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Human Comfort and Auxiliary Control Considerations in Passive Solar Structures

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HUMAN COMFORT AND AUXILIARY CONTROL CONSIDERATIONS IN PASSIVE SOLAR STRUCTURES

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OCTOBER 1980

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FOREWORD

This report was initiated to investigate the annual heating and cooling load impacts of varied glazing and mass levels in a prototypical residential direct gain design with ventilative cooling and thermostat control strategies. The study was conducted as a joint effort between the Passive Solar Group at Lawrence Berkeley Laboratory (LBL) and the Buildings Systems Development Branch at the Solar Energy Research Institute (SERI) and is an extension of earlier LBL direct gain studies.

An abbreviated version of this paper was presented at the 1980 annual meeting of the American Section of the International Solar Energy Society in Phoenix and may be found in the proceedings of that conference and in LBL report LBL-10034.

Michael J. Holtz
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SUMMARY

Energy consumption and human comfort implications of various passive solar and energy conservation strategies are investigated for single-family, one-story, slab-on-grade residences in Albuquerque, NM and Washington, D.C. The building energy analysis computer program BLAST* is used to perform annual dynamic heating and cooling load calculations for a building in which the glazing area, glazing location, and thermal mass are varied systematically. The impacts on building performance of forced-flow ventilative cooling and nighttime and weekday thermostat setpoint adjustments are investigated. The results indicate that the annual heating and cooling loads are highly sensitive to glazing area, glazing location, and thermostatic controls. Annual cooling loads are substantially reduced by increased thermal mass in the walls. In contrast, annual heating loads are fairly insensitive to increased thermal mass in the walls, unless very large areas of south glazing are involved. BLAST calculates the air temperaures (T_a) and mean radiant temperatures (T_{mr}) in each zone for every hour of the year; a weighted average of T_a and T_{mr} is used to evaluate comfort conditions under various circumstances.

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

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SECTION 1.0
INTRODUCTION

Results presented here are based on thermal and comfort analyses of a prototypical direct-gain residence simulated in Albuquerque, N. Mex. (ALB) and Washington, D.C. (WDC). The analyses utilize a developmental version of the public domain building energy analysis computer program BLAST to perform hourly calculations of the heating and cooling loads; the program utilizes thermal balance techniques to calculate sensible thermal loads simultaneously for each zone in the structure. Load calculations are driven by climatic data from Typical Meteorological Year (TMY) weather tapes.

Floor area and window area of the prototype house are based on the Hastings Ranch House [1]; this structure typifies much of the new residential construction and has been the basis of other comparative energy analyses [2]. To reflect more faithfully contemporary passive design, the building's proportions, overhangs, and roofline have been modified to conform with a passive solar design (1979) recently developed by the Tennessee Valley Authority [3]. Wall and ceiling insulation levels are based on the residential optimization studies being used to establish building energy performance standards (BEPS) [2]. Double glazing is assumed in all calculations. In Albuquerque, no carpets are simulated, while in Washington D.C., 50% of the floor slab is covered by carpets. The prototype structure is comprised of three thermal zones identifiable by function: (1) kitchen and living space, (2) bedrooms, and (3) service areas. The locations of partitions between thermal zones and the locations of the sources of internal loads are also based on the TVA house (Figs. 1-1 through 1-5).

The magnitudes of the loads associated with each internal heat source are chosen to be consistent with the BEPS studies. The assumed internal heat generation of 15.6 kWh (53,100 Btu) per day has a significant impact on the building heating and cooling loads. Elimination of the internal sources in ALB can increase the heating load by 97%, reduce the cooling load by 63%, and increase the combined heating and cooling loads by 43%. A similar calculation in WDC increases the heating load by 51%, reduces the cooling load by 67%, and increases the combined load by 36%.

Infiltration rates assumed in this study are also compatible with the BEPS assumptions; the analyses use the Achenbach-Coblentz equation [5] with coefficients adjusted to yield an average annual infiltration rate of 0.6 air changes per hour (ACH) in WDC. Even with the relatively tight construction assumed for the prototype, infiltration accounts for a substantial part of the thermal loads; in ALB, the heating load is cut almost in half by using an infiltration rate of 0.3 ACH.*

The cooling loads presented are the sensible loads that cannot be removed by simple ventilation. Future studies will account for latent loads and will assume a ventilation control based on both temperature and humidity. Ventilation is assumed to be fan-driven, with a total capacity for the three zones of 7.3 m^3/sec (15,500 ft^3/min). This fan capacity is far larger than would be installed in a residential building and was selected to

*This low level of infiltration can be achieved readily using common construction techniques; however, to ensure acceptable levels of indoor air quality, it may be desirable to provide additional ventilation utilizing an air-to-air enthalpy exchanger.

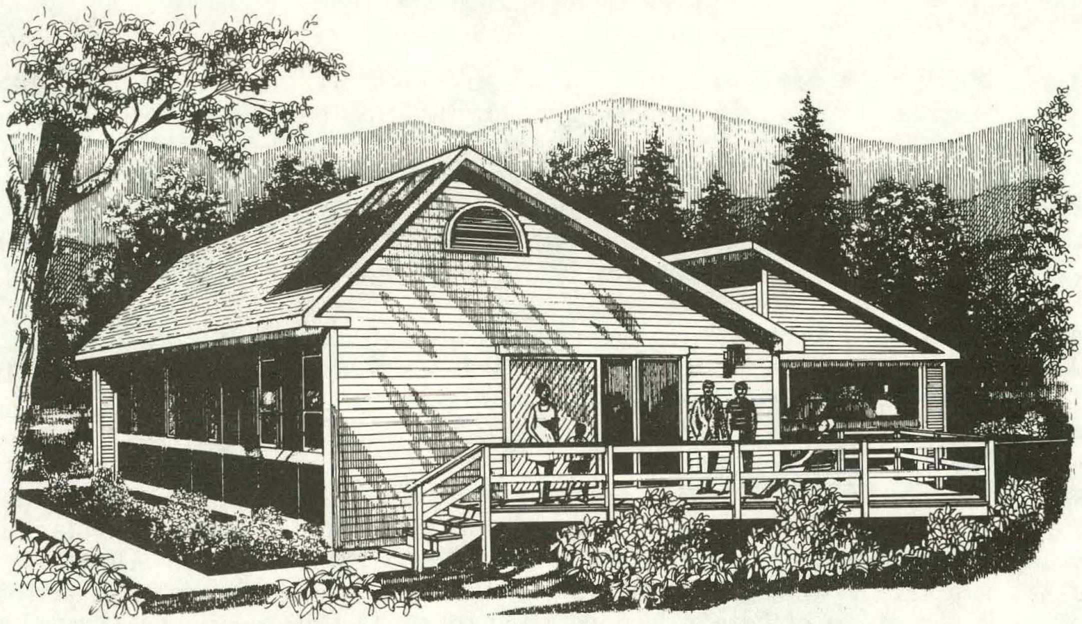


Figure 1-1. Perspective of TVA House

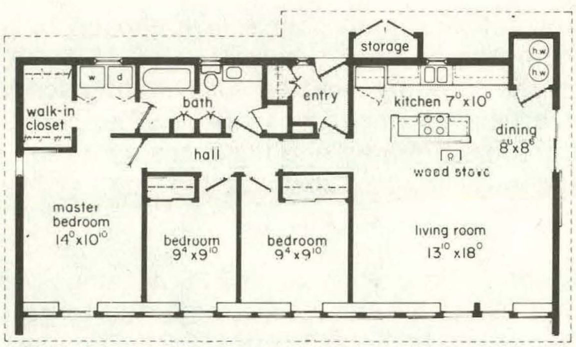


Figure 1-2. Floor Plan of TVA House

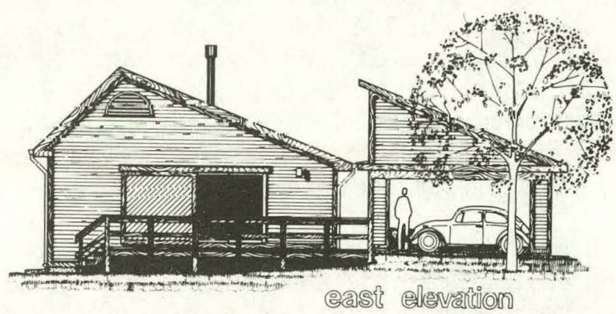


Figure 1-3. East Elevation

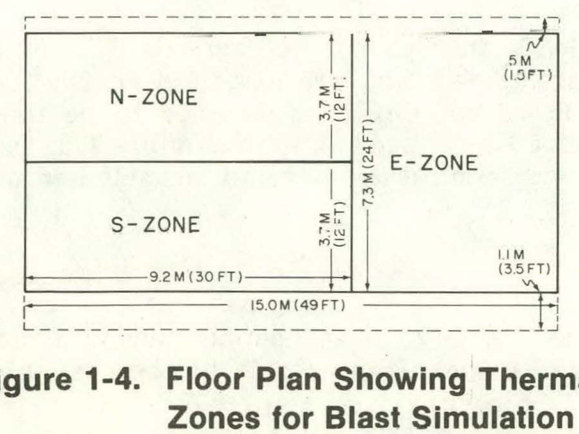


Figure 1-4. Floor Plan Showing Thermal Zones for Blast Simulation

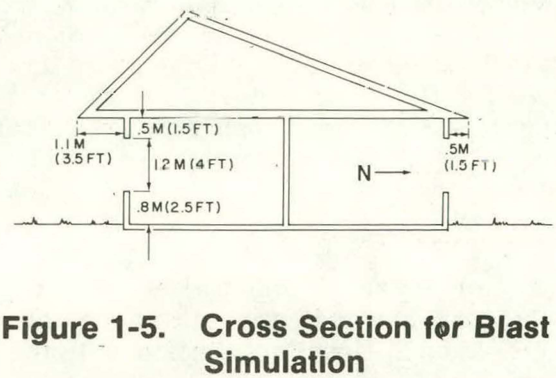


Figure 1-5. Cross Section for Blast Simulation

ensure maximum benefit from ventilation cooling. Fan control profiles for the three zones are separated in the analysis and for each zone; fan on-time during each hour of the simulation is automatically adjusted to satisfy the following control strategies:

- during those months of the year when the resulting cooling load reduction exceeds the heating load increase, a sufficient volume of outside air is added to the zone to provide an internal air temperature which is as close to the bottom of the thermostat deadband as ambient conditions will allow; and
- during the other months of the year the ventilation system provides only enough outside air to keep the interior air temperature below the thermostat cooling setpoint.

For most of the building configurations in both ALB and WDC, venting to the bottom of the deadband is desirable for May through September. The energy impact of ventilation is dramatic. In ALB, ventilation can reduce cooling loads by a factor of three and combined heating and cooling loads by a factor of two.

Table 1-1 summarizes some of the important building parameters. The values shown were used in all simulations, unless explicitly indicated to the contrary. Carroll, et al. [4] provide a complete description of the prototype structure.

Table 1-1. DIRECT-GAIN PROTOTYPE BUILDING DESCRIPTION

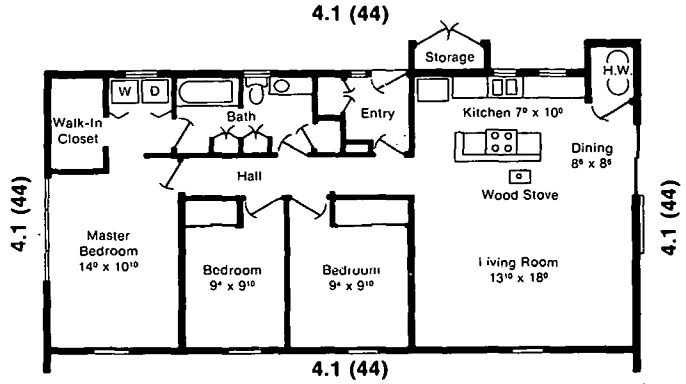
Floor Area	111 m^2 (1176 ft^2)
Total Glazing Area	16.6 m^2 (176 ft^2)
Number of Glazing Panes	2
Windows	
Position of Top	1.98m (6.5 ft) above floor
Position of Bottom	0.76 m (2.5 ft) above floor unless glazing area req's it being at the floor
South Overhang	
Length	1.07 m (3.5 ft)
Position	2.44 m (8 ft) above floor
Wall Construction Options	1.27 cm (0.5 in.) gypboard on frame (light gyp) 2 x 1.59 cm (2 x 0.625 in.) gyp on frame (heavy gyp) 4" solid concrete
Floor Construction	4" concrete slab
Ceiling Construction	1.27 cm (0.5 in.) gyp on frame
Envelope Conductances	
Ceiling	0.166 $W°C^{-1}m^{-2}$ (0.0293 $Btu\text{-}hr^{-1}°F^{-1}ft^{-2}$)
Walls	0.270 $W°C^{-1}m^{-2}$ (0.0476 $Btu\text{-}hr^{-1}°F^{-1}ft^{-2}$)
Floor	0.485 $W°C^{-1}m^{-2}$ (0.0856 $Btu\text{-}hr^{-1}°F^{-1}ft^{-2}$)
Thermostat Settings	
Heating	21.1°C (70°F)
Lower Vent	21.4°C (70.5°F)
Higher Vent	25.3°C (77.5°F)
Cooling	25.6°C (78°F)
Average Infiltration Rate	0.6 air changes per hour
Internal Load	15.6 $kWh\text{-}day^{-1}$ (53,100 $Btu\text{-}day^{-1}$)
Thermal Zones	
Unconditioned	Attic
Conditioned	North, South and East
Carpet Options	
Percent Solar Radiation Absorbed by:	
Furniture	25%
Carpet and Slab	60%
Walls and Ceiling	15%
Night Setback	6.5°C (10°F) unless otherwise specified

SECTION 2.0
EFFECTS OF GLAZING DISTRIBUTION

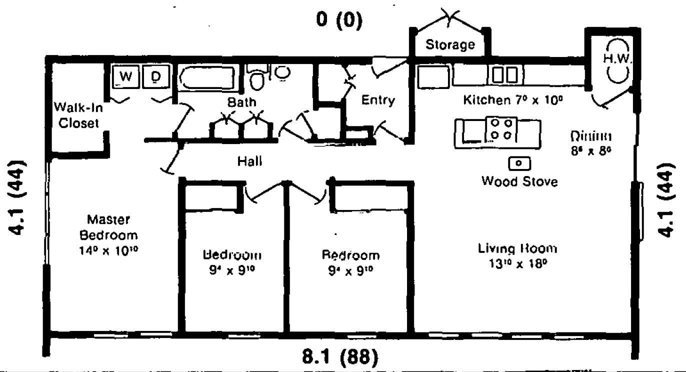
Figure 2-1 shows the annual heating and cooling loads corresponding to four different distributions of the 16.4 m^2 (176 ft^2) of double glazing in ALB and WDC. Each schematic represents a plan view of a building configuration, with the glazing areas for each wall indicated by the numbers outside the schematic. Annual heating and cooling loads (in thousands of kWh's) are given by numbers beside the schematic. The first schematic for both locations gives the thermal loads for a building configured with 4.1 m^2 (44 ft^2) of glazing on each wall. Comparing the second schematic to the first shows the effects of shifting 4.1 m^2 of glazing from the north to the south wall. For both locations, the heating load decreases significantly while the cooling load increases slightly. Comparing the third schematic to the first shows the effect of shifting all 8.2 m^2 (88 ft^2) of east and west glazing to the south wall. For both locations there is a significant decrease in both the heating and cooling loads, suggesting the general desirability of avoiding east and west glazing. The fourth schematic shows that the smallest combined heating and cooling load is achieved when all the glazing is placed on the south wall. Comparing the fourth schematic to the first shows reductions of 26% for the heating load and 28% for the cooling load in ALB, and reductions of 12% for the heating load and 15% for the cooling load in WDC.

The small reductions in heating loads are attributable in part to the large overhang, which was selected to optimize total annual performance considering both heating and cooling loads. The large overhang also explains why the third configuration shows a higher heating load than the second; monthly heating loads calculated by BLAST for the building in question show that the 8.2 m^2 of unshaded east and west glazing contributes more useful solar gain than the same amount of glazing divided between north and south, during all but the deepest winter months when direct-beam solar exposure on the south glazing is at a maximum. Studies are currently under way at LBL and SERI to examine the heating and cooling trade-offs associated with the length, shape, and position of the overhang and the height and position of the window. Since fixed shading obviously involves compromises, these studies will also evaluate the benefits of seasonally variable shading and movable insulation (for reducing summer solar loading as well as winter night losses).

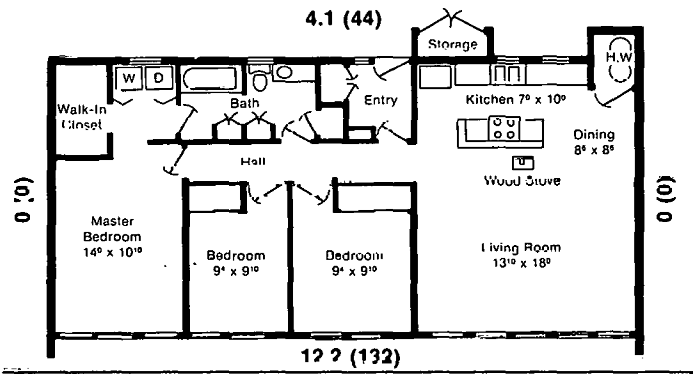
Comparing the fourth configuration to the third shows a very modest reduction in combined heating and cooling load, suggesting that there is little advantage in completely eliminating the north glazing for this particular building in these climates. A reasonable level of north glazing could be a desirable feature for providing views and for enhancing natural ventilation cooling for the north zone. In light of these arguments, the studies reported below assume 4.1 m^2 of glazing on the north wall.



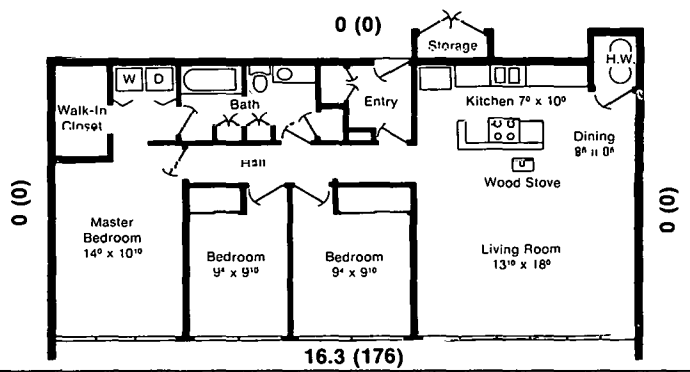
City	kWh	MBtu
Albuquerque		
Heating	2.37	8.08
Cooling	2.25	7.67
Total	4.62	15.75
Washington		
Heating	5.37	18.31
Cooling	1.71	5.83
Total	7.08	24.14



City	kWh	MBtu
Albuquerque		
Heating	1.84	6.28
Cooling	2.26	7.71
Total	4.10	13.99
Washington		
Heating	4.95	16.87
Cooling	1.74	5.93
Total	6.69	22.80



City	kWh	MBtu
Albuquerque		
Heating	2.04	6.94
Cooling	1.55	5.27
Total	3.59	12.21
Washington		
Heating	5.00	17.06
Cooling	1.36	4.64
Total	6.36	21.70



City	kWh	MBtu
Albuquerque		
Heating	1.76	6.01
Cooling	1.63	5.56
Total	3.39	11.57
Washington		
Heating	4.74	16.18
Cooling	1.45	4.94
Total	6.19	21.12

Building Description

- Standard Frame Construction
- Partitions: Light Gypboard
- Nominal Wall R Value: 19
- Number of Glazing Panes: 2
- Night Setback = 5.6°C (10°F)
- Number of Zones: 3

Note: Glazing distribution is designated in floor plans in m^2 (ft^2).

Figure 2-1. Glazing Distribution Studies

SECTION 3.0
SOUTH GLAZING AND THERMAL MASS

Figure 3-1 shows the effect of south glazing area on the thermal loads of a dwelling with 4.1 m^2 of north glazing and 0 m of east and west glazing. Annual heating, cooling, and total loads are plotted for (1) a standard frame building with internal partition walls of 1/2 in. gypboard on studs, and (2) a building with partitions of 0.10 m (4 in.) solid concrete but which is otherwise identical to (1). The hatched portions on the graph indicate the benefits of incorporating the concrete partitions. For small areas of south glazing, the higher-mass building requires more heating energy. This result is attributable to the use of a night setback [6]. In both climates the higher-mass building has a lower heating load for large glazing areas, reflecting the storage benefit of thermal mass in a highly solar-driven structure. As expected, the crossover of the two curves occurs at a smaller glazing area in ALB, the sunnier climate.

The heating benefits of thermal mass in the ALB building are greater than indicated in previous studies which treated the building as a single thermal zone [7]. In multizone configurations, which are more representative of occupied buildings, the surfaces in the south zones must accommodate all of the solar gains. The larger thermal excitations which result from confining the solar gains to the south zone can be expected to enhance the benefits of thermal mass; the multi-zone simulation used in the current study accounts properly for the exposed wall, floor, and ceiling area in each zone. The higher conductivity of the concrete partition in comparison to the stud wall also contributes to the reduction in heating load by enhancing conductive heat transfer between zones. For a building with 12.3 m^2 (132 ft^2) of south glazing, eliminating the airspace in the gypboard partition produces a reduction in heating load which is about half as large as the reduction achieved by using a concrete partition. Analyzing a geometrically identical structure as a single zone with a single internal air temperature produces a reduction in heating load which is more than twice as large as the reduction achieved by going to the concrete partition. Future studies will investigate the heating load reductions which can be achieved through use of convective transfer through doorways and other openings between zones.

In both ALB and WDC, adding thermal mass reduces the cooling load substantially more than it reduces the heating load. This is a manifestation of the fact that the daily heat fluxes in and out of the building are actually larger during the summer than during the winter. Internal loads and high solar loading conspire on summer days to produce large quantities of heat which can be absorbed by thermal mass within the structure and dissipated at night by ventilating the building; in contrast, the tight, well-insulated envelope, the internal loads, and the night setback conspire in winter to make the added mass inconsequential for all buildings except those that are highly solar driven by large south glazing areas. This interpretation is amply supported by load calculations made for ALB on ventilated and unventilated frame houses with equal glazing areas on each wall. For the unventilated house, the cooling load is almost three times as large as the heating load; with ventilation the cooling load is less than the heating load.

The heating load curves in Fig. 3-1 indicate a high sensitivity to south glazing area in ALB, with a much less pronounced effect in WDC. In both climates the heating load curves are substantially nonlinear, with the greatest benefits being accrued by the first few increments of glazing area. In contrast, the cooling loads increase in a rapid and reasonably linear fashion with increasing south glazing area. Adding the heating and cooling loads produces total load curves which initially dip down and then rise again with increasing area of south glazing. Making the crude assumption that heating and cooling load increments are roughly comparable in fossil fuel terms, the results suggest that there exists in each case a thermally optimal south glazing area, corresponding approximately to the minimum in the total load curve. In ALB, the minimum for the standard frame building occurs in the range of 6.5 to 10.2 m^2 (70 to 110 ft^2) and for the higher mass building in the range of 10.2 to 15.7 m^2 (110 to 170 ft^2). In WDC, the minimum for the standard frame building occurs in the range of 2.8 to 6.5 m^2 (30 to 70 ft^2) and for the higher-mass building in the range of 7.4 - 11.1 m^2 (80-120 ft^2). These results were obtained by analyzing a particular building assuming totally unmanaged glazing and a fixed shading overhang. Additional studies will be necessary in order to assess the applicability of the results to other building configurations and/or other end use variables. However, it is expected that incorporating more thermal mass, variable shading, or movable insulation would move the optimum to larger areas of south glazing.

The remaining studies presented in this paper are based on 12.3 m^2 of south glazing. Assuming modest window management in the form of movable curtains, this glazing area is probably not far from optimal in any of the cases discussed. Furthermore, the total glazing area is then consistent with the national average for new homes and with buyer expectations.

To emphasize the appropriateness of selecting zero east and west glazing area for the base passive building, the performance of combined east and west glazing is presented in Fig. 3-2. As in the case of south glazing, the thermal performance of east and west glazing would be substantially improved by movable insulation.

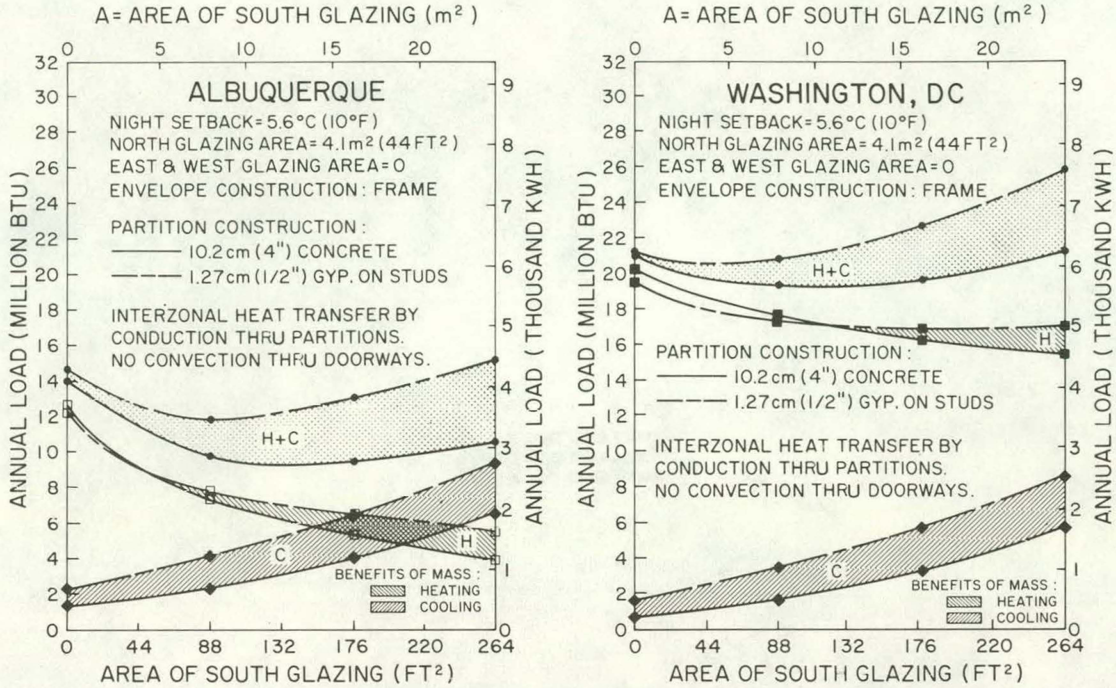


Figure 3-1. Effect of South Glazing Area on Building Thermal Loads

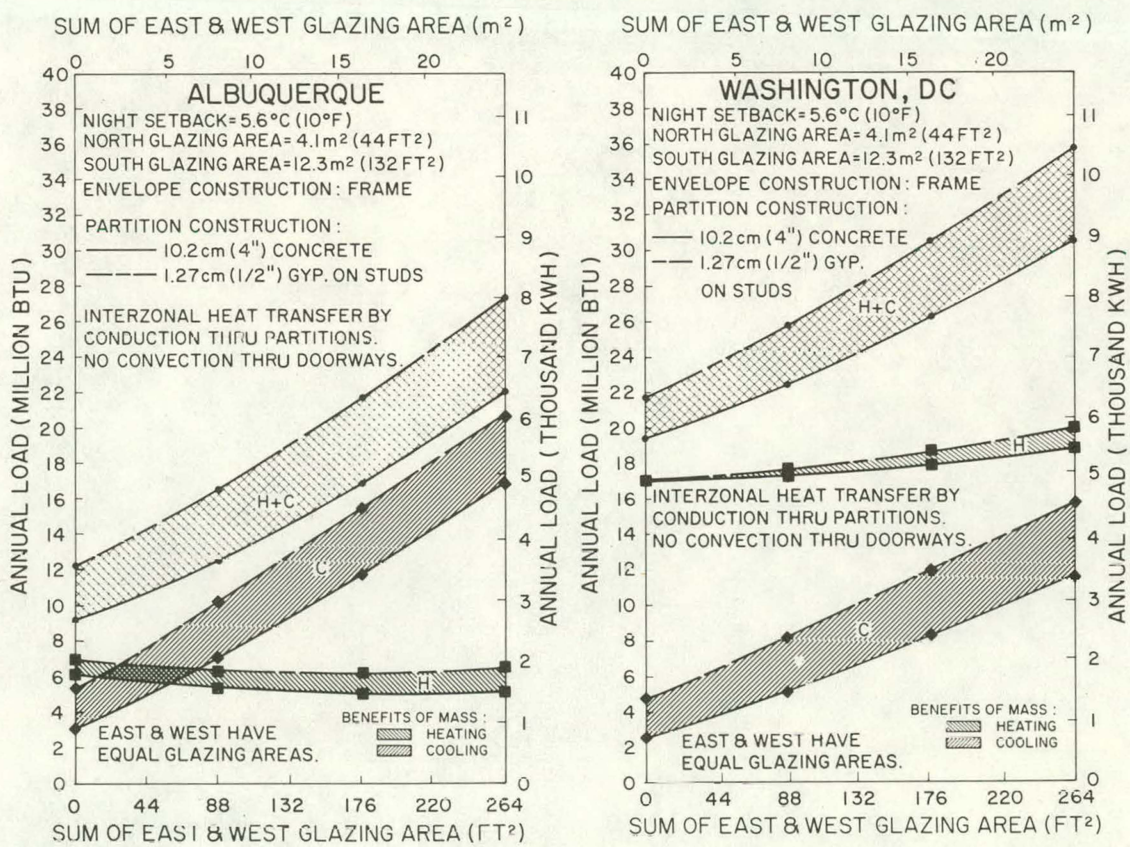


Figure 3-2. Effect of East and West Glazing Area on Building Thermal Loads

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SECTION 4.0
AUXILIARY SYSTEM CONTROL AND MASS

Figure 4-1 shows the effect on annual heating and cooling loads of common thermostat control strategies, partition construction, and carpeting on the floor slab. Thermostat adjustments include a night setback of the heating setpoint (NS), and a combination of night setback and weekday relaxation of interior comfort requirements as reflected in the heating and cooling thermostat setpoints (NDS). Expansion of the thermostat deadband on weekdays is a control strategy which is compatible with many residential buildings which are not occupied during the workweek. The results show that with no thermostat adjustment, the building with the massive partitions has lower heating and lower cooling loads in both climates. Heating loads decrease rapidly with increasing NS, while cooling loads are unaffected. The building with the gypboard partitions is most strongly benefited by the NS. For an NS greater than 6°C (10°F) in WDC, the heating load for the building with the gypboard partitions is actually lower than that of the building with concrete partitions. These results also show that the heating loads are quite insensitive to variations in (1) wall construction and (2) the fraction of the slab that is carpeted. In ALB, the sunnier climate, the heating benefit of thermal mass is more apparent; no crossover is observed for heating load curves of the standard and higher mass buildings. As noted earlier, this result is inconsistent with previous studies that treated a similar building as a single zone [6,7]. The results show that, in both climates, cooling loads are more sensitive than heating loads to thermal mass—either in the partitions or in the form of exposed slab. Relaxation of the daytime thermostat setpoints has a beneficial effect on heating and cooling loads in both climates. As for the case of the NS alone, the building with the gypboard partitions is most strongly benefited by combined night and weekday thermostat adjustments (NDS).

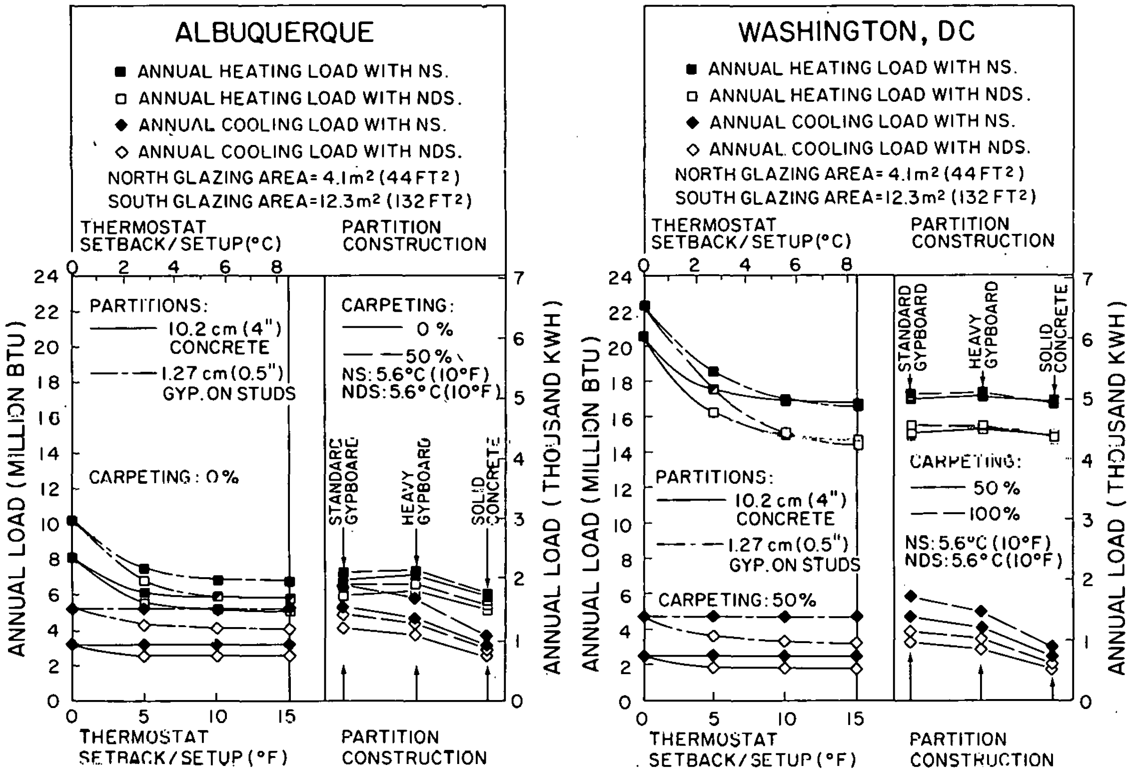

Figure 4-1. Effect of Thermostat Settings and Thermal Mass on Annual Heating and Cooling Loads

SECTION 5.0
COMFORT

BLAST calculates air temperatures (T_a) and mean radiant temperatures (T_{mr}) in each zone for every hour of the year. The equivalent uniform temperature, defined as $T_{eu} = 0.45T_{mr} + 0.55T_a$, is taken as the wintertime comfort index [8]. Preliminary studies of the standard frame building with gypboard partitions and a similar building with solid concrete partitions indicate that there are no radical differences in the comfort conditions assuming the two buildings are subjected to identical thermostat control strategies. There are some indications that comfort conditions are degraded in both structures during the first few hours immediately following a period of thermostat setback or setup. More extensive examinations of comfort issues in residential buildings are the subjects of future studies.

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SECTION 6.0
CONCLUSIONS

For the range of parameters investigated, results show that:

- Annual cooling loads in both ALB and WDC increase rapidly with added glazing anywhere on the building, with a particularly deleterious effect from glazing with east and west orientations.
- Annual heating loads decrease rapidly with increasing south glazing area for a building in ALB, but are otherwise fairly insensitive to changes in east, west, or north glazing areas in either climate.
- Annual cooling loads are substantially reduced in both climates by adding massive partitions or by increasing the exposure of the concrete floor slab.
- Annual heating loads are substantially reduced in both climates by adding massive partitions or exposing more floor slab in a building which is highly solar-driven during the winter (i.e., the south glazing area is large).
- The optimum area of south glazing increases with the quantity of added thermal mass.
- When accounting for both heating and cooling loads, the thermally optimal area of unmanaged south glazing is substantially lower than predicted by heating considerations alone.
- The comfort conditions in the standard building and the higher mass building do not appear to be substantially different if the same thermostat control strategy is used in both buildings.

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SECTION 7.0
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15. Supplementary Notes

16. Abstract (Limit: 200 words)

Energy consumption and human comfort implications of various passive solar and energy conservation strategies are investigated for single-family, one-story, slab-on-grade residences in Albuquerque, NM and Washington, DC. The building energy analysis computer program BLAST is used to perform annual dynamic heating and cooling load calculations for a building in which the glazing area, glazing location, and thermal mass are varied systematically. The impacts on building performance of forced-flow ventilative cooling and nighttime and weekday thermostat setpoint adjustments are investigated. The results indicate that the annual heating and cooling loads are highly sensitive to glazing area, glazing location, and thermostatic controls. Annual cooling loads are substantially reduced by increased thermal mass in the walls. In contrast, annual heating loads are fairly insensitive to increased thermal mass in the walls, unless very large areas of south glazing are involved. BLAST calculates the air temperatures (T_a) and mean radiant temperatures (T_{mr}) in each zone for every hour of the year; a weighted average of T_a and T_{mr} is used to evaluate comfort conditions under various circumstances.

17. Document Analysis

a. Descriptors : Auxiliary Systems ; Buildings ; Computer Calculations ; Computerized Simulation ; Cooling Loads ; Energy Conservation ; Energy Consumption ; Energy Efficiency ; Forced Convection ; Glazes ; Heating Load ; Houses ; Human Populations ; Paaasive Solar Cooling Systems ; Passive Solar Heating Systems ; Performance Radiant Heat Transfer ; Residential Sector ; Temperature Control ; Thermal Mass ; Buildings ; Coatings ; Control ; Convection ; Efficiency ; Energy Transfer ; Heat Transfer ; Heating Systems ; Populations ; Residential Buildings ; Simulation ; Solar Cooling Systems ; Solar Heating Systems

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