Area (A) ft^2	(m^2)	Thermal Transmittance (U) Btu/h•ft^2•°F	(W/m^2•K)	UA Product Btu/h•°F	(W/K)
Glazing	141.	(13.1)	0.485	(2.75)	68.4	(36.1)
Walls	959.	(89.1)	0.081	(0.460)	79.6	(42.0)
Floor/ Crawlspace[1]					44.4	(23.4)
Ceiling/ Attic[1]					61.1	(32.2)
Door	20.1	(1.87)	0.285	(1.62)	5.7	(3.0)
Infiltration[2]					167.3	(88.2)

Overall Envelope Heat-Transfer Coefficient 424.3 (224.9)

[1] Calculated from three node model

[2] Calculated from relation: $K_I = \rho \cdot V \cdot C_p \cdot I$

outdoor climate in Washington, DC. Note that a least-squares line correlates well the peak sensible cooling loads.

Daily peak sensible cooling loads for identical houses with the three different wall constructions located in Washington, DC were correlated with maximum outdoor temperatures for a 2-month period. The results are given in figure 3. Wall mass is seen to have a small effect on the peak sensible cooling loads. For instance, at an outdoor design temperature of 93°F (34°C), the house with outside mass had a peak sensible cooling load 4% below that for the house with wood-frame walls, and the house with inside mass had a peak sensible cooling load 9% below that for the house with wood-frame walls. An explanation is given below.

Components of the sensible cooling load during a diurnal period are given in figure 4A for the house with wood-frame wall construction and in figure 4B for the house with masonry wall construction (inside mass). Note that at the time of the peak load (i.e., 1700 hours), the walls contribute 0.5 kW in the house with wood-frame walls and 0.2 kW in the house with masonry walls (inside mass), or a reduction of 60%. However, the walls comprise a very small portion of the total peak sensible cooling load. The total peak sensible cooling load is reduced from 5.2 kW in the house with wood-frame walls to 4.8 kW in the house with masonry walls, or a reduction of 8%.

4.2. Winter Space Heating with Fixed Thermostat Settings

Correlations of the daily peak sensible heating loads for the indentical houses with the three wall constructions located in Washington, DC are compared in figure 5. Wall mass is seen to have a small effect on the peak sensible heating loads. For instance, at a design outdoor temperature of 14°F (-10°C) the house with innovative masonry wall construction (i.e., inside wall mass) has a peak sensible heating load of 5% below that for the house with wood-frame wall construction. The effect was less than 2% when the wall mass is positioned at the outside. The effect of wall mass on the peak sensible heating load is small chiefly because the peak heating load occurs during a period just before sunrise when the outdoor temperature is relatively steady and the dynamic performance of the house approaches the steady-state performance. Another contributing factor is that the heat transfer through walls comprises only 19% of the overall envelope heat-transfer coefficient. As a result, wall heat transfer does not contribute much to the peak sensible heating load.

It is a common practice to use steady-state theory to predict peak space heating loads for sizing HVAC heating equipment. The procedure is to predict peak sensible heating loads (Q_{hmax}) using the the relation:

$$Q_{hmax} = K \cdot (T_b - T_{omin}) \tag{1}$$

Here T_{omin} is the design outdoor temperature. The minimum outdoor temperature generally occurs during a period just before sunrise when the outdoor temperature is relatively steady. The overall steady-state envelope heat-transfer coefficient (K) and night balance-point temperature (T_b) are computed by the relations:

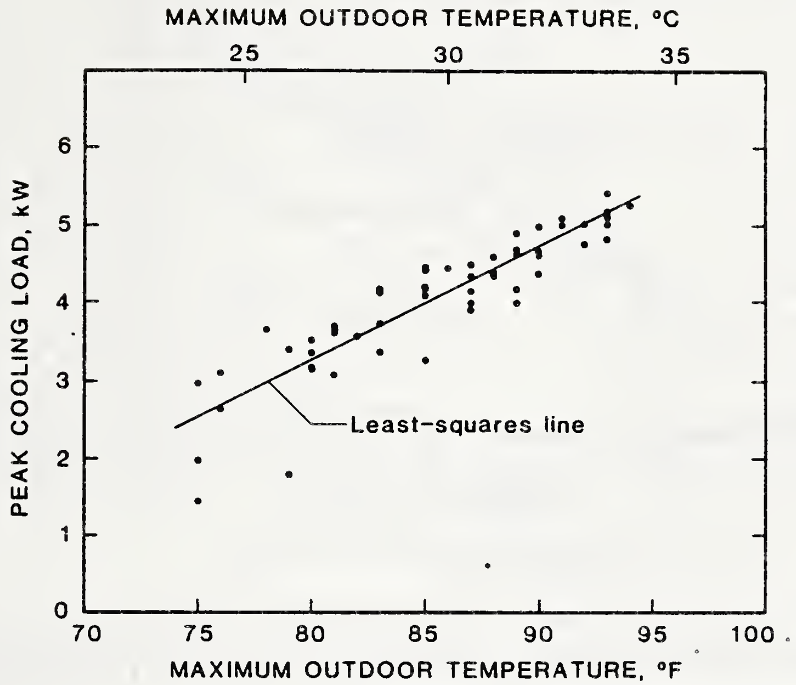


Figure 2. Illustration of the analysis procedure

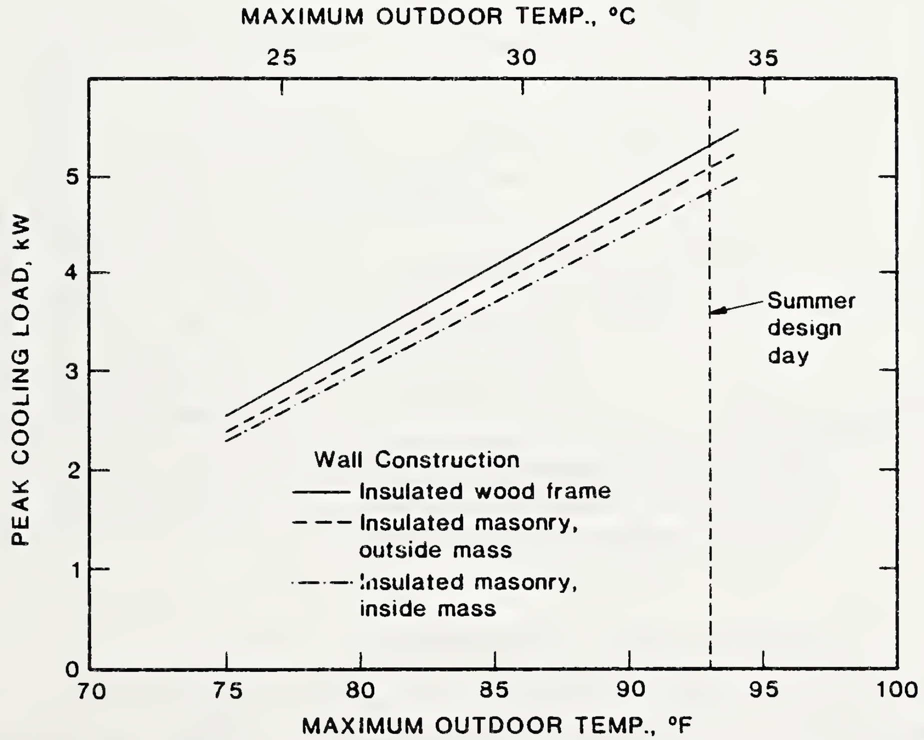
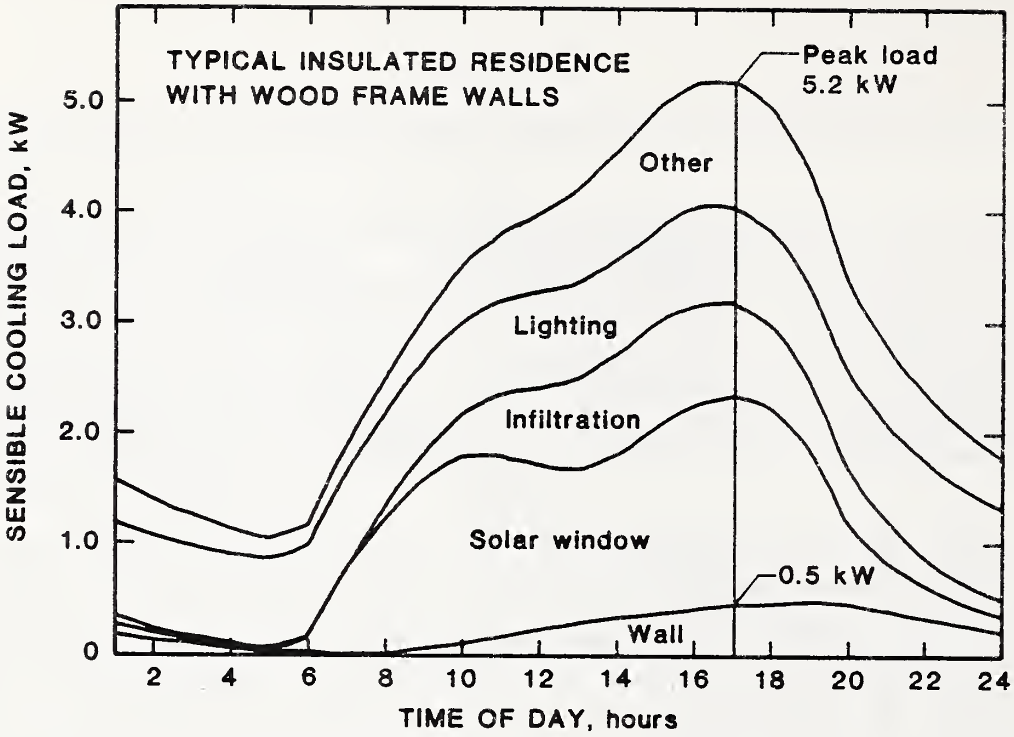
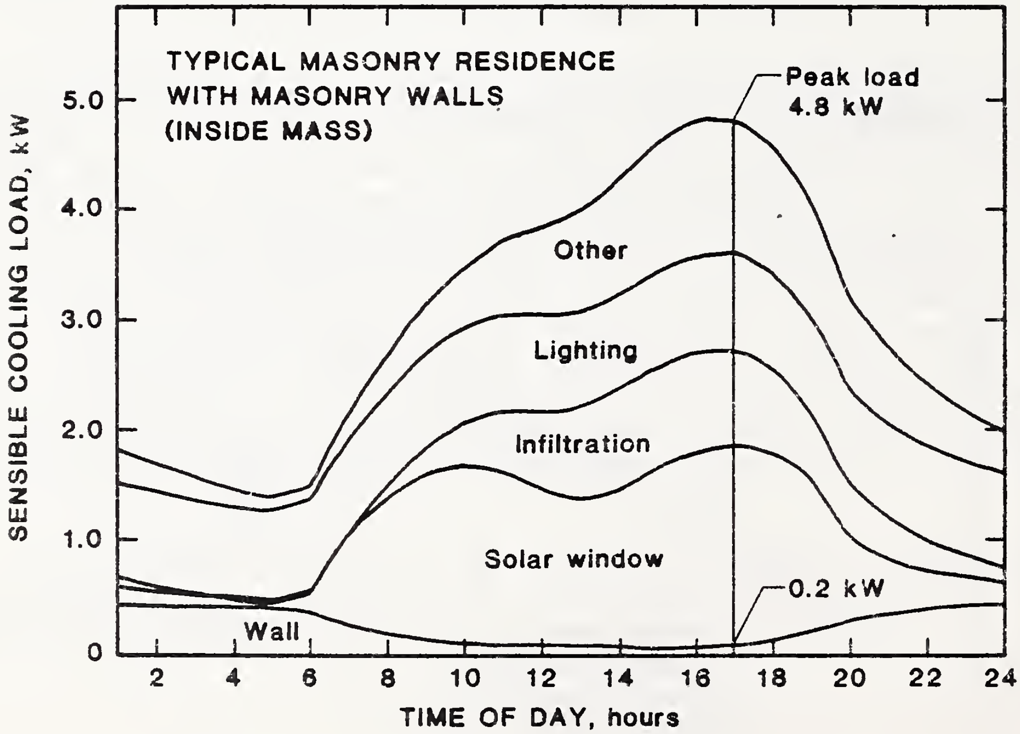


Figure 3. Comparison of peak sensible cooling load correlations for identical houses with three wall constructions



A. Wood-frame walls



B. Masonry walls (inside mass)

Figure 4. Components of the sensible cooling load for identical houses with different wall constructions during a diurnal period

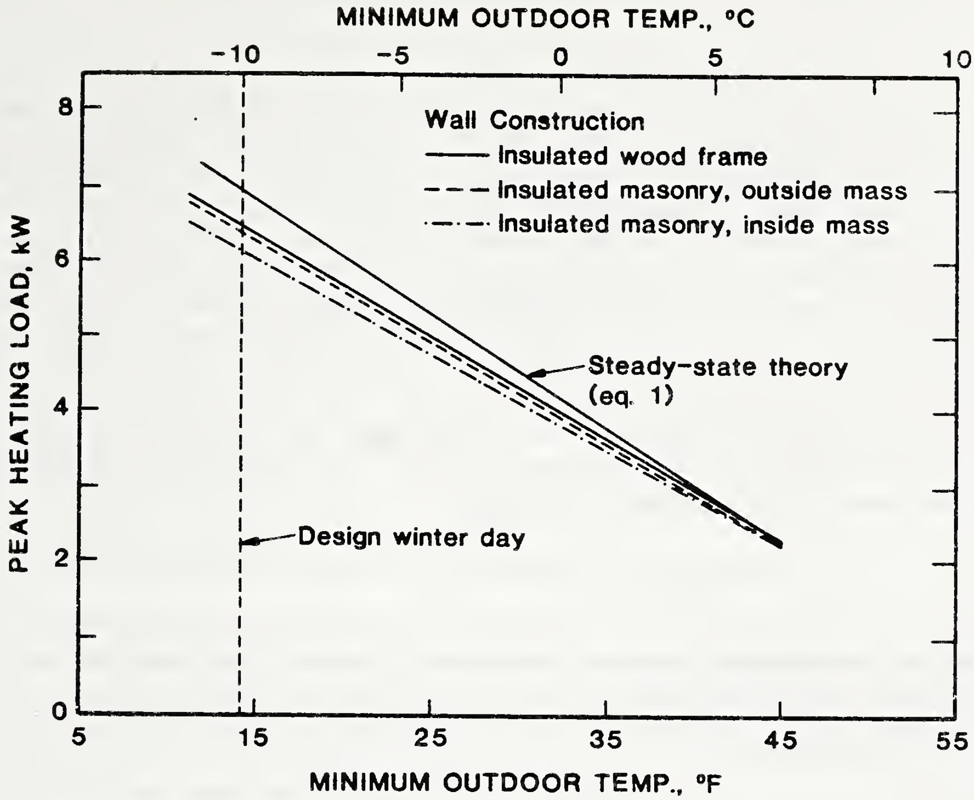


Figure 5. Comparison of peak sensible heating load correlations for identical houses with three wall constructions operated with fixed thermostat settings

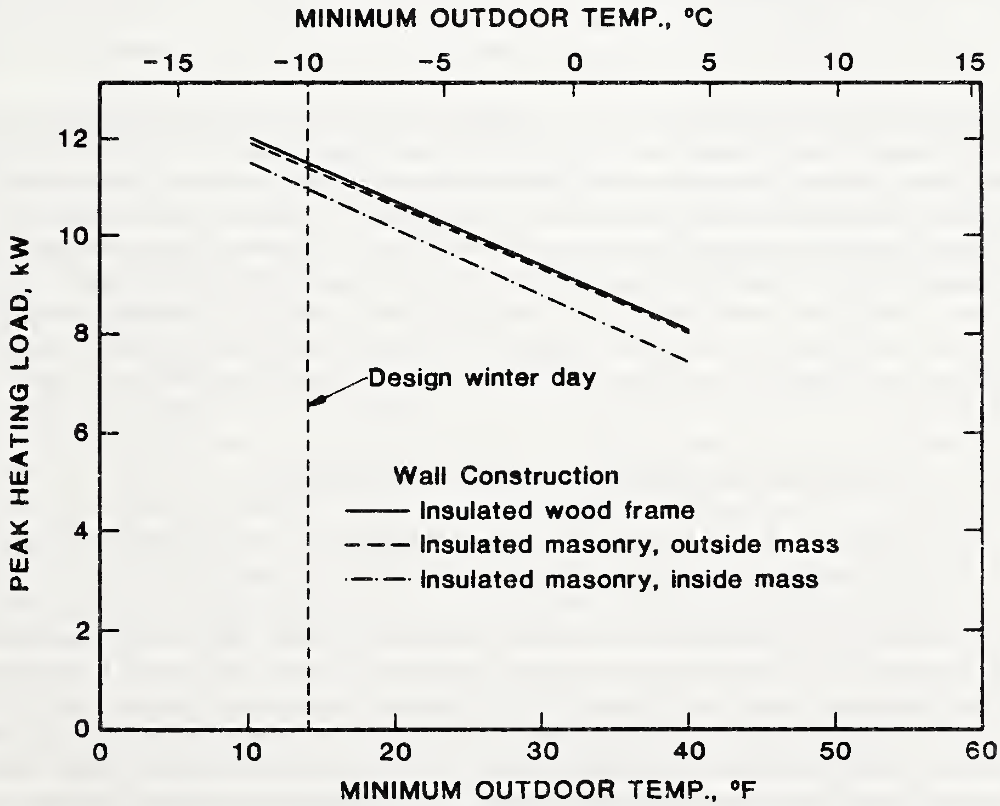


Figure 6. Comparison of peak sensible heating load correlations for identical houses with three wall constructions operated with night temperature setback

$$K = \sum_{i=1}^{N} U_i \cdot A_i + \rho \cdot V \cdot I \cdot C_p \quad (2)$$

$$T_b = T_i - \frac{Q_i}{K} \quad (3)$$

where

$U_i \cdot A_i$ = product of thermal transmittance and surface area for ith building component;

ρ = density of air;

V = volume of conditioned space;

I = air infiltration rate;

C_p = specific heat of air;

T_i = indoor temperature; and

Q_i = rate of internal heat generation.

The above steady-state theory was used to predict the peak sensible heating loads given in figure 5. Steady-state theory over-predicted by less than 10% the peak sensible heating load at design outdoor conditions for the house with lightweight wood-frame walls and the house with conventional masonry walls (i.e., outside wall mass) located in Washington, DC. For the case of innovative masonry wall construction (i.e., inside wall mass), steady-state theory overpredicted the peak sensible heating load by 13%. Since steady-state theory only over predicted the peak sensible heating load by a small amount, the use of steady-state theory to estimate peak heating loads appears to be a viable practice.

4.3. Winter Space Heating with Night Temperature Setback

Daily peak sensible heating load correlations for the house operated with a 10°F (5.6°C) night temperature setback during an 8-hour period from 11:00 p.m. to 7:00 a.m. are given in figure 6. Here it is seen that the daily peak sensible heating loads are a little more than twice those without night temperature setback (see figure 5). The peak sensible heating loads occur in the morning when the indoor temperature is raised to the upper setpoint temperature of 68°F (20°C). As in the case of the previous peak load comparisons, wall mass is seen to have a small effect on peak loads for the house. The peak heating load correlation for the house with masonry walls (inside mass) is seen to be slightly below those for the other two houses. An explanation is given below.

An analysis of the hourly sensible heating loads during a diurnal period with night temperature setback was carried out. The results of this analysis are given in figure 7. The charts on the left pertain to the house with wood-frame walls, and those on the right pertain to an identical house with masonry walls with inside wall mass. From figure 7A, it is seen that the indoor temperature in the house with masonry walls is still decreasing at the end of the 8-hour setback period. From figure 7B, it is seen that the peak hourly heating load at the time of temperature setup is larger in the house with wood-frame walls. This result is consistent with the previous results of figure 6. The wall heat loss is plotted as a function of time in figure 7C. Note that at the time of the peak load, the rate of wall heat loss is larger in the wood-frame walls. This is because the wood-frame walls are able to absorb heat more quickly (i.e., they have a shorter time constant).

4.4. Spring Space Heating with Fixed Thermostat Settings

Some climates within the continental U.S. have mild winter heating seasons that coincide with spring heating conditions in colder climates. Peak sensible heating load correlations for identical houses with the three wall constructions exposed to a spring heating period in Washington, DC are given in figure 8. As in the case of the winter heating results, wall mass is seen to have a small effect of the peak sensible heating loads.

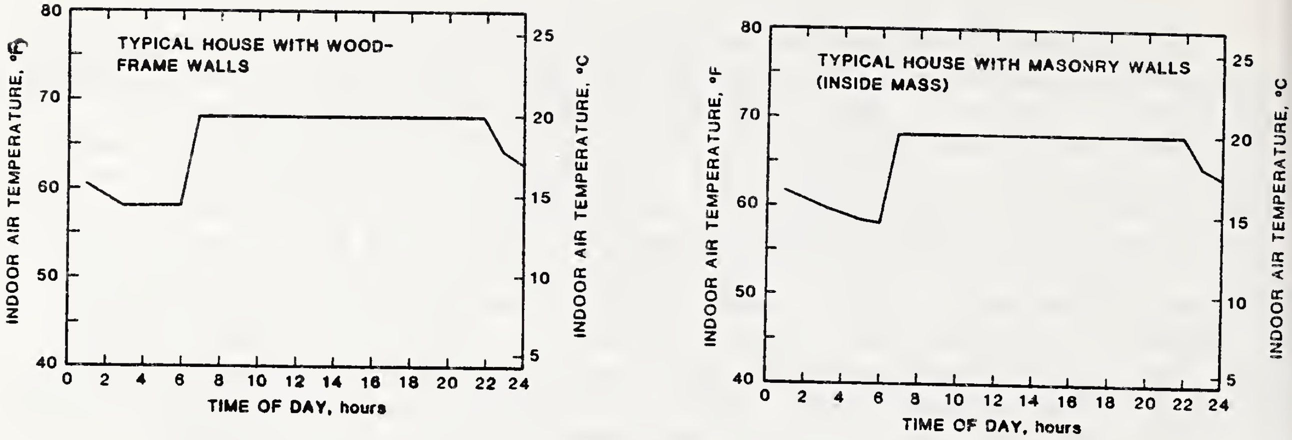
5. EFFECT OF CLIMATE

A similar analysis was carried out for Madison, WI and Lake Charles, LA. These cities were selected to represent the climates of the northern and southern United States, respectively. The results are summarized in Table 3. The peak sensible loads given in the table are based on the ASHRAE 99% winter drybulb and ASHRAE 1% summer drybulb temperatures.

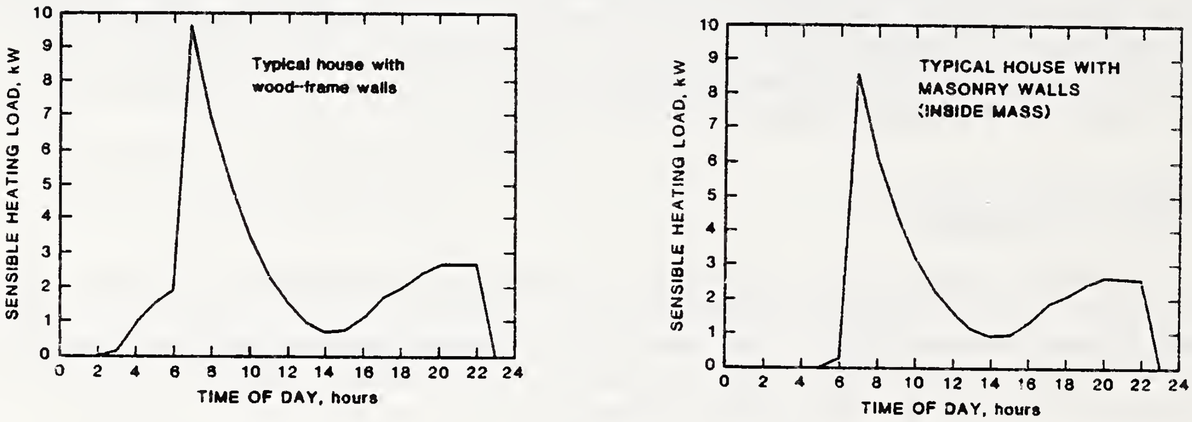
The daily peak sensible cooling loads for the house with conventional masonry construction (i.e., outside wall mass) are less than those for the identical house with wood-frame walls. Wall mass is seen to be more effective when it is positioned inside, as opposed to outside, the wall insulation. Wall mass is seen to be more effective in reducing peak sensible heating loads in mild cooling climates. In all cases, the effect of wall mass on peak sensible cooling loads is less then 11%.

A similar set of results is given in Table 3 for reductions in peak sensible heating loads. In general, the reductions in peak heating loads tend to be smaller than those for space cooling. Wall mass is again seen to be more effective when it is located inside, as opposed to outside, the wall insulation. It is more effective in mild heating climates. In all cases, the effect of wall mass on peak sensible heating loads is less than 12%.

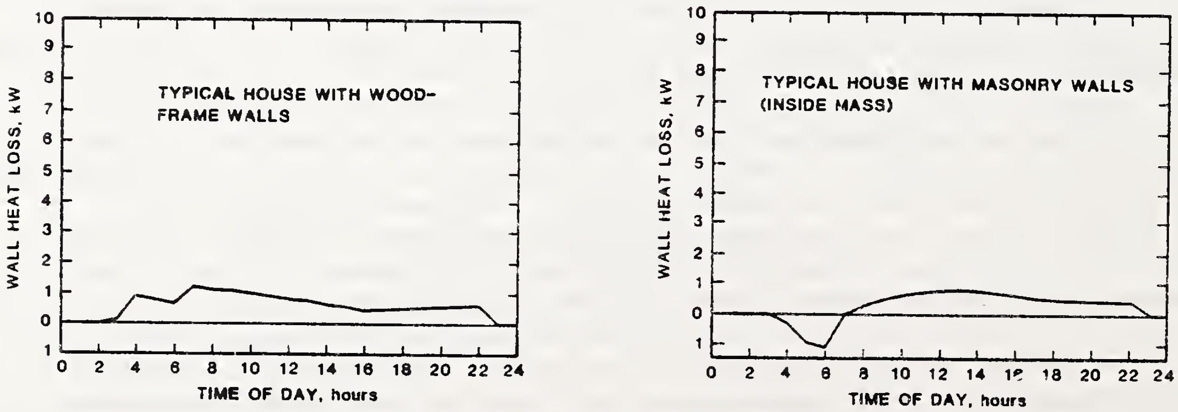
For the case of Lake Charles, LA, where the house operates near its balance point, the steady-state theory was found to overpredict the peak sensible heating load by 15% for the house with wood-frame walls, by 20% for the house with walls with outside mass, and by 30% for the house with masonry walls with inside wall mass. For the other geographic locations, the steady-state theory overpredicted the peak sensible heating loads for the house with wood-frame wall construction and conventional masonry wall construction by less than 11%. The results indicate some error may occur in using steady-state theory to size HVAC heating equipment in mild heating climates.



A. Indoor air temperature



B. Sensible Load



C. Wall heat loss

Figure 7. Variation in the hourly sensible heating loads during a diurnal period with night temperature setback for identical houses with wood-frame walls (left) and masonry walls with inside mass (right)

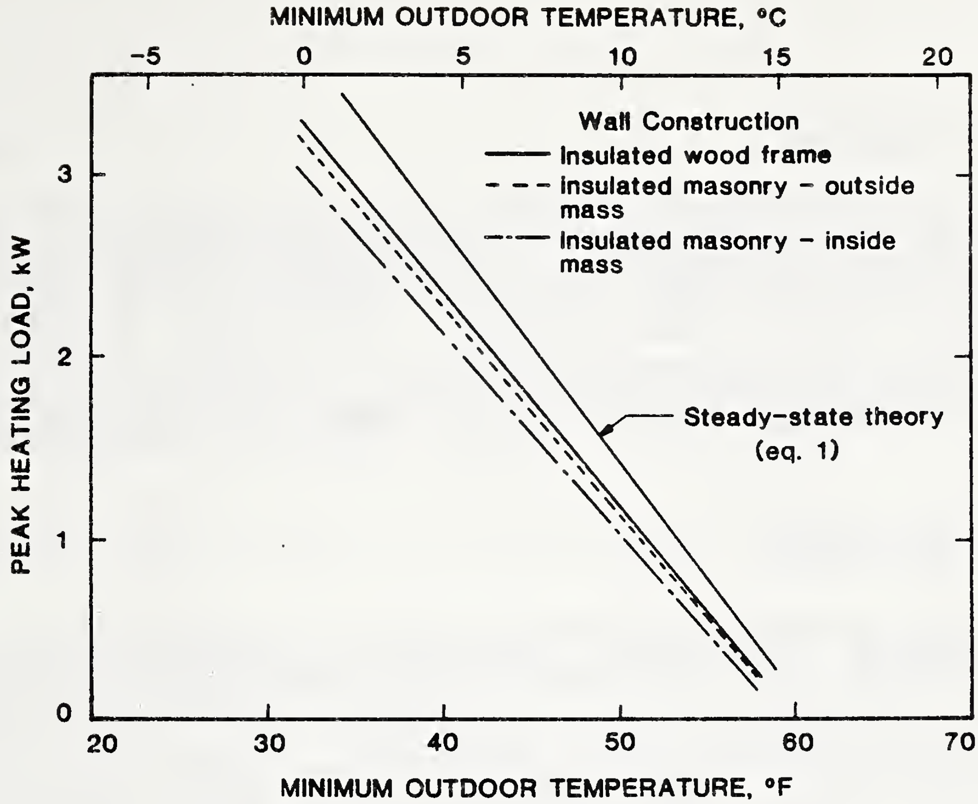


Figure 8. Comparison of peak sensible heating load correlations for identical houses with different wall constructions exposed to spring heating with fixed thermostat settings

Table 3. Reductions[3] in Peak Sensible Heating and Cooling Loads

(House with Masonry Walls Compared to an Identical House with Wood-Frame Walls)

Geographic Location	City	Cooling: Outside Mass %	Cooling: Inside Mass %	Heating: Outside Mass %	Heating: Inside Mass %
Northern U.S.	Madison, WI	4.8	10.5	1.7	4.1
Middle U.S.	Washington, DC	4.3	8.9	1.5	4.9
Southern U.S.	Lake Charles, LA	4.2	8.8	3.7	11.4

[3] Based on ASHRAE summer 1% and winter 99% design drybulb temperatures

6. DELAYS IN PEAK LOADS

In all the above cases, wall mass was observed to have a very small effect (i.e., less than 1 hour) on delaying the peak sensible conditioning loads. The peak hourly heating loads generally occur very late at night when the outdoor temperature is relatively steady. Under such a condition, a very small effect on the timing or peak loads would be expected. In the summer, the peak cooling loads are largely driven by internal heat gains (i.e., the simulated occupancy load and the solar gain through windows) and the heat gains due to infiltration. These gains are relatively quick and have very small time delays associated with them.

7. CAVIATS AND CAUTIONS

The results presented in this paper are dependent upon the manner in which a house is operated. For instance, different results would have occurred if the house had been ventilated at night for the summer cooling analysis. In addition, the results are dependent upon the physical geometry and the heat transfer characteristics for the house used in the analysis. For instance, it was pointed out during the review of the paper that an air infiltration rate of 1 volume change per hour is somewhat large for a house built to current energy conservation practice. If the house had a smaller rate of infiltration, then wall mass would have had a larger effect on peak loads.

8. SUMMARY AND CONCLUSIONS

When the house was operated with fixed thermostat settings, the effect of wall mass on the peak sensible heating and cooling loads was found to be less than 12% for the house with inside wall mass and 5% for the house with outside wall mass for the three climatic regions considered. The effect of wall mass was largest in mild climates. In all cases, wall mass was found to produce less than a 1-hour delay in the peak sensible loads.

When the house was operated with a 10°F (5.6°C) night temperature setback during an 8-hour period, the peak sensible heating loads were approximately twice those for an identical house operated without night temperature setback. Wall mass was found to have a small effect on the results.

Steady-state theory overestimated the peak sensible heating loads of the houses with masonry walls in cold climates by less than 11%. Since it is customary to include a factor of safety and to size equipment conservatively, it would be acceptable to use steady-state theory to size HVAC heating equipment in cold climates. However, in mild heating climates, steady-state theory overestimated the peak heating loads by 20% for the house with outside wall mass and 30% for the house with inside wall mass.

ACKNOWLEDGMENTS

The authors would like to thank the Electric Power Research Institute for funding this study.

REFERENCES

1. Burch, D. M., Remmert, W. E, Krintz, D. F., and Barnes, C. S., "A Field Study of the Effect of Wall Mass on the Heating and Cooling Loads of Residential Buildings," Proceedings of the Building Thermal Mass Seminar, CONF-826130, Oak Ridge National Laboratory, 1982.

2. Burch, D. M., Krintz, D. F., and Spain, R. S., "The Effect of Wall Mass Winter Heating Loads and Indoor Comfort - An Experimental Study," ASHRAE Transaction, V. 90, Pt. 1, 1984.

3. Burch, D. M., Malcolm, S. A., and Davis, K. L., "The Effect of Wall Mass on the Summer Space Cooling of Six Test Buildings," ASHRAE Transaction, V. 90, Pt. 2, 1984

4. Burch, D. M.; Jacobsen, T., Johns, W. L., Walton, G. N., and Reeve, C. P., "The Effect of Thermal Mass on Night Temperature Setback Savings," ASHRAE Transaction, V. 90, Pt. 2, 1984.

5. Walton, G. N., "Thermal Analysis Research Program - Reference Manual," NBSIR 83-2655, National Bureau of Standards, 1983.

6. Burch, D. M., Walton, G. N., Cavanaugh, K., and Licitra, B. A., "The Effect of Wall Mass on Annual Heating and Cooling Loads of Single-Family Residences for Five Selected Climates," Proceedings of the Symposium on Thermal Insulation Materials and Systems, Dallas, TX, Dec. 2-6, 1984.

7. Burch, D. M., Walton, G. N., and Cavanaugh, K., "Comparison of Measured and Predicted Sensible Heating and Cooling Loads for Six Test Buildings," NBSIR 86-3399, National Bureau of Standards, June, 1986.

8. Arumi-Noe, Francisco and Burch, D. M., "DEROB Simulation of the NBS Thermal Mass Test Buildings," ASHRAE Transaction, V. 90, Pt. 2, 1984.

9. Burch, D. M., Peavy, B. A., and Powell, F. J., "Comparison between Measured and Computer-Predicted Hourly Heating and Cooling Energy Requirements for an Instrumented Wood Frame Townhouse Subjected to Laboratory Tests," ASHRAE TRANSACTIONS, V. 81, Pt. 2, 1975.

10. Anderson, B., Bauman, F., and Kammerud, R., "Verification of BLAST by Comparison with Direct Gain Test Cell Measurements," Report No. LBL-10619, Lawrence Berkely Laboratory, Nov., 1980.

11. Judkoff, R., Wortman, D., and Burch, J., "Measured Versus Predicted Performance of the SERI Test House: A Validation Study," National Heat Transfer Conference, Seattle, WA, July, 1983.

12. Hastings, S. R., "Three Proposed Typical House Designs for Energy Research," NBSIR 77-1309, National Bureau of Standards, October 1977.

13. Crow, L. W., "Development of Hourly Data for Weather Year for Energy Calculations (WYEC)," ASHRAE Journal, Vol. 23, No. 10, October 1981.

APPENDIX

ANALYSIS OF FIELD MEASUREMENTS FOR SIX TEST BUILDINGS

1. INTRODUCTION

This appendix presents an analysis of daily peak sensible conditioning load measurements for six thermal mass test buildings at the National Bureau of Standards. The wall heat transmission of the test buildings was a considerably larger part of the overall envelope heat transfer compared to that for a typical house (i.e., the wall heat transfer comprised 53% of the overall envelope heat-transfer coefficient for the insulated test buildings and 19% for the typical house analyzed in the main body of the report). Therefore, the peak load analysis for the test buildings is not directly applicable to residential buildings.

2. DESCRIPTION OF TEST BUILDINGS

Six 20 ft (6.1 m) wide and 20 ft (6.1 m) long one-room test buildings with a 7.5 ft (2.3 m) high ceiling were constructed outdoors at the National Bureau of Standards located at Gaithersburg, Maryland. A photograph of one of the test buildings is given in figure A-1. These buildings had the same floor plan and orientation, and were essentially identical, except for wall constuction.

A detailed description of the walls of the buildings is given in ref. 1. The basic characteristics of the walls are given in Table A-1. The steady-state thermal resistances for the walls of building Nos. 1, 3, 5, and 6, and for building Nos. 2 and 4 were designed to be approximately equivalent. With the exception of building No. 6, an effort was made to make the construction representative of current practice in the United States.

Each test building contained two double-hung windows on the north wall and two on the south wall. Each window contained an insulating glass window fitted with an exterior storm window.

Each test building had a 19.5 ft^2 (1.8 m^2) hollow metal door on the east wall. The door cavities were filled with perlite insulation. The edges of the concrete slab-on-grade floors were insulated with 1-in-thick (2.5 cm) extruded polystyrene insulation at both the inner and outer surface of the footing, and a 2-in-thick (5.0 cm) layer of extruded polystyrene was installed over the concrete floor slabs in order to reduce the effect of seasonal variations in earth heat transfer.

A description of the instrumentation and measurement techniques is given in refs. [1, 2].

3. WINTER SPACE HEATING WITH FIXED THERMOSTAT SETTINGS

3.1. Experimental Procedures

From January 4 to April 11, 1982, winter heating season measurements were conducted. During this 14-week measuring period, the thermostats of the six test buildings were set for space heating at 68 ± 0.5°F (20 ± 0.3°C). The

Table A-1. Characteristics of Walls of Test Buildings

Building	Wall Description	Thermal Resistance* h•ft^2•°F/Btu	(m^2•K/W)	Mass lb/ft^2	(kg/m^2)
1	Insulated wood frame	12.2	(2.15)	4.5	(22.)
2	Uninsulated wood frame	3.6	(0.63)	4.3	(21.)
3	Insulated masonry (outside mass)	13.7	(2.41)	63.5	(310.)
4	Uninsulated masonry	4.6	(0.81)	43.0	(210.)
5	Log	10.3	(1.81)	17.0	(83.)
6	Insulated masonry (inside mass)	12.4	(2.18)	84.0	(410.)

* The thermal resistance values are based on guarded-hot-box measurements.

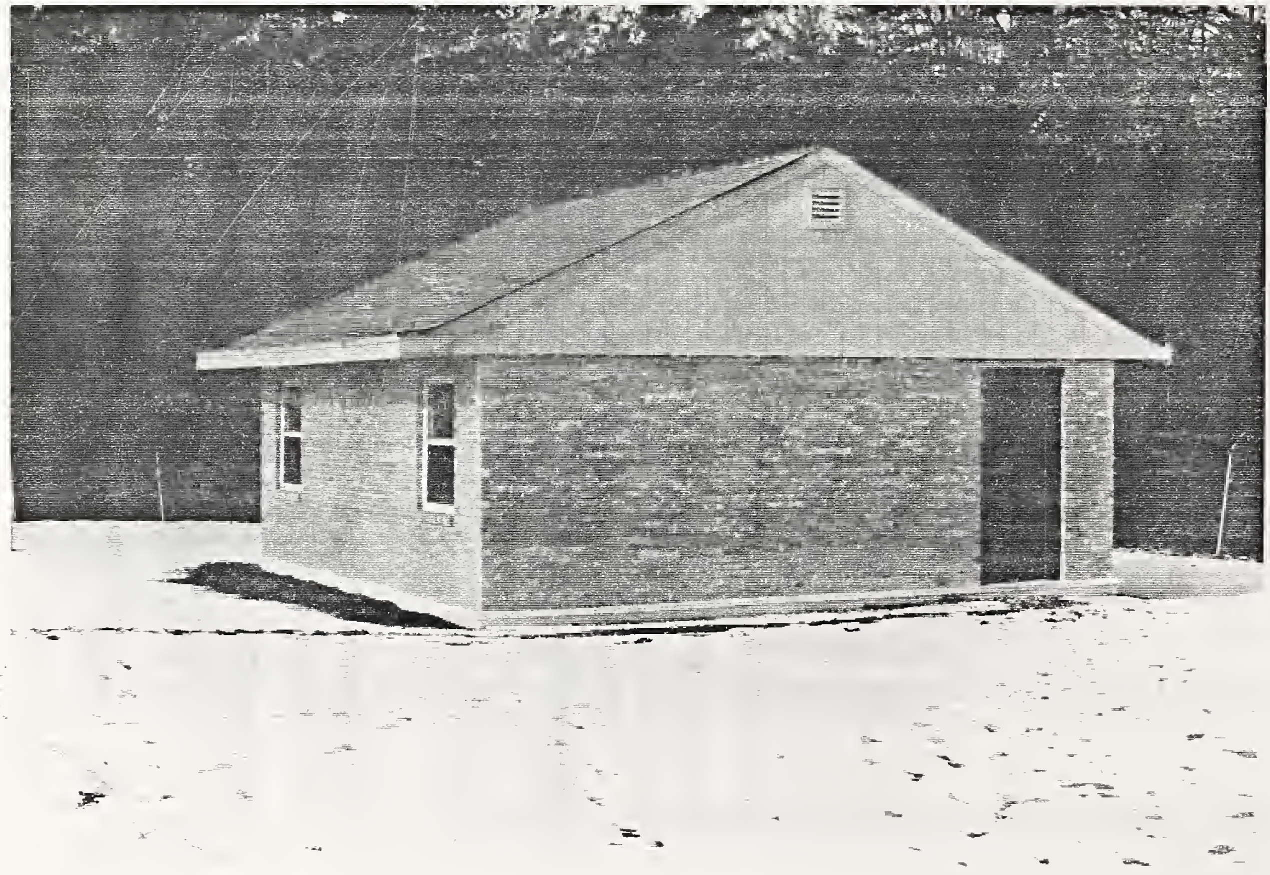


Figure A-1. A photograph of one of the test buildings windows were maintained in a closed position, and a constant internal load of 290 W was maintained within each building. During the measurements, space heating was typically provided each hour of the day (i.e., the indoor temperature did not rise above the thermostat setpoint temperature).

3.2. Results

The daily peak sensible heating loads for each test building were correlated with the minimum daily outdoor temperature using the method of least-squares. The daily peak sensible heating loads generally occurred several hours after the daily minimum outdoor temperature due to thermal storage effects. The analysis procedure is illustrated for the uninsulated wood-frame building (No. 2) in figure A-2A. The peak load correlations for the six test buildings are compared in figure A-2B.

The peak sensible heating loads at a minimum outdoor temperature of 35°F (1.7°C) are compared to steady-state theory (eq. 1) in Table A-2. The steady-state theory used for this analysis is the same as that described in the main body of the report. In this table, buildings with similar envelope heat-transfer coefficients have been grouped together to facilitate comparisons. The last column gives the ratios of measured to predicted peak sensible heating loads. These results indicate that thermal mass does not have a significant effect on peak sensible heating loads during the winter season. However, the presence of wall insulation is seen to reduce the peak sensible heating load by about a factor of two.

An analysis of the timing of peak loads indicated that wall mass had little or no effect on the timing of peak loads during the winter heating season.

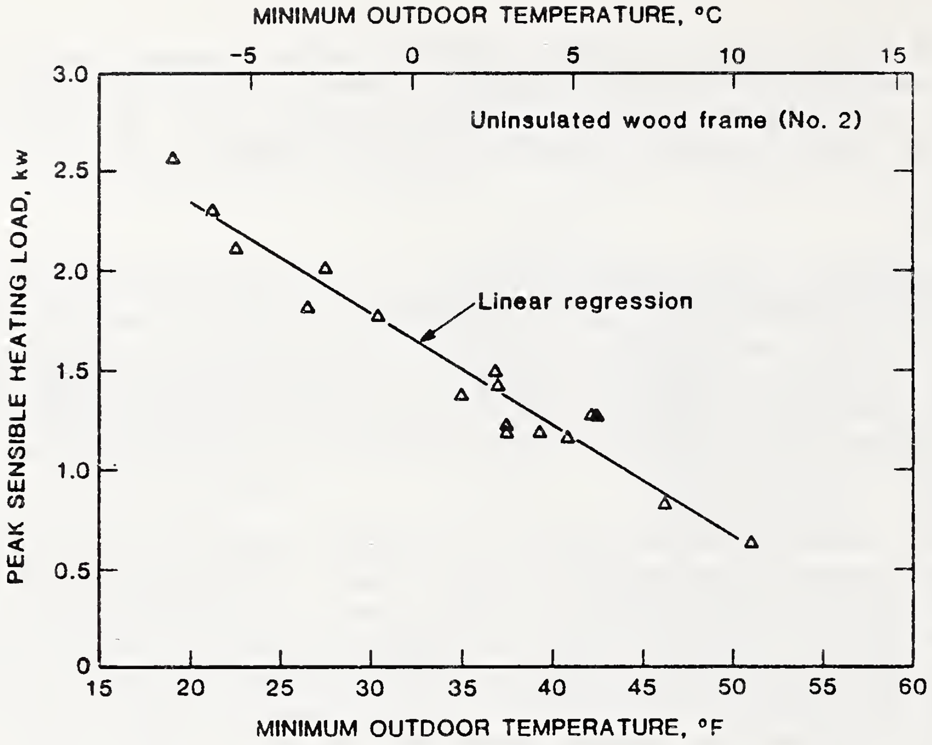
4. INTERMEDIATE (SPRING) SPACE HEATING WITH FIXED THERMOSTAT SETTINGS

4.1. Experimental Procedure

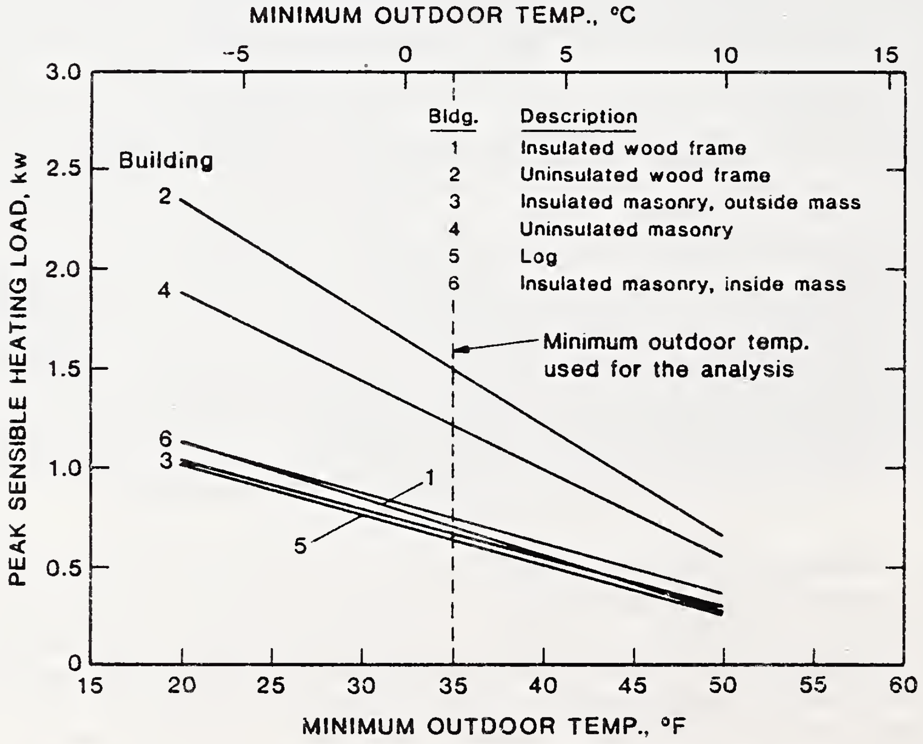
From April 12 to May 2, 1982, intermediate (spring) heating season measurements were conducted. During this 3-week period, the test buildings were operated in the same fashion as for the winter heating season. During these measurements, space heating was typically not provided during warm day periods when internal heat gains caused the indoor temperature to rise above the thermostat setpoint temperature.

4.2. Results

The same procedure as used for the winter heating season was used to analyze the intermediate heating season. Linear regressions for the daily peak sensible heating loads as a function of minimum outdoor temperature are compared in figure A-3. These results show that heavyweight buildings had considerably smaller peak sensible heating loads than identical lightweight buildings having equivalent thermal resistance in their walls. For instance, at a minimum outdoor temperature of 45°F (7.2°C), the masonry building with inside wall mass (No. 6) had a peak sensible heating load 54% less than the equivalent building with wood-frame walls (No. 1). Considering the insulated buildings (Nos. 1, 3, 5, and 6) as a separate group, wall mass is seen to be more effective when it was positioned inside (No. 6), as opposed to



A. Illustration of analysis procedure



B. Comparison of peak sensible heating load correlations

Figure A-2. Results for winter space heating with fixed thermostat settings

Table A-2. Comparison[1/] of Peak Sensible Heating Loads to Steady-State Theory (Winter Space Heating with Fixed Thermostat Settings)

Building	Q_{hmax}, W Measured (M)	Predicted (P)	M/P
1	702.	676.	1.04
3	670.	610.	1.02
5	636.	648.	0.98
6	747.	721.	1.04
2	1503.	1464.	1.03
4	1220.	1287.	0.95

[1/] At outdoor temperature of 35°F (1.7°C).

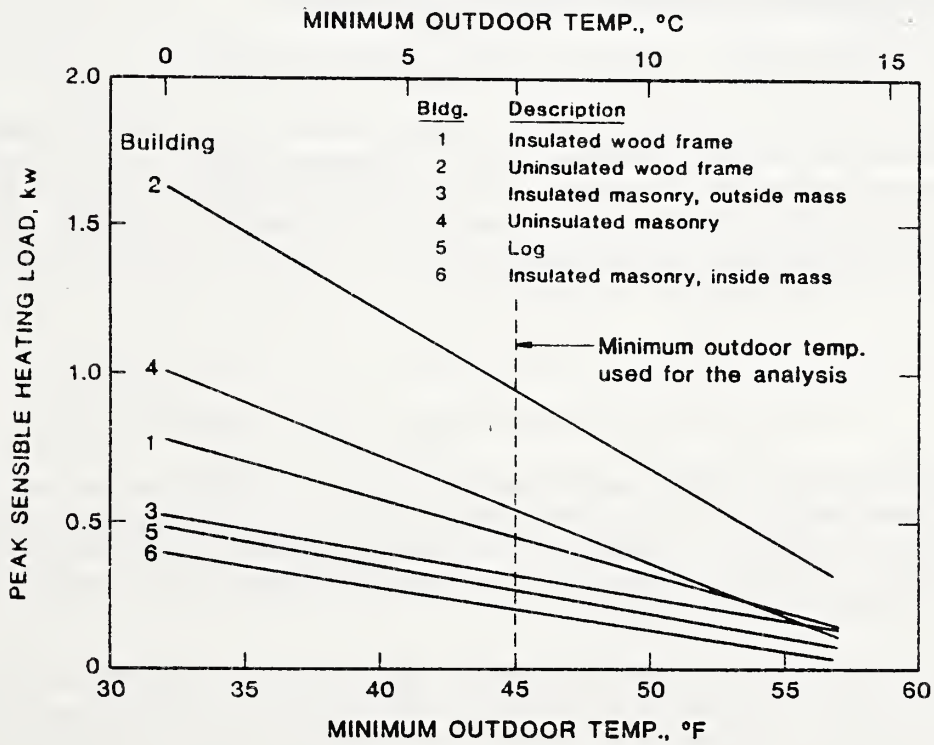


Figure A-3. Daily peak sensible heating load correlations for the six test buildings during the intermediate (spring) heating season outside (No. 3), the wall insulation. The log building, having its wall mass uniformly distributed, performed midway between buildings with mass on the inside and mass on the outside. A thermal mass effect was also observed for the uninsulated test buildings (i.e., the peak hourly sensible heating load for the uninsulated masonry building was less than that for the uninsulated wood-frame building). The peak sensible heating loads at a minimum outdoor temperature of 45°F (7.2°C) are compared to steady-state theory in table A-3. These results indicate that heavyweight buildings had smaller peak sensible heating loads than predicted with steady-state theory (i.e., the ratio of M/P for the heavy-weight test buildings were significantly less than one). The insulated masonry building with inside mass (No. 6) had a peak sensible heating load less than one-half the value predicted with steady-state theory. The number in the last column is the thermal time constant. It is defined as the time for the indoor temperature of a building to decay 63.2% from an initial temperature level to a final temperature level after the heating plant is suddenly turned off when the building is exposed to a steady winter outdoor temperature. Thermal time constant measurements for the test buildings are described in ref. [2]. It is interesting to note that, when insulated and uninsulated buildings are considered as separate groups, the peak sensible heating loads for the intermediate heating season were ranked in reverse order of the thermal time constants.

An analysis of the timing of peak sensible heating loads similar to that for the the winter season was carried out for the intermediate heating season. As for the case of the winter heating season, the timing of peak sensible heating loads generally coincided with the minimum outdoor temperature, and no significant effect of wall mass was apparent in the results.

5. WINTER SPACE HEATING WITH NIGHT TEMPERATURE SETBACK

5.1. Experimental Procedure

From January 24 to May 2, 1983, winter measurements with night temperature setback were conducted on the insulated test buildings (Nos. 1, 3, 5, and 6). During this 14-week period, the insulated test buildings were operated in the same fashion as for the winter heating season without setback, except that clock thermostats setback the indoor temperature 10 ± 1°F (5.6 ± 0.6°C) during an 8-hour period from 11:00 p.m. to 7:00 a.m.

5.2. Results

Linear regressions of daily peak sensible heating loads plotted as a function of minimum outdoor air temperature for the four insulated test buildings are given in figure A-4. Peak sensible heating loads at minimum outdoor temperature of 35°F (1.7°C) are compared to corresponding values predicted using steady-state theory in Table A-4.

The peak sensible heating loads occurred between 7:00 to 8:00 a.m. when the indoor temperature setpoints were returned to 68°F (20°C), and the heating plants operated continuously. The results in Table A-4 indicate that the peak sensible heating loads for building Nos. 1, 3, and 5, were more then 3 times larger than comparable steady-state values that would have occurred without night temperature

Table A-3. Comparisons[1] of Peak Sensible Heating Loads to Steady-State Theory (Intermediate Heating Season)

Building	Q_{max}, W Measured (M)	Q_{max}, W Predicted (P)	$\frac{M}{P}$	Time Constant h
1	451.	412.	1.09	8.8
3	324.	365.	0.89	11.0
5	273.	395.	0.69	14.1
6	209.	440.	0.47	30.8
2	946.	968.	0.98	4.8
4	545.	839.	0.65	8.8

[1] At minimum outdoor temperature of 45°F (7.2°C)

Table A-4. Comparisons[1] of Peak Sensible Heating Loads to Steady-State Theory (Winter Space Heating with Night Temperature Setback)

Building	Q_{hmax}, W Measured (M)	Q_{hmax}, W Predicted (P)	$\frac{M}{P}$	Time Constant h
1	2074.	667.	3.11	8.8
3	1916.	597.	3.21	11.0
5	1860.	616.	3.02	14.1
6	1573.	714.	2.20	30.8

[1] At minimum outdoor temperature of 35°F (1.7°C)

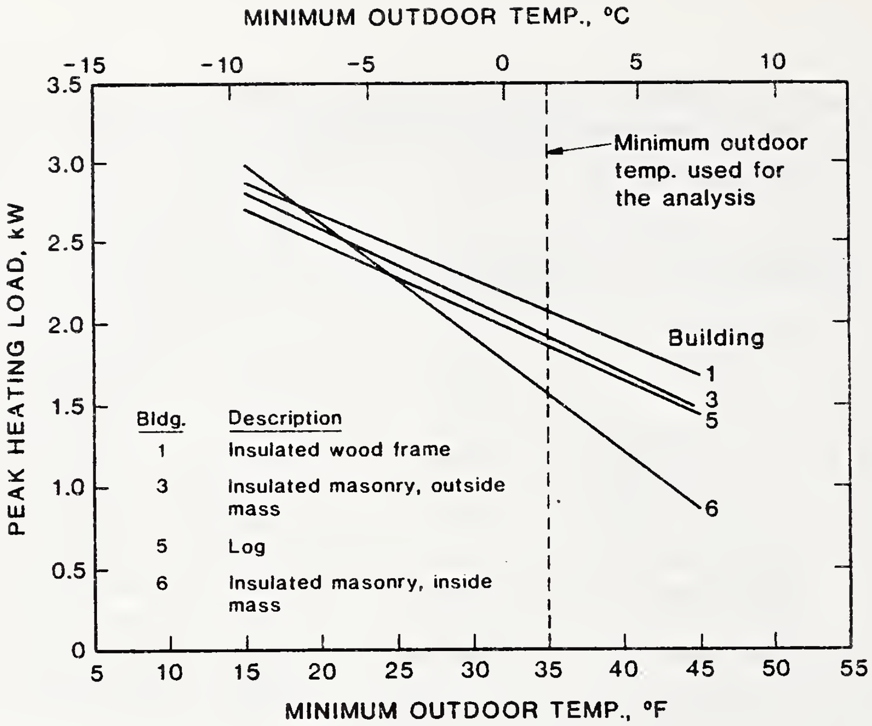


Figure A-4. Comparison of peak sensible heating load correlations for the four test buildings for winter space heating with night temperature setback

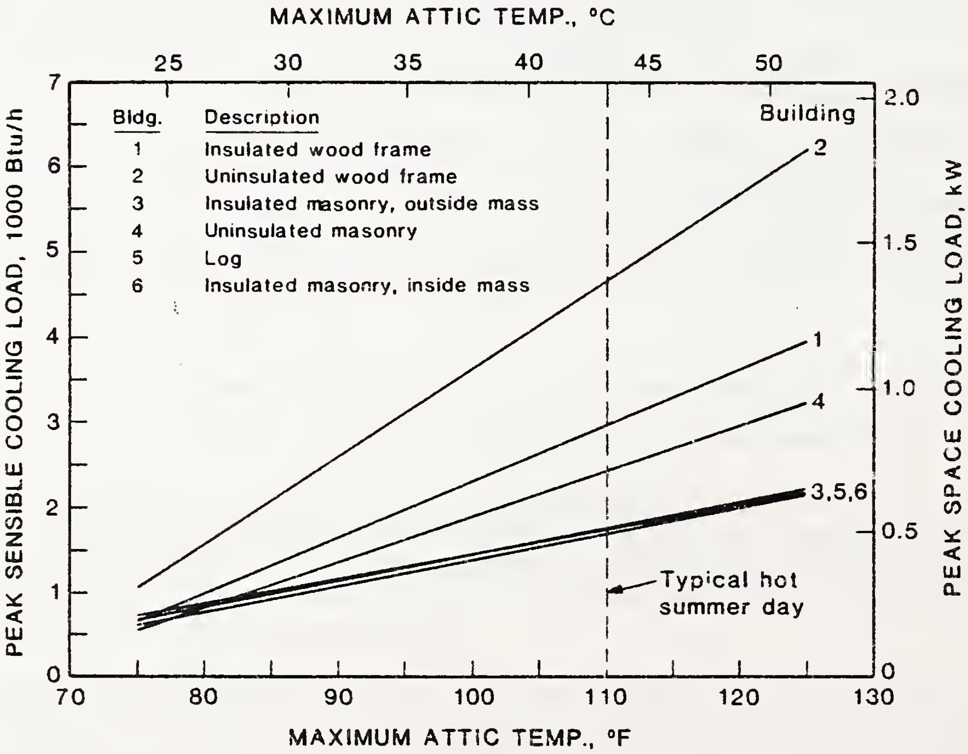


Figure A-5. Comparison of peak sensible cooling load correlations for the six test buildings for summer space cooling with fixed thermostat settings setback. The peak sensible heating loads for building No. 6 were only 2.2 times larger than the steady-state theory values. The peak sensible heating loads were smaller in building No. 6 because its walls had a longer thermal time constant and absorbed heat more slowly. It should be pointed out that the heating energy savings achieved by night temperature setback were attained at the expense of creating considerably higher peak sensible heating loads.

6. SUMMER SPACE COOLING WITH FIXED THERMOSTAT SETTINGS

6.1. Experimental Procedure

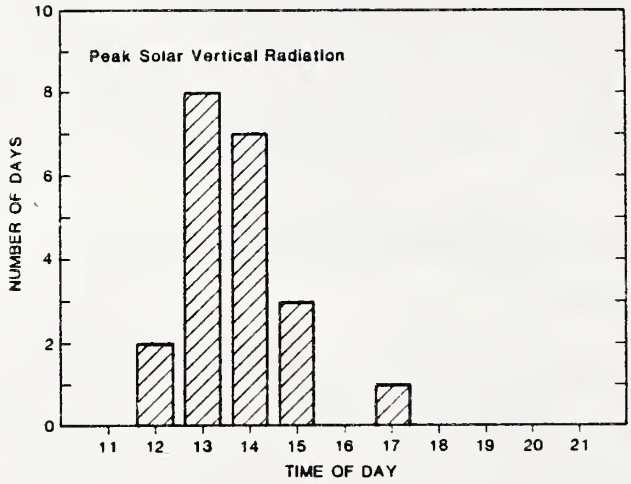
From July 26 to August 17, 1982, a summer cooling test was conducted on the six test buildings. During this 3-week period, the thermostats of the buildings were set for space cooling at 76 ± 0.5°F (24 ± 0.3°C). The windows of the test buildings were maintained in a closed position and a constant internal load of 290 W was maintained within each building. During the measuring period, the solar altitude was sufficiently high that the soffit regions of the roofs shaded the windows from direct solar radiation. The night outdoor temperature was sufficiently low to cause the indoor temperature to decrease below the indoor setpoint temperature. For the test period, door openings occurred only at 10:00 a.m. each day when technicians entered the buildings to collect data and check internal loads.

6.2. Results

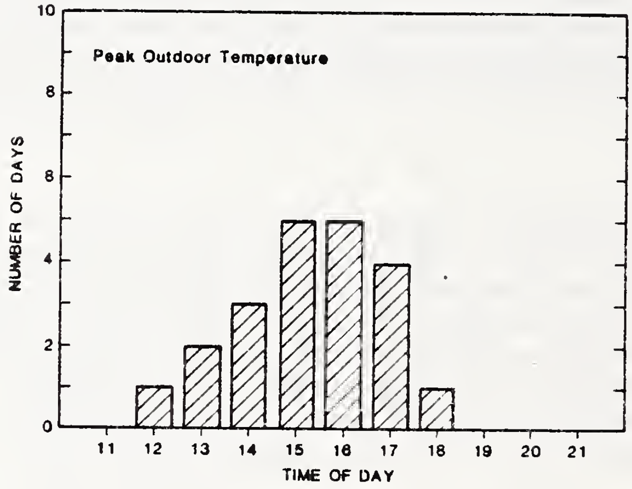
The daily peak sensible cooling loads were plotted as a function of maximum attic air temperature. The maximum attic air temperature is a parameter which is a measure of the combined effect of outdoor temperature and solar loading on the building envelope. Moreover, the use of maximum attic air temperature as a correlation parameter provided linear correlations with less scatter than those obtained by using either maximum outdoor temperature or maximum solar insolation. For this reason,the maximum attic air temperature was used to correlate daily peak sensible cooling loads.

Linear regressions of daily peak sensible cooling loads for the six test buildings are compared in figure A-5. On typical hot summer days, the attic air temperature frequently attained a value of 110°F (43°C). Therefore, peak sensible cooling loads are compared at this attic air temperature. These results show that the insulated wood-frame building (No. 1) had a peak sensible cooling load 800 W less than that for the uninsulated wood-frame building (No. 2). Thus, the presence of insulation in the wood-frame building reduced the peak sensible cooling load 800 W, or a reduction of 36%. The peak sensible cooling load for the insulated masonry buildings (Nos. 3, 5, and 6) were 43% less than that for the insulated wood-frame building (No. 1).

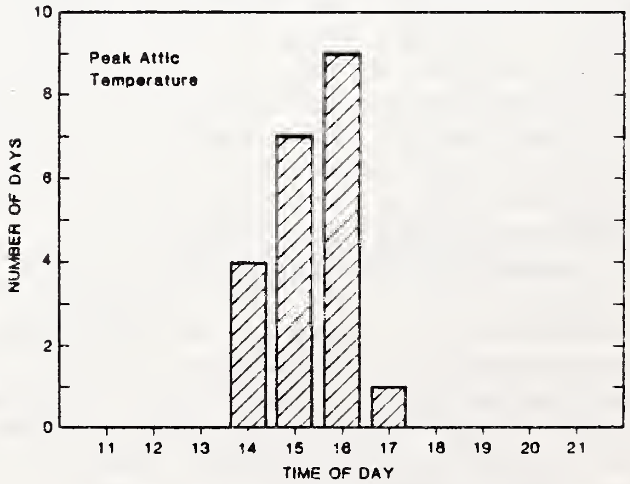
The effect of wall mass on the timing of peak sensible cooling loads is now considered. The distributions in the maximum climatic factors as a function of time of day are given in figure A-6. The maximum solar vertical radiation generally tended to occur between 1:00 and 2:00 p.m., whereas the maximum outdoor temperature and maximum attic temperature generally occurred between 3:00 and 4:00 p.m. The distributions in the daily peak sensible cooling loads for the six test buildings are given in figure A-7. The peak sensible cooling loads for the lightweight buildings (Nos. 1 and 2) generally occurred



A. Peak solar vertical radiation



B. Peak outdoor temperature



C. Peak attic temperature

Figure A-6. Distribution of maximum climatic factors as a function of time of day for summer space cooling with fixed thermostat settings

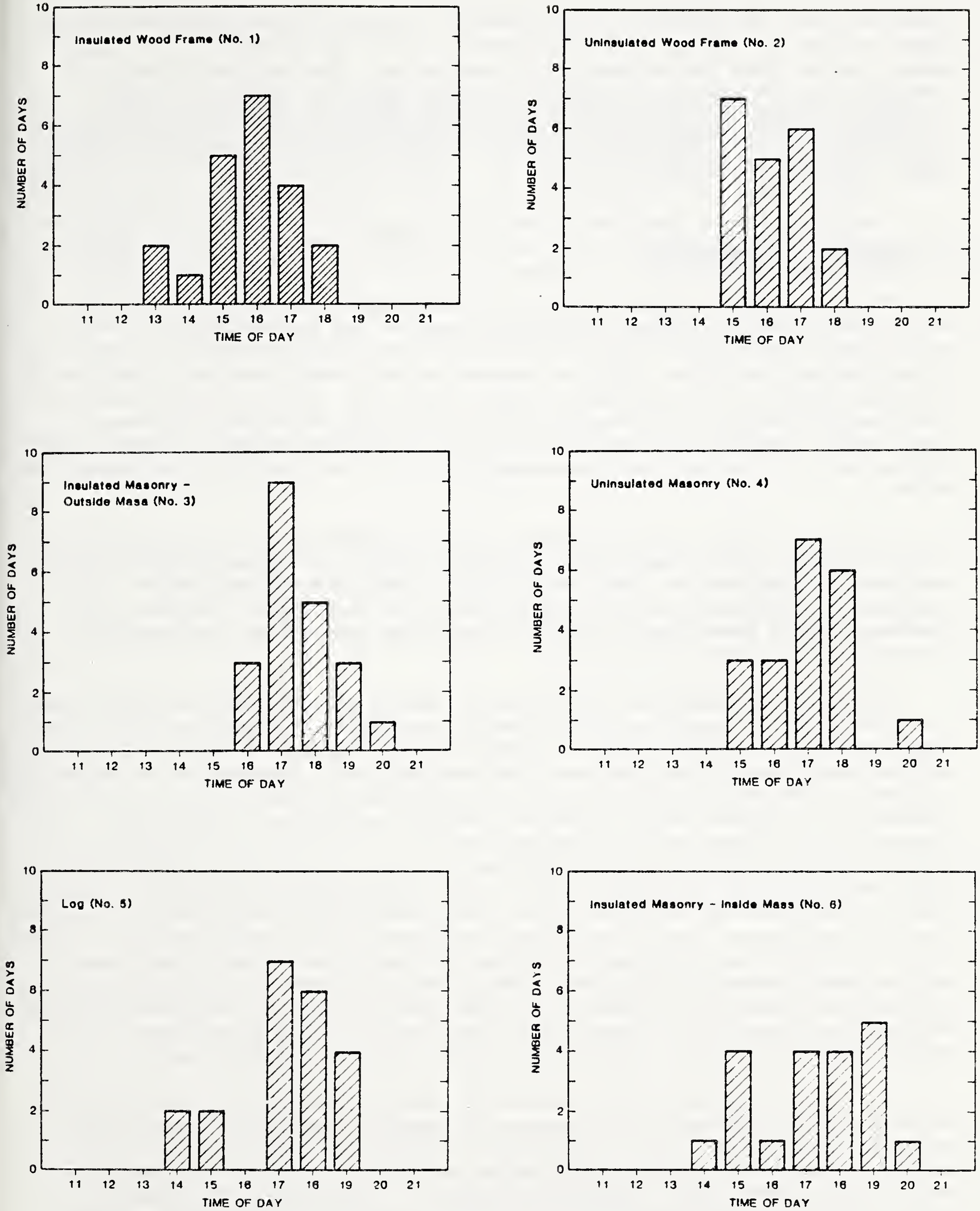


Figure A-7. Distribution of daily peak sensible cooling loads for the six test buildings during summer space cooling with fixed thermostat settings coincident with the maximum attic temperature, while the peak sensible cooling loads for the heavyweight buildings (Nos. 3, 4, 5, and 6) generally occurred about 2 hours after the maximum attic temperature. Similar load delays are obtained when the individual sensible cooling loads are compared for particular test days. These results indicate that the presence of masonry materials in the walls of the heavyweight buildings delayed their peak sensible cooling loads by less than two hours.

7. SUMMARY AND CONCLUSIONS

Field measurements were conducted to investigate the effect of wall mass on the peak sensible heating and cooling loads of six test buildings. While these measurements were of technical interest, they were not directly applicable to residential buildings. This is because the wall heat transfer of the test buildings comprised a considerably larger portion of the the overall envelope heat-transfer coefficient compared to that for a typical house. Moreover, direct solar radiation did not enter the test buildings during the summer space cooling tests. The peak load measurements for the test buildings are summarized below.

During the winter heating season, when the heating plants operated each hour of the day, daily peak sensible heating loads for the test buildings were predicted by steady-state theory using the minimum outdoor temperature. Wall mass was not observed to affect significantly the peak loads. However, the presence of wall insulation in the test buildings reduced the peak sensible heating load by about a factor of 2.

During the intermediate (spring/fall) heating season, when the solar window and occupancy heat gains caused the indoor temperature to rise above the indoor setpoint temperature during warm day periods, the presence of both wall insulation and wall mass reduced the peak sensible heating loads. Heavyweight buildings were observed to have considerably smaller peak sensible heating loads than comparable lightweight buildings having equivalent thermal resistance in their walls. For instance, at a minimum outdoor temperature of 45°F (7.2°C), the masonry building with inside wall mass had a peak sensible heating load 54% less than the equivalent building with wood-frame walls. Wall mass was more effective in reducing peak sensible heating loads when it was positioned inside, as opposed to outside, the wall insulation. The log building, which had its wall mass uniformly distributed, performed midway between buildings with inside and outside wall mass. The insulated masonry building with inside mass was shown to have peak sensible heating loads less than one-half the values predicted using steady-state theory. The building thermal time constant was shown to be a building parameter that characterized the effect of wall mass on peak sensible heating loads.

The heating energy savings achieved by night temperature setback during the winter were attained at the expense of creating considerably higher peak sensible heating loads. The peak sensible heating loads for the insulated buildings operated with night temperature setback were found to be more than twice those without night temperature setback. These higher peak sensible heating loads occurred during the period when the indoor thermostat was reset to 68°F (20°C).

During the summer, when air-conditioning was only provided during warm day periods (i.e., at night the indoor temperature decreased below the indoor setpoint temperature), the presence of both wall insulation and wall mass reduced peak sensible cooling loads. For example, on typical hot summer days, the presence of insulation in the lightweight buildings reduced the peak sensible cooling load by 36%. The presence of wall mass in the insulated buildings reduced the peak sensible cooling load by a further 43%. The position of thermal mass within the walls did not appear to affect the summer results.

FORM NBS-114A (REV.11-84)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** *(See instructions)*	1. PUBLICATION OR REPORT NO. NBSIR-86/3458	2. Performing Organ. Report No.	3. Publication Date OCTOBER 1986

4. TITLE AND SUBTITLE

The Effect of Wall Mass on the Peak Sensible Heating and Cooling Loads of a Single-Family Residence

5. AUTHOR(S)

D. M. Burch, G. N. Walton, B. A. Licitra, K. Cavanaugh, and M. D. Klein

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

NATIONAL BUREAU OF STANDARDS
U.S. DEPARTMENT OF COMMERCE
GAITHERSBURG, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

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)*

The effect of wall mass on the peak sensible heating and cooling loads of a single-family residence was investigated using a sophisticated computer program called the Thermal Analysis Research Program (TARP). The computer simulation accuracy was verified by comparing its predicted sensible heating and cooling loads to measured values for six test buildings each having different wall constructions at the National Bureau of Standards. Good agreement was obtained for the load comparisons. The computer program subsequently was used to simulate the performance of identical houses each having the following three insulated wall constructions: wood frame, conventional masonry (outside wall mass), and innovative masonry (inside wall mass).

When the house was operated with fixed thermostat settings, the effect of wall mass on the peak sensible heating and cooling loads was found to be less than 11% for the climatic regions analyzed. Operating the typical house with a 10°F (5.6°C) night temperature setback during an 8-hour night period caused the daily peak sensible heating loads to be approximately twice those without setback.

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

night temperature setback; peak sensible heating loads; peak sensible cooling loads; thermal mass; whole house performance.

13. AVAILABILITY

☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

☒ Order From National Technical Information Service (NTIS), Springfield, VA 22161

14. NO. OF PRINTED PAGES

32

15. Price

$9.95