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THERMAL MASS: ITS ROLE IN RESIDENTIAL CONSTRUCTION*

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ABSTRACT

The effects of thermal mass on the energy consumption of residential structures have been studied in four climates (1). The computer program BLAST was used to determine heating and cooling loads of residential structures as a function of glazing distribution, level of thermal mass, insulation location, and ground coupling. A related paper by Kammerud and Place, "The Effect of Occupant Use Patterns on the Performance of Direct-Gain Passive Solar Systems," (2) presents heating and cooling loads for a similar structure as a function of thermostat profiles. Mass effects are found to be small, especially in comparison to user effects.

INTRODUCTION

Thermal mass has long been recognized as a key element in various energy conservation strategies and in passive heating and cooling systems. In some climates, substantial portions of the year are characterized by large diurnal temperature swings about a daily average temperature which lies within the comfort zone; in light constructions this frequently results in daytime cooling and nighttime heating. Under such conditions, the moderating influence of thermal mass may significantly reduce energy consumption. Thermal mass can serve a similar function if coupled to environmental energy sources or sinks capable of maintaining the mass at an appropriate daily average temperature. For example, in many climates solar radiation received through south glazing will frequently elevate the building temperature up to, or above, the comfort zone even during the deep heating season. Thermal mass can then moderate the temperature swings caused by alternating daytime gains and nighttime losses.

The potential benefits of thermal mass are widely acknowledged in the solar and conservation communities (3). However, because little solid data exists to quantify the effects of thermal mass there is no consensus as to the magnitude of the effect and there are no technically proven guidelines for application of thermal mass. The objective of this study is to assess the *potential* benefits that might

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accrue from increased use of thermal mass in otherwise conventional residential construction. Past evaluations of massive construction (3) have typically ignored many factors which are important for determining the energy consumption of a building: occupancy, internal thermal loads, infiltration, and the rest of the building envelope. This study evaluates mass in the context of the entire building.

The public domain building energy analysis computer program BLAST (Building Loads Analysis and Systems Thermodynamics) was used to simulate the thermal performance of residential-scale buildings in four climates. BLAST calculates hourly heating and cooling loads and simulates the performance of air handling systems and central plants. In order to emphasize the interaction of building and environment, only sensible load calculations were performed for this study: latent effects diminish the effectiveness of thermal mass, especially in hot humid climates. The results presented here, therefore, give optimistic estimates of the effectiveness of thermal mass. It is also noted that BLAST was used less as a means of simulating absolute performance than as a guide to understanding the thermodynamic effects of building configuration and thermal mass; the program served primarily as an evaluative tool in assessing the *relative* effects of climate, placement of insulation, and window orientation on the energy consumption of a structure containing significant amounts of thermal mass.

In each location, buildings with three different mass levels were analyzed. Each alternative was described for BLAST in terms of its component building materials, thermostatic control system, occupancy level, lighting and equipment schedules, and infiltration rate. Climate information from TMY (typical meteorological year) tapes provided weather data for each of four cities: Lake Charles, Louisiana (LC); Albuquerque, New Mexico (AL); New York, New York (NY); and Madison, Wisconsin (MA). Climates in these cities can be characterized respectively as hot-humid, hot-arid, temperate, and cold; the heating degree days (65°F base) for each location are 1459, 4348, 4811, and 7863, respectively.

BUILDING DESCRIPTION

A standard wood frame building configuration was defined and analyzed in each climate. Construction details were allowed to vary from climate to climate so that results would more faithfully typify regional influences in building design. Building descriptions are summarized below.

Building Description: Climate-Independent Characteristics

The basic geometry of the building was common to all climates; it consisted of a rectangular, single-story structure with a flat roof and slab-on-grade floor:

- Dimensions: 50 ft × 25 ft × 8 ft wall height
- Orientation: North and south exposure for 50 ft walls
- Glazing: 60 ft^2 of double glazing on each wall, 20% of total wall area
- Shading: 1 ft roof overhang, no detached shading
- Internal Partition Walls: None
- Floor Construction: 3 in. concrete, density = 140 lb/ft^3
- Soil Conductivity: 0.075 BTU/hr·ft°F (typical of dry sand or loam)
- Scheduled Internal Loads (Maximum/Weekly Average):
  - Occupancy: 4.0/2.9 people
  - Lighting: 1000.0/290.0 BTU/hr
  - Equipment: 3000.0/1012.5 BTU/hr
- Thermostat Settings: - Heating: 68°F (67-69°F throttling range)
  - Cooling: 78°F (77-79°F throttling range)
- Design Infiltration Load: 0.5 air changes per hour.

Design infiltration conditions assume a zero temperature differential between the inside and outside of the building and a 7.5 mile per hour wind velocity. BLAST adjusts the infiltration level based on variations of the two parameters from

these design assumptions.

In BLAST, all internal loads are treated as both radiant and convective heat sources, and building occupancy and equipment loads are reflected as both sensible and latent heat gains for the space. As noted above, results presented here neglect latent loads (including those produced by air infiltration).

Building loads were calculated based on pre-specified thermostat settings. The control schedules were constant throughout the day. Between the endpoints of the thermostat deadband (69°F and 77°F), the internal air temperature was allowed to float freely in response to all of the available excitations (solar irradiance, internal loads, conductive loads, infiltration loads). The effects of infiltration and internal loads are described in Ref. 2.

Building Description: Climate-Dependent Characteristics

Table 1 summarizes the construction details and calculated thermal loads of the standard building in each of the locations used in this study. In addition to these location-dependent building parameters, a monthly schedule for soil temperature (4) was used for each site.

EFFECT OF GLAZING DISTRIBUTION ON LOW-MASS CONSTRUCTION

A second base building was defined which permitted evaluation of mass under the influence of large winter solar gains. The standard building was modified by redistributing the windows such that the east and west walls each contained 30 ft^2 and the south wall contained 180 ft^2 of glazing. The total window area was not changed. The percent reductions in loads resulting from redistribution of glazing in the low-mass structure are presented for each location in Fig. 1. Heating loads show substantial reductions in all four climates, ranging from about 10% in New York and Madison to about 30% in Albuquerque; the latter has a moderate heating load and highly favorable solar radiation conditions.

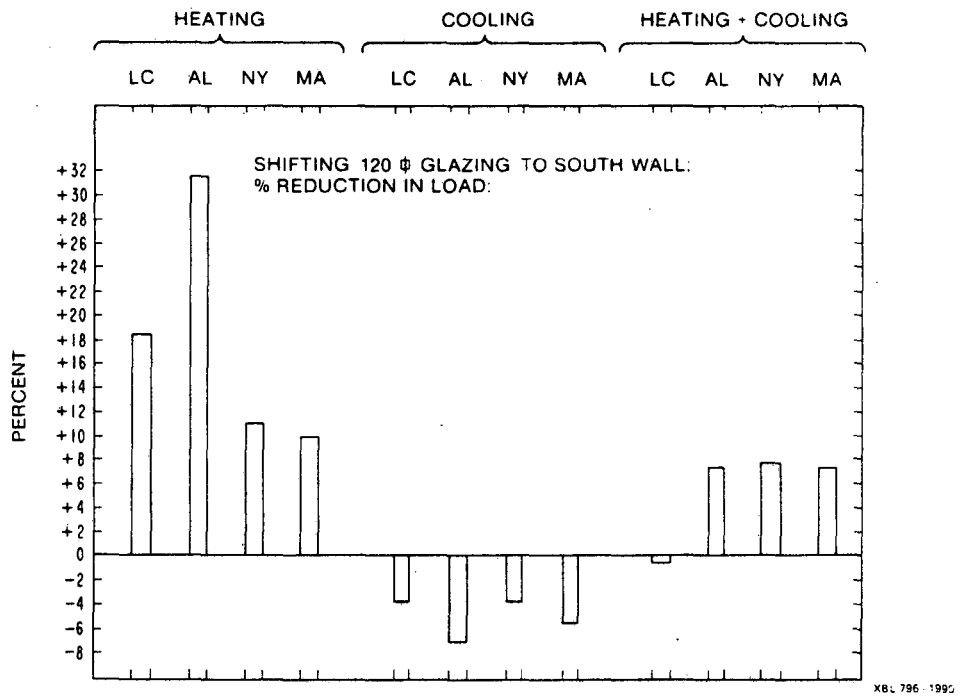
In all cases cooling loads are increased by small amounts: 4-7%. The annual cooling load profile is substantially altered by the glazing redistribution. The movement of east and west glazing to the south wall decreases summer cooling loads, but increases cooling loads in spring and fall. The net effect is small and might be controlled by careful design of shading devices for south windows.

Albuquerque, New York, and Madison all show a 7-8% reduction of total load, resulting from the glazing redistribution. In each of these climates the heating load (Table 1) is a substantial part of the total annual load. In contrast, the total load increases slightly in Lake Charles, resulting in part from the dominance of the cooling load.

TABLE 1 Standard Building Description

Building Characteristics	LC	AL	NY	MA
Roof Insulation	R19	R19	R30	R30
External Wall Finish	1" stucco	1" stucco	4" face brick	4" face brick
External Wall Insulation	R11	R19	R19	R19
Floor Slab Insulation	None	None	None	R7
Steady-State Conductance, $\frac{Btu}{ft^2 hr °F}$				
• Roof	0.052	0.052	0.033	0.033
• Floor	0.073	0.073	0.073	0.029
• Glazing	0.546	0.546	0.546	0.546
• Walls	0.082	0.052	0.052	0.052
Annual Dynamic Load, 10^6 Btu				
• Heating	5.7	15.9	36.7	51.6
• Cooling	33.4	42.2	9.6	10.7

Fig. 1 EFFECT OF GLAZING DISTRIBUTION ON LOW-MASS CONSTRUCTION



EFFECT OF THERMAL MASS

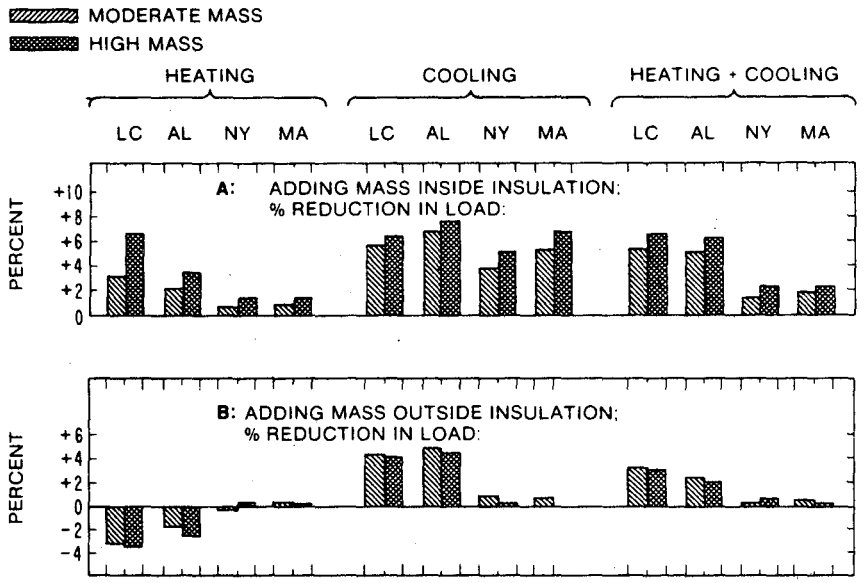
Standard Building Configuration

For both moderate- and high-mass alternatives, 4" of concrete was added to the wall construction; the density was varied to add 27 lb/ft^2 and 47 lb/ft^2 to the moderate- and high-mass walls, respectively. In each location, a constant steady-state conductivity was maintained for the complete wall construction by reducing the insulation level to compensate for the resistance added by the concrete.

Chart A of Fig. 2 shows the percent reductions in heating, cooling, and total loads resulting from the addition of mass inside the insulation of the standard configuration building (equal glazing on all walls). The effects are quite small (in the range of 1-8%) with cooling loads more affected than heating loads. The changes are smallest for the coldest climates, where the entire envelope, including mass, is continuously kept in a loss mode for long periods; this effectively negates the use of mass as thermal storage. The step from moderate to high mass results in reductions to the heating load which are nearly as great as those resulting from the initial addition of mass. However, in each of the cooling loads, increasing mass has a greatly diminished effect.

Chart B of Fig. 2 shows the percent reduction in heating, cooling, and total loads resulting from adding moderate and high mass outside of the wall insulation. Comparing the two sets of results in the figure illustrates that mass located inside the wall insulation consistently performs better than mass outside the insulation, and that in most cases external mass produces only a small fraction of the reduction that internal mass produces. The isolation of external mass from the conditioned space prevents the mass from acting as effective thermal storage. In colder climates the effect is negligible. An unexpected effect of external mass is the increase in heating loads with greater mass in both Lake Charles and Albuquerque.

Fig. 2 EFFECT OF MASS ON STANDARD CONFIGURATION



Direct-Gain Building Configuration

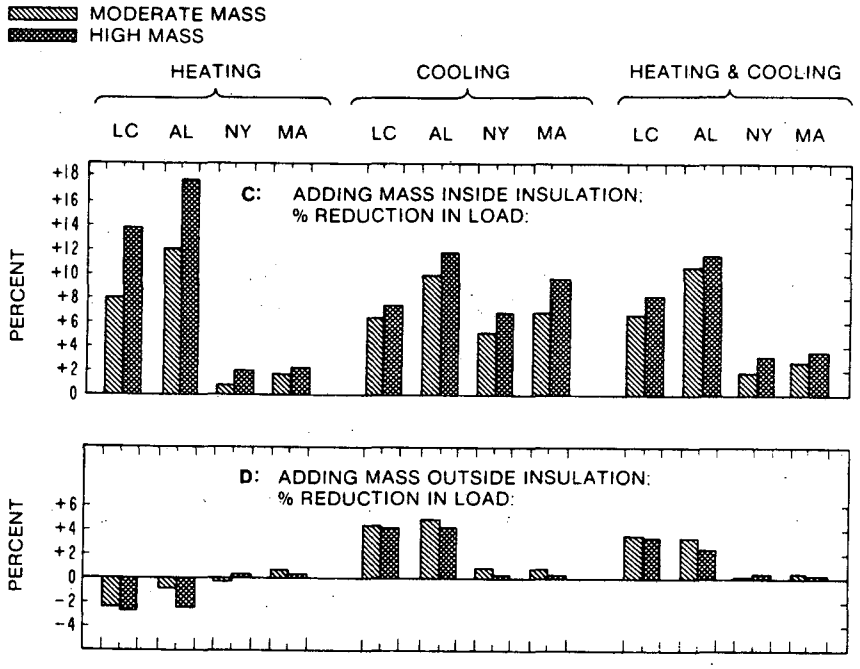
Figure 3 shows an identical investigation, using the low-mass direct-gain building (with redistributed glazing) as the base case. The thermal load reductions displayed in the charts reflect the effects of increased thermal mass when applied to a building with substantial internal solar gains.

A comparison of Chart A (Fig. 2) and Chart C (Fig. 3) reveals that in every case the percentage reduction in loads resulting from adding mass to the direct-gain configuration exceeds those from adding mass to the standard configurations. This does not come as a surprise: with glazing oriented toward the south, larger solar gains during the winter result in storage of part of the solar gains, and a more pronounced moderating influence of mass.

In each climate, the reduction in cooling load caused by the addition of mass more than offsets the increase in cooling load caused by movement of the windows to the south wall. In other words, the combined effect of shifting the glazing and adding mass is a net reduction in the cooling load at all locations. Just as in the case of the standard configuration, the reduction in total load caused by adding mass to the direct-gain building is largest in the hotter climates. In Albuquerque, where large diurnal temperature swings are common, redistributing the glazing produced only a 7½% reduction in total load; adding the high-mass walls resulted in additional reductions of over 13½%.

Chart D of Fig. 3 indicates that effects caused by additional thermal mass on the outside of the walls of the direct-gain building are virtually identical to those seen for the standard building configuration. This is hardly surprising when one considers that the mass is thermally isolated from the effect of the solar gains inside the building. This results in even larger differences between the effect of mass inside and outside the wall insulation.

Fig. 3 EFFECT OF MASS ON DIRECT-GAIN CONFIGURATION



INFLUENCE OF GROUND PROPERTIES

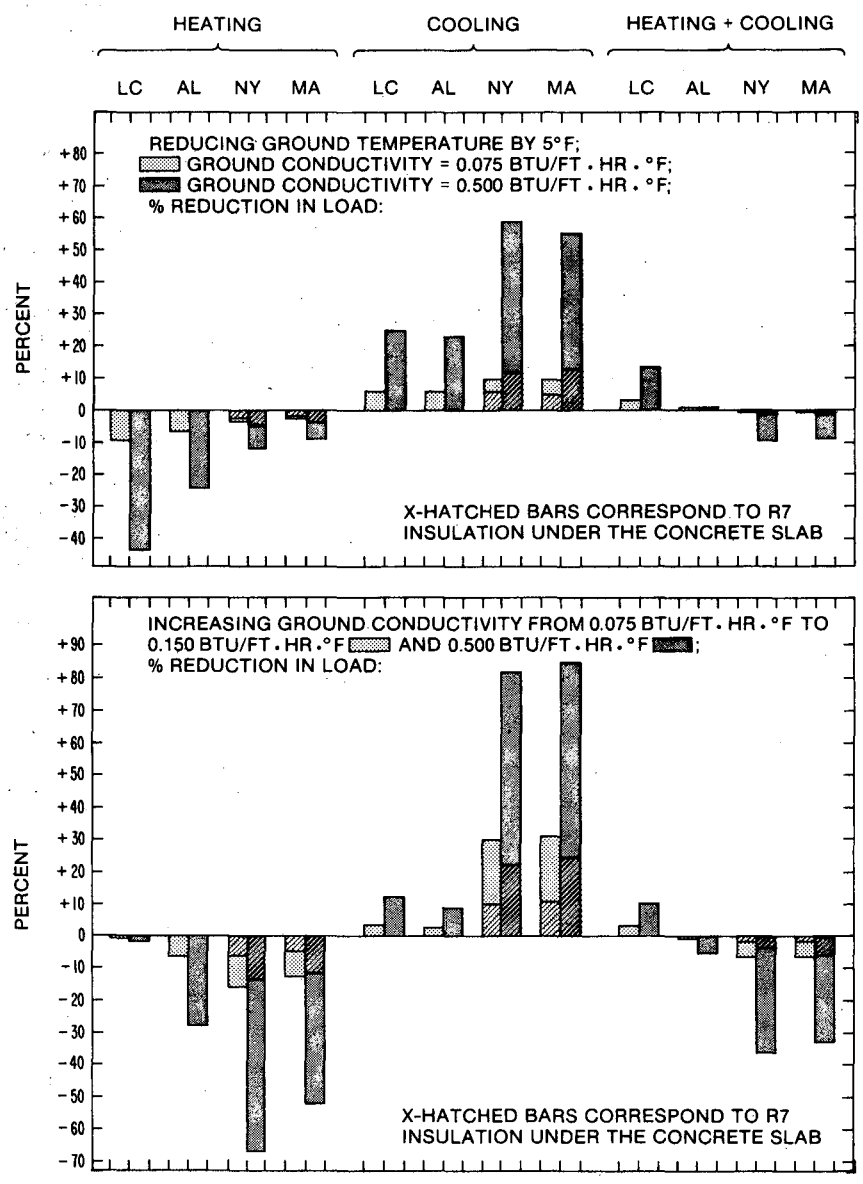
BLAST handles gains and losses through the floor with a one-dimensional dynamic heat transfer analysis. In the simulations presented here, soil temperatures (4) at a depth of one foot beneath the concrete floor slab were assigned for each month of the year; the thermal mass and thermal resistance of a one-foot layer of soil is thereby incorporated into the composite floor properties. Perimeter effects were accounted for by assigning a soil temperature beneath a portion of the floor which is a weighted average of the ambient air temperature and the normal ground temperature.

Ground temperatures can vary widely as a result of soil composition, rainfall, and underground water flow. Sensitivity of the loads to ground temperatures was tested by uniformly reducing the average monthly ground temperature assignments. Chart E of Fig. 4 indicates the percent reduction in heating, cooling, and total load resulting from a 5°F reduction in ground temperatures beneath an uninsulated slab. For each location, data is presented for ground conductivities of 0.075 and 0.500 BTU/hr·ft·°F. For New York and Madison, the cross-hatched part of the bars show the effect of reducing the ground temperatures beneath an insulated (R7) slab. As expected, reducing the ground temperature increases the heating load and reduces the cooling load at all sites. Not surprisingly, the fractional change in either the heating or cooling load is small if the initial load is large, and it can be large if the initial load is small. The changes in the heating and cooling loads are counteractive, and, for the cases presented here, the change in the total load tends to be small. Reducing the ground temperatures seems to affect the total load favorably in cooling climates and unfavorably in heating climates. These sensitivities to ground temperatures might be more pronounced at different thermostat settings.

The energy implications of ground coupling were also tested by increasing the ground conductivity used in the program. Chart F of Fig. 4 indicates the percent reduction

in heating, cooling, and total load resulting from increasing the conductivity of the soil beneath an uninsulated slab from 0.075 to 0.150 and 0.500 BTU/hr·ft·°F. As before, the cross-hatched part of the New York and Madison bars show the effect on annual building performance of varying the soil conductivity when the slab is insulated. Increasing the ground conductivity increases the heating load and reduces the cooling load at all locations. The fractional effect on both the heating and

Fig. 4 EFFECT OF GROUND ON STANDARD CONFIGURATION
(All Data for Moderate-Mass Structure)



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cooling loads is greatest where heating demand is high. Greater soil conductivity seems to have a somewhat favorable effect in severe cooling climates and a distinctly unfavorable effect in severe heating climates. These results might be quite sensitive to the thermostat settings and internal loads assumed in the simulations.

Perimeter effects predicted by the model were generally small. For the extreme case of no slab insulation and ground conductivity of 0.500 BTU/hr·ft·°F, the increase in total load resulting from including a perimeter calculation ranged from 1.6% in New York to 4.6% in Albuquerque. In the massive constructions, one would expect the actual effect to be somewhat larger than predicted, since vertical heat flow in the massive walls could increase the effective heat exchange surface for perimeter gains and losses. Analysis of the two- and three-dimensional heat flow problems associated with perimeter effects in massive construction awaits further research.

CONCLUSIONS

The effects of thermal mass in several building configurations have been investigated for four climates. The results presented here evaluate only total annual heating and cooling loads--no peak loads effects are considered. The results include examination of excitation of thermal mass by passive solar direct gain; other techniques for reducing the load in massive buildings (e.g., night ventilation) are the subjects of continuing research.

The results of the simulations indicate that thermal mass is most beneficial when located inside the insulation, i.e., when tightly coupled to the occupied space. In general, however, the effect of mass is observed to be relatively small, even in the direct-gain configuration. This result is not altogether unexpected. Gains and losses through the windows and massless ceilings dominate those through the massive walls, which represent only 25% of the overall envelope conductance for the structure. Internal heat sources and infiltration also contribute significantly to the load. The fractional impact of additional mass in the walls is diminished by the presence of a 3" floor slab in the base building. These conditions are not atypical of the way massive residences might be built; under these realistic conditions, mass does not have a large opportunity to contribute to the thermal performance of the structure.

Increasing building-to-ground connectivity generally has a beneficial effect on the cooling load and a deleterious effect on the heating load; the total load seems to be favorably affected in severe cooling climates and unfavorably affected in severe heating climates.

Additional results and conclusions regarding the effect of mass on building thermal performance are presented in the paper, "The Effect of Occupant Use Patterns on the Performance of Direct-Gain Passive Solar Systems," also published in these proceedings.

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