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A PARAMETRIC ANALYSIS OF THERMAL MASS IN RESIDENTIAL BUILDINGS

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ABSTRACT

This paper summarizes an analysis of the impact of various wall and building design characteristics on the energy savings due to thermal mass in exterior walls of residential buildings. Thermal mass effects on annual heating and cooling loads were examined in 12 climates for three types of exterior walls -- insulation either inside or outside of the mass layer and with insulation and mass well mixed. Using a parametric series of computer simulations and multiple regression analysis, the results were reduced to simple equations that predict the performance of massive walls in typical residences. These regression equations are suitable for use in microcomputer energy analysis programs and other simplified design and analysis tools. Although the use of thermal mass can be an effective means of reducing both heating and cooling loads, the magnitude of the savings is shown to depend on a complex interaction of parameters including the climate, the amount and physical properties of the mass, the location and amount of insulation in the exterior walls and building design parameters that affect either solar gain or natural ventilation rate.

INTRODUCTION

The use of thermal mass has been shown to be an effective means of reducing both heating and cooling loads in residential buildings (Arumi 1977; Burch et al. 1983,1984; Carroll et al. 1985; Goodwin and Catani 1979; Petersen et al. 1980; Rudoy and Douglas 1979). The magnitude of the savings depends on a complex interaction of factors including the climate, the amount and physical properties of the mass, and other building design parameters such as the area and orientation of windows, the type of window glass, the natural ventilation rate, and the building thermal integrity. In previous research (Huang et al. 1985), we quantified the mass effects in 12 climates for various types of massive walls with insulation either inside or outside of the mass layer or with insulation and mass well mixed. That work resulted in the development of a slide rule used to calculate the thermal mass effect, as well as the performance of other conservation measures, for typical building designs and operating conditions. Our current research extends the previous work to account for the thermal mass effect due to variations in the building design, including changes that affect solar gain and natural ventilation rate.

This paper describes the results of a series of parametric simulations of various wall characteristics such as mass density, thickness and conductivity, insulation location, and wall U-value, as well as building design features such as solar gain and natural ventilation rate. We used a detailed, hourly building energy model, DOE-2.1C (BESG 1985), which enabled us to predict the main effects of each parameter as well as several levels of interaction affecting the whole building energy performance. First, we provide a description of the building prototype and operating conditions and the three types of massive exterior walls that we examined. Next, we outline the method used to analyze various wall material properties and design configurations and provide results of our parametric study. Finally, we describe the equation used to summarize the mass effect and the regression coefficients that are suitable for inclusion in microcomputer energy analysis programs.

Stephen J. Byrne is a staff scientist and Ronald L. Ritschard is a group leader, both with the Building Energy Analysis Group, Applied Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720.

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MODELING ASSUMPTIONS

We modeled a modified version of the Hastings (1977) one-story ranch house with a floor area of 1540 ft^2 (143 m^2) and a total window area of 15% of the floor area. Figure 1 shows a representative floor plan; construction and occupancy characteristics are given by Huang et al. (1985). The following building design characteristics and operating conditions were used for the base case simulations described in this report:

Interior Mass
- Furniture:
  - 3.30 lb/ft^2 (16.1 kg/m^2) of floor area
  - 0.30 Btu/lb·F (1.26 kJ/kg C) specific heat
  - 0.17 ft (0.05 m) thick
- Interior Walls:
  - 3.57 lb/ft^2 (17.4 kg/m^2) of floor area
  - 0.26 Btu/lb·F (1.09 kJ/kg C) specific heat
  - 0.04 ft (0.01 m) thick

Thermostat Set Points
- 70 F (21 C) Heating, 6 AM through midnight
- 60 F (16 C) Heating, midnight through 6 AM
- 78 F (26 C) Cooling

Floor
- 0.33 ft (0.10 m) carpet covered concrete slab with perimeter insulation

Ceiling
- 0.033 Btu/h·ft^2·F (0.189 W/m^2 C) batt insulation in wood-frame truss

Window Type
- Single pane clear glass
- 0.88 transmittance
- 0.07 reflectance
- 0.63 drapery shading coefficient

Window Area
- 15% of floor area
- Equally distributed in four orientations

We assumed a natural ventilation rate of 10 air changes per hour. The indoor dry-bulb temperature to which the model attempts to cool through natural ventilation (in lieu of mechanical cooling) is set by:

$$T_{vent} = T_{heat} + \left(\frac{\sum Q_{heat}}{\sum Q_{heat} + \sum Q_{cool}} \right) \left(T_{cool} - T_{heat} \right) \tag{1}$$

$$T_{vent} \geq 70\ F\ (21\ C) \tag{2}$$

where:

- T_{vent} = ventilation set point temperature
- T_{heat} = heating set point temperature
- T_{cool} = cooling set point temperature
- $\sum Q_{heat}$ = sum of heating load for past 24 hours
- $\sum Q_{cool}$ = sum of cooling load for past 24 hours

This has the effect of setting the ventilation temperature equal to the cooling set point during the winter season and equal to the heating set point during the summer. If the previous 24 hours contains hours of both heating and cooling (e.g., spring and autumn), the ventilation temperature is adjusted between the heating and cooling set points. The ventilation temperature is never allowed to fall below 70 F (21 C) for comfort reasons.

We simulated three wall constructions (see Figures 2a - 2c) in a parametric series with DOE-2.1C using custom weighting factors to account for the thermal storage characteristics of the mass. The wall with integral insulation, shown in Figure 2a, represents a log wall and approximates a brick or concrete masonry unit with the cores filled with insulation. Figures 2b and 2c represent brick or concrete masonry with a layer of insulation either inside or outside the mass. We ran sensitivity tests to quantify the effect of changes in specific parameters and then developed an extensive data base representing the performance of mass walls in 12 climate zones.

THE EFFECT OF WALL HEAT CAPACITY

Thermal mass in exterior walls is an effective means of reducing both heating and cooling loads in residential buildings because of the ability of mass to store excess heat gains that can offset heating loads during the winter or be vented to the exterior in the summer. The performance of massive walls varies greatly in different climates because of the impact of solar gain and the average as well as the diurnal range of the outside temperature. In order to understand the potential magnitude of the savings due to thermal mass, we ran simulations with DOE-2.1C of several mass wall configurations in a variety of climates and compared the results to simulations of wood-frame walls.

Shown in Figure 3 are the results of simulations for Phoenix. The total annual heating and cooling loads are plotted against wall heat capacity -- defined here as the thickness times the density times the specific heat of the mass layer. Three wall types are shown -- insulation outside the mass (Figure 2c), insulation inside the mass (Figure 2b), and insulation and mass well mixed (Figure 2a). All three walls were modeled with a total wall U-value of 0.20 Btu/h·ft^2·F (1.13 W/m^2 C) For reference, the loads for wood-frame walls with a total wall U-value of 0.20 Btu/h·ft^2·F (1.13 W/m^2 C) and 0.10 Btu/h·ft^2·F (0.57 W/m^2 C) are shown.

The figure shows a total heating plus cooling load reduction for all three wall types as the wall heat capacity is increased, with the most significant load savings when the wall has insulation outside of the mass. The difference between the three massive walls is nearly constant as the wall heat capacity increases. With outside insulation and a heat capacity of 14 Btu/ft^2·F (286 kJ/m^2 C), which is typical for a 0.67 ft (0.20 m) concrete block, the annual heating plus cooling load is approximately the same as that of a wood-frame wall with a U-value of 0.10 Btu/h·ft^2·F (0.57 W/m^2 C), a difference of 0.11 Btu/h·ft^2·F (0.62 W/m^2 C). The effect of wall heat capacity in reducing the need for insulation is clearly indicated. In the case shown, there is a greater savings in cooling than heating. However, the magnitude of the effect on heating and cooling load will vary with climate and the characteristics of the wall and building design.

PARAMETRIC SIMULATIONS OF WALL CHARACTERISTICS

We performed a sensitivity analysis in four climates (Albuquerque, NM, Chicago, IL, Miami, FL, and Phoenix, AZ) for a wide variety of mass wall configurations to determine how several complex interactions could be reduced to a set of simple equations. We varied parameters such as density, thickness, conductivity, and specific heat of the mass layer as well as the location and U-value of the insulation layer within the full range found in common residential construction. We found that this large set of parametric simulations (representing various types of concrete masonry, brick and log) could be substantially reduced by combining certain parameters and using nonlinear multiple regression to interpolate between the others.

We show the DOE-2.1C simulations as a series of plots of delta load versus wall heat capacity where the delta load is the difference in the annual heating or cooling load between a lightweight wood-frame wall and a massive wall, both with the same total wall U-value. We present the results here for the Phoenix parametrics. Although the magnitude of the results are different in each of the four climates examined, the trends in the data shown are consistent with the full set of simulations.

Mass Conductivity

The effectiveness of thermal mass in reducing heating and cooling loads depends on its ability to dampen interior temperature swings by storing excess heat gains during the day that, at night, can offset heating loads during the winter or be vented to the outside during the summer. The more quickly the mass can respond to surface temperature fluctuations, the more effective it will be in reducing heating and cooling loads. The conductivity of the mass has a direct impact on this response time and consequently on the load reduction.

We performed sensitivity runs to quantify the effect of changes in mass conductivity. We held the wall U-value constant by varying the thickness of the insulation layer as the conductivity and thickness of the mass layer was changed. Figure 4 shows typical results, in this case for a 0.67 ft (0.20 m) masonry wall with insulation outside of the mass and a total wall U-value of 0.20 Btu/h·ft^2·F (1.13 W/m^2 C). As the mass conductivity increases, the difference in load between a massive and a lightweight wall also increases. The higher the conductivity of the mass, the more effective it is in reducing loads compared to a lightweight wall with the same total wall U-value. This effect is more pronounced in cooling than heating. Although the results shown here are climate and building specific, the trends are representative of all four climates and several building designs.

Mass Density and Thickness

In order to quantify the effect of changes in mass density and thickness, we ran a series of simulations for a massive exterior wall with insulation outside, a constant wall U-value of 0.20 Btu/h·ft^2·F (1.13 W/m^2 C) and a constant mass conductivity of 0.50 Btu/h·ft·F (0.86 W/m C). We held the total wall U-value constant by varying the thickness of the exterior insulation layer as the thickness of the mass layer was changed. Figure 5 shows the annual heating and cooling load savings (delta load) due to various amounts of mass for three levels of mass density.

The figure shows that for a constant heat capacity, the thermal mass effect increases as the mass density is increased and the mass thickness is decreased. A thinner, more dense layer of mass can respond more quickly to surface temperature fluctuations and consequently will store excess heat gains and dampen interior air temperatures more effectively. For this reason, brick, with a higher density and conductivity, is more effective per unit of heat capacity than average concrete block.

Insulation Location

The location of the insulation relative to the mass layer affects both the time lag of the heat flux through a wall and the ability of the wall mass to dampen interior temperature swings. We studied this phenomenon by simulating three wall configurations (Figures 2a-2c), with insulation either inside or outside of the mass or with the insulation and mass well mixed. The total wall U-value was held constant at 0.20 Btu/h·ft^2·F (1.13 W/m^2 C) and the heat capacity of the mass layer was varied from 5.0 to 15.0 Btu/ft^2·F (102 to 306 kJ/m^2 C) by changing the thickness of the mass. In the two multiple layered walls, the mass conductivity was 0.50 Btu/h·ft·F (0.86 W/m C) and in the homogeneous wall the conductivity varied with the wall thickness in order to hold the U-value constant.

Figure 6 shows typical results. The wall with insulation outside always performed better than the wall with insulation inside of the mass. The savings in heating load for the integral insulation case was normally greater than either of the other wall types and the cooling load savings was normally between the performance of the other walls. However, the relative performance of the three wall types changed slightly with climate, building design and total wall U-value. In general, if the wall mass is exposed directly to the interior space it will be more effective in dampening interior temperature fluctuations and in reducing both heating and cooling loads. For this reason, many commonly built masonry walls that are furred out (with gypsum board and a narrow airspace or insulation) on the interior surface do not make the most effective use of the available wall heat capacity.

Wall U-Value

We conducted a sensitivity analysis for several wall configurations in which the mass layer was held constant while the U-value of the insulation layer was varied. Several representative cases -- 0.67 ft (0.20 m) light, medium and heavy weight mass -- with insulation outside of the mass are shown in Figure 7.

For both heating and cooling, the thermal mass effect is diminished as the U-value of the wall decreases. Further, the effect of thermal mass is nearly linear with the wall U-value. It should be noted that in average residential buildings, the total heating load is usually more sensitive to changes in wall U-value than to changes in the amount of thermal mass. However, total cooling load can often be impacted more by the addition of thermal mass than by wall insulation. Although the magnitude of these results will change with building design, the importance of thermal mass in cooling dominated climates is clearly shown.

Regression Analysis

By analyzing the thermal mass effect for a small number of wall configurations in 45 base locations, we were able to reduce to 12 the number of locations (shown in Table 1) for the set of extensive mass wall parametric simulations. We then developed a data base of mass wall performance from DOE-2.1C simulations of 51 wall configurations (shown in Table 2) in each of the 12 climate zones. We reduced the large number of possible combinations of wall characteristics by making the following simplifying assumptions:

- Mass Conductivity
  Although the conductivity of the wall mass can have a significant impact on the thermal mass effect, we simplified the regression equations by holding the conductivity constant at 0.50 Btu/h·ft·F (0.86 W/m C), which is representative of concrete block used in residential construction (ASHRAE 1985).
- Mass Density and Thickness
  We allowed the density and thickness of the wall mass to vary within the full range found in typical residential construction. We then averaged the variation of the resulting thermal mass effect with the least squares regression procedure.
- Insulation Location
  We did the regression analysis separately for each of the three wall types, thus accounting explicitly for variation due to insulation location.
- Wall U-value
  We assumed that the first order effect of wall U-value could be represented by a simple linear function. The interaction of the effects of U-value and heat capacity are accounted for in the regression model equation.

These assumptions allowed us to reduce the number of independent variables to wall U-value, mass heat capacity, insulation location, and climate. We regressed the heating and cooling load savings against wall U-value and mass heat capacity using the following model equation:

$$\phi = e^{(\beta_0 \, * \, HC)} \tag{3}$$

$$\Delta Q = \beta_1 + \beta_2\,\phi + \beta_3\,U_T + \beta_4\,\phi\,U_T \tag{4}$$

where:

ΔQ = thermal mass savings (MBtu/yr or GJ/yr)
β_{0-4} = regression coefficients
HC = mass heat capacity (Btu/ft^2·F or kJ/m^2 C)
U_T = total wall U-value (Btu/h·ft^2·F or W/m^2 C)

The model accounts for the exponential decay effect of wall mass heat capacity, the linear effect of wall U-value, and the interaction between these two effects. We developed separate regression coefficients to account for the location of insulation in the wall (inside or outside the mass, or insulation and mass well mixed) and the effects of climate in each of the 12 locations. As shown in Figures 8a and 8b, this regression equation accurately interpolates between the results of the DOE-2.1C simulations. We used the regression coefficients, given in Table 3, to develop tables of mass wall performance indexes to be used with the slide rule. The same coefficients have since been implemented in the Program for Energy Analysis of Residences (PEAR), a microcomputer analysis and design tool (Ritschard et al. 1985). The result is a set of simple equations that enable a designer to quickly evaluate the average impact of thermal mass for a wide variety of commonly built exterior walls in typical houses.

INTERACTIONS WITH BUILDING DESIGN PARAMETERS

The ability of thermal mass to reduce heating and cooling loads depends not only on the climate and the wall type, but also on the design of the building itself. In particular, any design feature that affects solar gain or the natural ventilation rate is likely to affect the load savings due to thermal mass. Other design parameters that can have an effect include the amount of internal mass (e.g., furniture, walls, appliances, etc.), the thermal integrity of the building, the building operating conditions (e.g., thermostat setting, night setback, etc.) and the schedule of occupancy. In developing the slide rule, we attempted to analyze typical building designs and operating conditions to quantify the thermal mass effect in typical cases. Our current research extends the earlier work by analyzing the impact of changes in the prototypical building design and the interaction of those changes with the thermal mass effect and the resulting level of human comfort.

Solar Gain

As the amount of solar gain in a building changes due to different window areas, glazing types, draperies or external shading devices, the thermal mass effect is also likely to change, due to the ability of mass to store excess solar heat gain. To quantify this interaction effect, we performed a parametric series of simulations in several climates by varying the window shading coefficient as well as the amount of mass in the exterior walls.

A typical case -- a total wall U-value of 0.20 Btu/h·ft^2·F (1.13 W/m^2 C), insulated on the outside and with a mass conductivity of 0.50 Btu/h·ft·F (0.86 W/m C) -- is shown in Figures 9a and 9b. The cooling load savings due to 0.67 ft (0.20 m) of thermal mass increases 40% from 4.13 MBtu/yr (4.36 GJ/yr) to 5.78 MBtu/yr (6.10 GJ/yr) as the shading coefficient increases from 0.4 to 1.0. As the amount of mass decreases, the impact of solar gain also decreases, but there continues to be an interactive effect even for low heat capacity walls. Figure 10 shows the thermal mass effect on a monthly basis for a 0.67 ft (0.20 m) massive wall. The shaded area represents the difference between a shading coefficient of 1.0 and 0.4. We found the thermal mass effect to be much larger during the months when the outside air temperature fluctuates about the building balance point temperature. During those months, the case with a higher shading coefficient shows a significantly greater savings.

The prototype building used for this study is modeled with typical exterior shading devices (roof overhangs and adjacent buildings). In a building designed specifically to maximize the beneficial effects of mass and solar gain, the shading systems would be optimized and the level of interaction would likely be larger than that shown here. The impact of solar gain on the thermal mass effect changes with climate as well as wall type, necessitating a careful balancing of window sizing, glazing type and shading system with the amount of mass exposed to the building interior.

Natural Ventilation Rate

In typical tract homes with average window areas and shading systems, the addition of thermal mass frequently reduces the cooling load more than the heating load. Two processes act simultaneously to reduce the cooling load as the amount of thermal mass is increased. First, increasing the heat capacity of a wall increases the time lag of the heat flux through the wall. This acts to delay conduction heat gains until hours when ventilation is more likely to be able to exhaust the load. It also causes some of the heat gain to be transmitted back to the outside as the ambient temperature decreases. Second, excess internal and solar heat gains are temporarily stored in the mass and then vented to the exterior when ambient conditions permit. Both of these processes depend on the air change rate used for ventilation. As the ventilation rate increases, more excess heat gain can be exhausted, making the thermal mass more effective in reducing the cooling load.

The rate of wind induced natural ventilation can be modified by changing the orientation and area of openings such as windows and doors and by modifying the building shape with architectural features such as wing walls and overhangs. We ran a parametric series of simulations with DOE-2.1C to examine the potential cooling load savings due to natural ventilation and the interaction of that effect with the savings due to thermal mass. We varied the ventilation rate from 0 to 20 air changes per hour and the heat capacity of the exterior walls from 5.0 to 15.0 $Btu/ft^2 \cdot F$ (102 to 306 kJ/m^2 C) with insulation outside of the mass and a total wall U-value of 0.20 $Btu/h \cdot ft^2 \cdot F$ (1.13 W/m^2 C).

The results for Phoenix, AZ, shown in Figure 11, indicate a cooling load reduction due to thermal mass even with no ventilation and a significantly higher thermal mass effect as the ventilation rate is increased. The effects of both ventilation rate and wall heat capacity decay exponentially as the parameter is increased. The effects on heating load are not shown as the effects of properly controlled natural ventilation on heating load are insignificant. These effects will change with building design and climate, but the importance of both thermal mass and natural ventilation rate on residential cooling load is clear. As in the case of solar gain, a well designed building will properly balance the effects of both natural ventilation and thermal mass to achieve maximum benefit from both.

CONCLUSIONS

We have shown the heating and cooling load reduction due to thermal mass in exterior walls to be a result of a complex set of interactions between the amount and physical properties of the mass, the location and amount of insulation in the wall and building design features that affect solar gain and natural ventilation rate. We developed an extensive data base of DOE-2.1C simulations of the ranch house prototype and then reduced the results to a set of regression equations that account for changes in mass thickness and density and wall U-value for three wall insulation locations in 12 climates. The load savings for two wall types in 12 locations are shown in Table 4. The results are an indication of the average thermal mass effect in typical houses.

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Table 1.
Locations of Thermal Mass Parametric Simulations

Location	HDD Base 65 F	HDD Base 18 C	CDD Base 65 F	CDD Base 18 C
Atlanta, GA	3095	1719	1589	883
Brownsville, TX	650	361	3874	2152
Buffalo, NY	6927	3848	437	243
Cincinnati, OH	5070	2817	1080	600
Denver, CO	6016	3342	625	347
Los Angeles, CA	1819	1011	615	342
Medford, OR	4930	2739	562	312
Miami, FL	206	114	4038	2243
Phoenix, AZ	1552	862	3508	1949
San Diego, CA	1507	837	722	401
San Francisco, CA	3042	1690	108	60
Seattle, WA	5185	2881	129	72

Table 2.
Wall Characteristics Used in Parametric Simulations

Wall Characteristic	Wall Type: Mass Wall with Insulation Outside	Mass Wall with Insulation Inside	Mass Wall with Integral Insulation	Light-Weight Wood-Frame
Mass Conductivity				
Btu/h·ft·F	0.50	0.50	0.03,0.05,0.07	-
			0.10,0.13	-
W/m C	0.86	0.86	0.05,0.09,0.12	-
			0.17,0.22	-
Mass Thickness				
ft	0.33,0.50,0.67	0.33,0.50,0.67	0.33,0.50,0.67	-
m	0.10,0.15,0.20	0.10,0.50,0.20	0.10,0.15,0.20	-
Mass Density				
lb/ft^3	50,75,100	50,75,100	50,75,100	-
kg/m^3	800,1200,1600	800,1200,1600	800,1200,1600	-
Mass Specific Heat				
Btu/lb·F	0.20	0.20	0.20	-
kJ/kg C	0.84	0.84	0.84	-
Wall U-Value				
Btu/h·ft^2·F	0.05,0.20	0.05,0.20	0.05,0.10	0.05,0.10,0.20
W/m^2 C	0.28,1.13	0.28,1.13	0.28,0.57	0.28,0.57,1.13

Table 3a.
Delta Load Regression Coefficients (I-P Units)

	β_0	β_1	β_2	β_3	β_4
Atlanta, GA					
O Cooling	-0.31033170	1.98560154	-1.01026225	14.41404343	-29.63875771
O Heating	-0.16856453	0.30816579	-0.39358902	3.92055178	-6.12171364
I Cooling	-0.17361312	-0.64337611	1.14777040	19.47826958	-27.13255310
I Heating	-0.09658411	-0.07908358	0.16546948	6.64464235	-8.16489750
M Cooling	-0.29143831	0.37657726	1.20341718	20.03146362	-42.51749039
M Heating	-0.14415453	0.41500840	-0.27052307	5.52224779	-5.57048845
Brownsville, TX					
O Cooling	-0.19282086	2.72659254	-2.50365162	5.50640869	-10.54868698
O Heating	-0.10684901	0.66877317	-0.72056955	4.29262972	-5.60885334
I Cooling	-0.03986632	-0.43693703	0.55389285	15.08236599	-15.57272148
I Heating	-0.06646303	-0.10134790	0.13894524	7.48766804	-8.51593676
M Cooling	-0.12518367	1.01473081	-1.05398750	13.88278484	-16.63009834
M Heating	-0.11157196	0.51145381	-0.44548643	4.08825159	-5.18963957
Buffalo, NY					
O Cooling	-0.25319937	0.86564881	-0.60677916	5.22092962	-9.22351837
O Heating	-0.15597723	0.39356562	-0.47796059	5.72248459	-10.63172245
I Cooling	-0.13625047	-0.27593467	0.47430557	8.10883713	-10.71153069
I Heating	-0.04361864	-0.17218265	0.22908160	10.41266823	-11.59384827
M Cooling	-0.24513686	0.20182616	0.27681655	7.46171236	-14.34758854
M Heating	-0.05786215	0.47754827	-0.53525257	13.34937859	-9.65328598
Cincinnati, OH					
O Cooling	-0.26564309	1.81593859	-1.16619873	11.63267326	-21.93136406
O Heating	-0.15218517	0.25163874	-0.41165686	4.20144129	-7.22594023
I Cooling	-0.16505212	-0.60325122	1.08083475	16.61412621	-23.72812843
I Heating	-0.07695776	-0.08061322	0.12568545	5.68816757	-6.56403930
M Cooling	-0.24102692	0.33290505	0.78830659	17.20302963	-32.29616165
M Heating	-0.07325753	0.24936835	-0.25168762	9.06789398	-6.58984613
Denver, CO					
O Cooling	-0.27836037	1.28018177	-0.54463863	11.74938583	-21.45341682
O Heating	-0.19521606	0.36457345	-0.51844519	6.68187475	-10.50294495
I Cooling	-0.18208922	-0.57391769	1.02465951	15.80735016	-22.47966194
I Heating	-0.11020503	-0.19842374	0.29190937	9.46208477	-11.84701840
M Cooling	-0.27426261	0.16989145	1.09394729	15.86125374	-31.86371040
M Heating	-0.13803351	0.40041184	-0.23829436	10.68175793	-9.58891487
Los Angeles, CA					
O Cooling	-0.25018331	0.32478523	-0.20692101	3.02613902	-3.87581301
O Heating	-0.27050284	0.44646174	-0.20042038	6.94669437	-13.84564686
I Cooling	-0.18214102	-0.15266848	0.24329290	4.01516628	-5.12441778
I Heating	-0.14563049	-0.30322817	0.51252455	11.28443623	-15.35463559
M Cooling	-0.26927316	0.01161079	0.15529487	4.12260962	-6.46043015
M Heating	-0.26194468	0.24154402	0.55916643	8.92164707	-17.64890862

Wall Type O = Mass Wall With Insulation Outside of Mass
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Wall Type M = Mass Wall With Insulation and Mass Well Mixed

Table 3a.
Delta Load Regression Coefficients (I-P Units) cont'd

	β_0	β_1	β_2	β_3	β_4
Medford, OR					
O Cooling	-0.31235337	1.46315753	-0.56911618	15.26815414	-30.02867317
O Heating	-0.21427679	0.46151346	-0.40688482	11.75613976	-19.70692825
I Cooling	-0.19997521	-0.78522438	1.50964141	20.27443886	-30.47970963
I Heating	-0.14285178	-0.39751139	0.75037092	16.02144623	-22.23238683
M Cooling	-0.32368144	0.11819975	2.25913572	20.25464249	-49.27121353
M Heating	-0.20958303	0.35532618	0.77464628	14.87691975	-24.67847252
Miami, FL					
O Cooling	-0.19166204	2.47168994	-2.33949280	6.97748756	-9.40568352
O Heating	-0.14687890	0.17821832	-0.19399278	1.43998659	-2.14092708
I Cooling	-0.23285460	-0.55313832	0.63219172	9.25009346	-13.34974670
I Heating	-0.06767942	-0.05504773	0.07704289	2.89916515	-3.35923093
M Cooling	-0.09437819	0.61620796	-0.42350870	17.67057419	-18.78199005
M Heating	-0.13109516	0.15303041	-0.11791853	1.53641510	-2.20868325
Phoenix, AZ					
O Cooling	-0.25548711	2.19324684	-1.26547158	19.27495384	-32.99242401
O Heating	-0.27271420	0.42256454	-0.21221262	9.36290169	-17.20839119
I Cooling	-0.18983062	-0.99315703	1.69976151	24.59542656	-34.26731873
I Heating	-0.16557455	-0.39192408	0.72540897	13.44741058	-18.43807586
M Cooling	-0.25948146	0.16380972	1.51999617	27.44420624	-47.78850555
M Heating	-0.28524593	0.21967442	1.10688996	11.14248753	-25.16121483
San Diego, CA					
O Cooling	-0.30582818	0.38934463	-0.29491019	3.60768294	-4.99154472
O Heating	-0.26192224	0.43905640	-0.31630176	6.69234324	-11.64267540
I Cooling	-0.19655822	-0.20018288	0.38021469	4.96283960	-7.60612059
I Heating	-0.16391607	-0.26856500	0.47820309	10.03506947	-14.06073881
M Cooling	-0.33723348	0.15623753	0.26372176	4.21565342	-10.72881985
M Heating	-0.26403114	0.21705136	0.41533273	8.26024914	-15.58840752
San Francisco, CA					
O Cooling	-0.30864921	0.16552071	0.00405509	2.57778955	-4.38464928
O Heating	-0.19099370	0.33358997	-0.27059460	4.17903709	-9.14344406
I Cooling	-0.18991084	-0.11967507	0.17740139	3.20604539	-4.14381075
I Heating	-0.12139977	-0.19788454	0.36545214	8.85691643	-12.02775264
M Cooling	-0.28150588	0.05569848	0.13027377	2.91186881	-5.24989605
M Heating	-0.22089767	0.42664668	0.23063689	5.74322939	-9.85311604
Seattle, WA					
O Cooling	-0.24266867	0.44669309	-0.26091349	3.12594604	-5.02568722
O Heating	-0.15296170	0.14933537	-0.36994049	5.51922226	-9.64529324
I Cooling	-0.15875621	-0.13945979	0.28538117	4.63341427	-6.70571375
I Heating	-0.08287608	-0.12169401	0.21666963	7.26270151	-8.90933749
M Cooling	-0.26355827	0.15049157	0.19835152	4.17797518	-9.07191372
M Heating	-0.06911375	0.17817804	0.07409954	11.23699665	-9.81671524

Wall Type O = Mass Wall With Insulation Outside of Mass
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Wall Type M = Mass Wall With Insulation and Mass Well Mixed

Table 3b.
Delta Load Regression Coefficients (SI Units) cont'd

	β_0	β_1	β_2	β_3	β_4
Medford, OR					
O Cooling	-0.01528017	1.54371309	-0.60044944	2.83691644	-5.57951116
O Heating	-0.01048231	0.48692253	-0.42928627	2.18436264	-3.66166758
I Cooling	-0.00978269	-0.82845569	1.59275615	3.76711463	-5.66331624
I Heating	-0.00698824	-0.41939676	0.79168332	2.97688269	-4.13091325
M Cooling	-0.01583433	0.12470736	2.38351464	3.76343631	-9.15489292
M Heating	-0.01025270	0.37488902	0.81729519	2.76422262	-4.58541107
Miami, FL					
O Cooling	-0.00937601	2.60777115	-2.46829581	1.29645979	-1.74763345
O Heating	-0.00718524	0.18803030	-0.20467325	0.26755831	-0.39779735
I Cooling	-0.01139113	-0.58359188	0.66699767	1.71872389	-2.48046445
I Heating	-0.00331084	-0.05807844	0.08128457	0.53868258	-0.62416565
M Cooling	-0.00461693	0.65013391	-0.44682539	3.28330063	-3.48980855
M Heating	-0.00641311	0.16145565	-0.12441065	0.28547531	-0.41038683
Phoenix, AZ					
O Cooling	-0.01249830	2.31399822	-1.33514332	3.58140420	-6.13019418
O Heating	-0.01334104	0.44582924	-0.22389619	1.73968434	-3.19742417
I Cooling	-0.00928642	-1.04783630	1.79334354	4.56998062	-6.36707735
I Heating	-0.00809982	-0.41350186	0.76534706	2.49861097	-3.42590713
M Cooling	-0.01269370	0.17282842	1.60368108	5.09930133	-8.87939643
M Heating	-0.01395409	0.23176882	1.16783082	2.07034230	-4.67510747
San Diego, CA					
O Cooling	-0.01496096	0.41078037	-0.31114677	0.67032951	-0.92745954
O Heating	-0.01281310	0.46322906	-0.33371606	1.24347829	-2.16328024
I Cooling	-0.00961553	-0.21120416	0.40114778	0.92212594	-1.41326367
I Heating	-0.00801869	-0.28335109	0.50453103	1.86457717	-2.61257123
M Cooling	-0.01649729	0.16483934	0.27824122	0.78329414	-1.99348032
M Heating	-0.01291627	0.22900133	0.43819928	1.53480482	-2.89642143
San Francisco, CA					
O Cooling	-0.01509896	0.17463362	0.00427835	0.47896904	-0.81469464
O Heating	-0.00934331	0.35195610	-0.28549245	0.77649063	-1.69890773
I Cooling	-0.00929034	-0.12626390	0.18716840	0.59570283	-0.76994538
I Heating	-0.00593881	-0.20877928	0.38557246	1.64566922	-2.23482990
M Cooling	-0.01377112	0.05876502	0.13744612	0.54104304	-0.97546279
M Heating	-0.01080620	0.45013613	0.24333483	1.06712710	-1.83076918
Seattle, WA					
O Cooling	-0.01187123	0.47128621	-0.27527833	0.58081990	-0.93380338
O Heating	-0.00748281	0.15755717	-0.39030793	1.02550518	-1.79215443
I Cooling	-0.00776627	-0.14713788	0.30109310	0.86091667	-1.24596261
I Heating	-0.00405426	-0.12839399	0.22859859	1.34945428	-1.65540921
M Cooling	-0.01289314	0.15877703	0.20927195	0.77629334	-1.68561697
M Heating	-0.00338101	0.18798780	0.07817917	2.08790254	-1.82400572

Wall Type O = Mass Wall With Insulation Outside of Mass
Wall Type I = Mass Wall With Insulation Inside of Mass
Wall Type M = Mass Wall With Insulation and Mass Well Mixed

Table 3b.
Delta Load Regression Coefficients (SI Units)

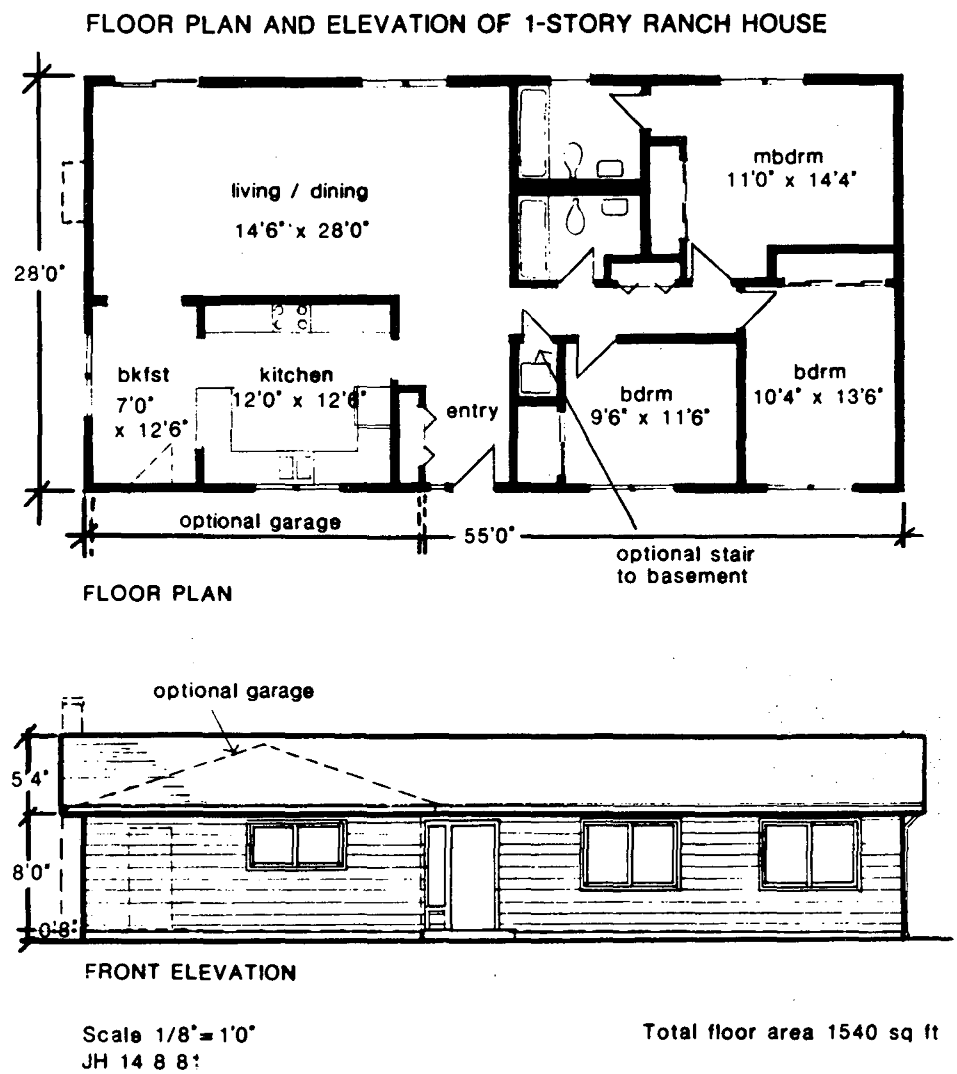
	β_0	β_1	β_2	β_3	β_4
Atlanta, GA					
O Cooling	-0.01518127	2.09492087	-1.06588327	2.67821741	-5.50706243
O Heating	-0.00824609	0.32513216	-0.41525844	0.72846246	-1.13745176
I Cooling	-0.00849306	-0.67879784	1.21096205	3.61918139	-5.04139423
I Heating	-0.00472485	-0.08343760	0.17457956	1.23461520	-1.51708793
M Cooling	-0.01425701	0.39731008	1.26967251	3.72196841	-7.90000963
M Heating	-0.00705197	0.43785709	-0.28541699	1.02606737	-1.03503084
Brownsville, TX					
O Cooling	-0.00943270	2.87670779	-2.64149260	1.02312433	-1.96001052
O Heating	-0.00522700	0.70559311	-0.76024121	0.79759681	-1.04215919
I Cooling	-0.00195024	-0.46099302	0.58438796	2.80239582	-2.89350676
I Heating	-0.00325134	-0.10692771	0.14659500	1.39125442	-1.58231306
M Cooling	-0.00612392	1.07059776	-1.11201584	2.57950615	-3.08997392
M Heating	-0.00545804	0.53961241	-0.47001311	0.75962216	-0.96426672
Buffalo, NY					
O Cooling	-0.01238638	0.91330796	-0.64018595	0.97008061	-1.71378612
O Heating	-0.00763033	0.41523376	-0.50427520	1.06327259	-1.97543895
I Cooling	-0.00666530	-0.29112652	0.50041890	1.50667142	-1.99026787
I Heating	-0.00213380	-0.18166234	0.24169391	1.93473732	-2.15420794
M Cooling	-0.01199197	0.21293789	0.29205695	1.38643169	-2.66586971
M Heating	-0.00283059	0.50384015	-0.56472141	2.48039603	-1.79363954
Cincinnati, OH					
O Cooling	-0.01299512	1.91591691	-1.23040497	2.16142177	-4.07498168
O Heating	-0.00744482	0.26549295	-0.43432102	0.78065348	-1.34262382
I Cooling	-0.00807427	-0.63646382	1.14034116	3.08700609	-4.40883111
I Heating	-0.00376473	-0.08505145	0.13260520	1.05689632	-1.21963858
M Cooling	-0.01179091	0.35123345	0.83170760	3.19642806	-6.00082397
M Heating	-0.00358372	0.26309758	-0.26554453	1.68487012	-1.22443366
Denver, CO					
O Cooling	-0.01361725	1.35066342	-0.57462424	2.18310761	-3.98617601
O Heating	-0.00954987	0.38464540	-0.54698873	1.24153316	-1.95151138
I Cooling	-0.00890771	-0.60551530	1.08107316	2.93710231	-4.17685842
I Heating	-0.00539117	-0.20934816	0.30798072	1.75811314	-2.20124840
M Cooling	-0.01341679	0.17924498	1.15417563	2.94711780	-5.92047214
M Heating	-0.00675253	0.42245692	-0.25141388	1.98473584	-1.78167903
Los Angeles, CA					
O Cooling	-0.01223884	0.34266660	-0.21831325	0.56227511	-0.72014976
O Heating	-0.01323286	0.47104213	-0.21145472	1.29073822	-2.57260584
I Cooling	-0.00891025	-0.16107379	0.25668761	0.74604243	-0.95214814
I Heating	-0.00712417	-0.31992269	0.54074210	2.09671711	-2.85298514
M Cooling	-0.01317271	0.01225003	0.16384478	0.76600605	-1.20038735
M Heating	-0.01281420	0.25484246	0.58995187	1.65769648	-3.27927517

Wall Type O = Mass Wall With Insulation Outside of Mass
Wall Type I = Mass Wall With Insulation Inside of Mass
Wall Type M = Mass Wall With Insulation and Mass Well Mixed

Table 4.
Total Annual Heating Plus Cooling Load Savings Due to Thermal Mass in the Base Case House with a 0.67 ft (0.20 m) Concrete Block Wall with Insulation Outside of the Mass Layer.

	Wall U-Value			
Location	0.20 Btu/h·ft^2·F	1.13 W/m^2 C	0.05 Btu/h·ft^2·F	0.28 W/m^2 C
	(MBtu/yr)	(GJ/yr)	(MBtu/yr)	(GJ/yr)
Atlanta, GA	5.2	5.5	3.0	3.2
Brownsville, TX	4.4	4.6	3.3	3.5
Buffalo, NY	2.8	3.0	1.5	1.6
Cincinnati, OH	4.4	4.6	2.6	2.7
Denver, CO	4.5	4.7	2.4	2.5
Los Angeles, CA	2.4	2.5	1.2	1.3
Medford, OR	6.3	6.6	3.1	3.3
Miami, FL	3.7	3.9	2.7	2.8
Phoenix, AZ	7.1	7.5	3.8	4.0
San Diego, CA	2.5	2.6	1.3	1.4
San Francisco, CA	1.5	1.6	0.8	0.8
Seattle, WA	1.8	1.9	0.8	0.8

Figure 1: A representative floor plan of the one-story ranch prototype used for the base case simulations.



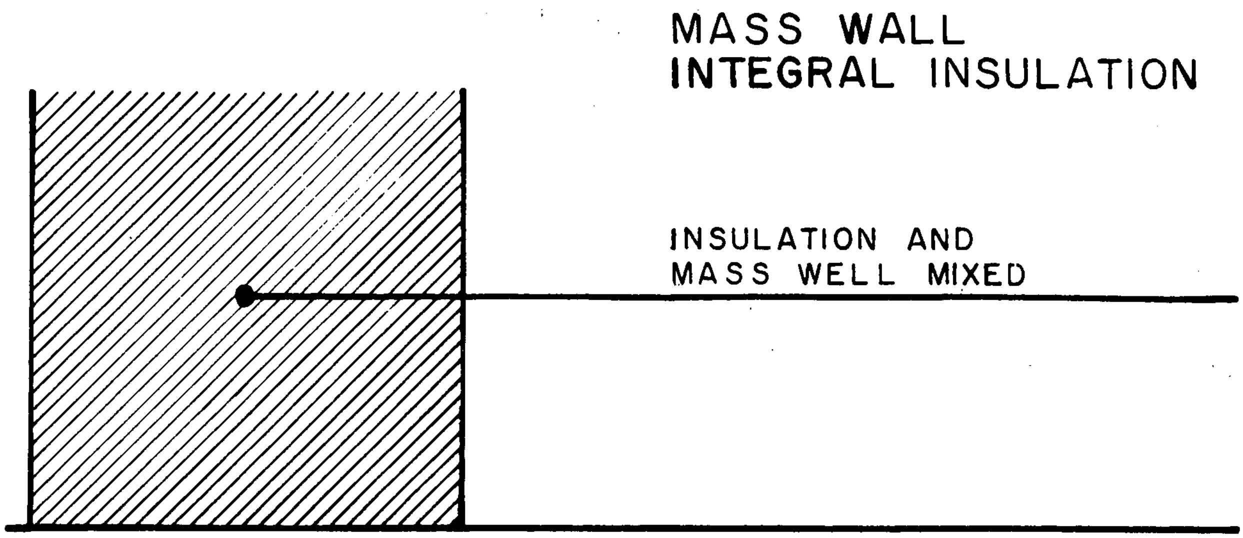


Figure 2a: Massive wall with insulation and mass well mixed.

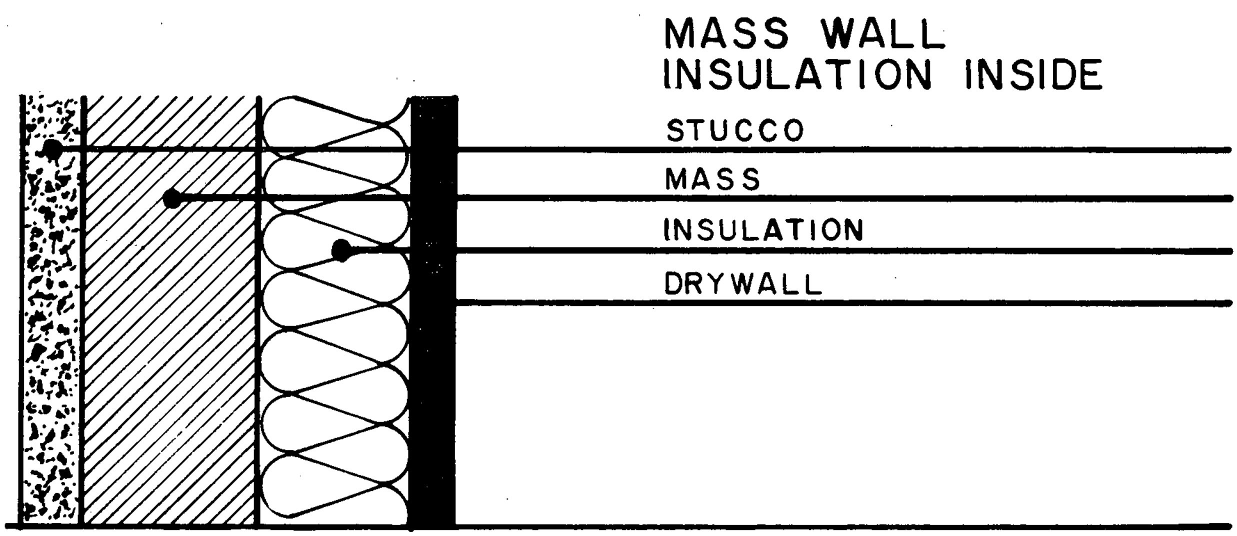


Figure 2b: Massive wall with insulation on the outside of the mass layer.

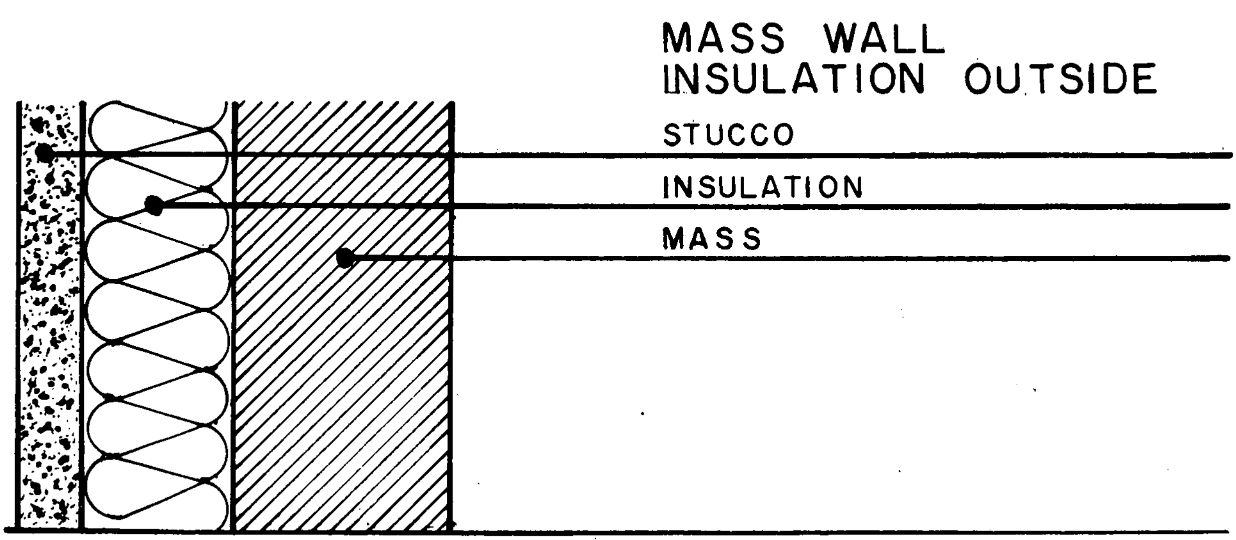


Figure 2c: Massive wall with insulation on the inside of the mass layer.

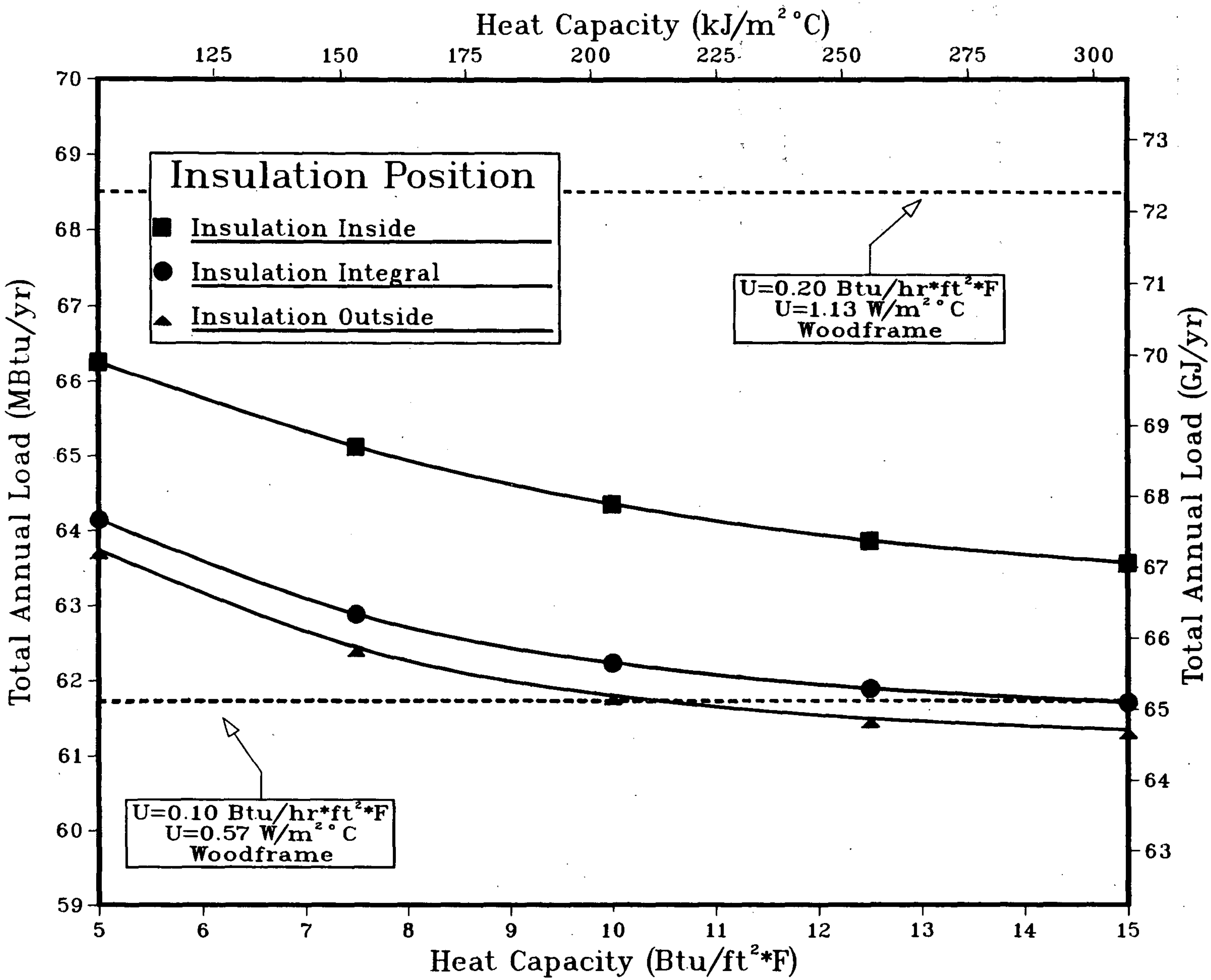


Figure 3: Total annual heating load (Phoenix, AZ) as a function of mass heat capacity for three wall types.

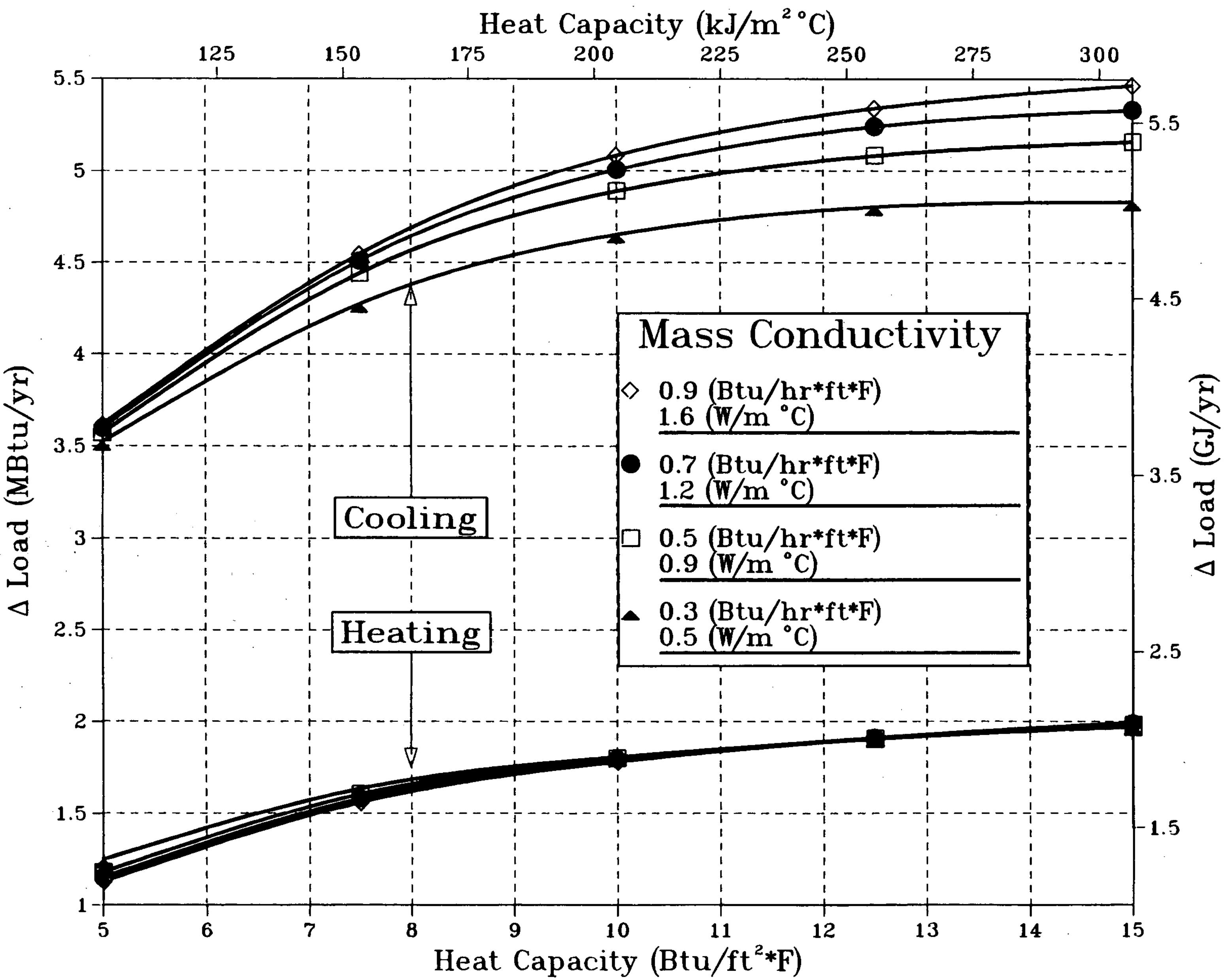


Figure 4: Annual delta heating and cooling loads (Phoenix, AZ) as a function of mass heat capacity for walls with four levels of mass conductivity and with insulation outside of the mass layer.

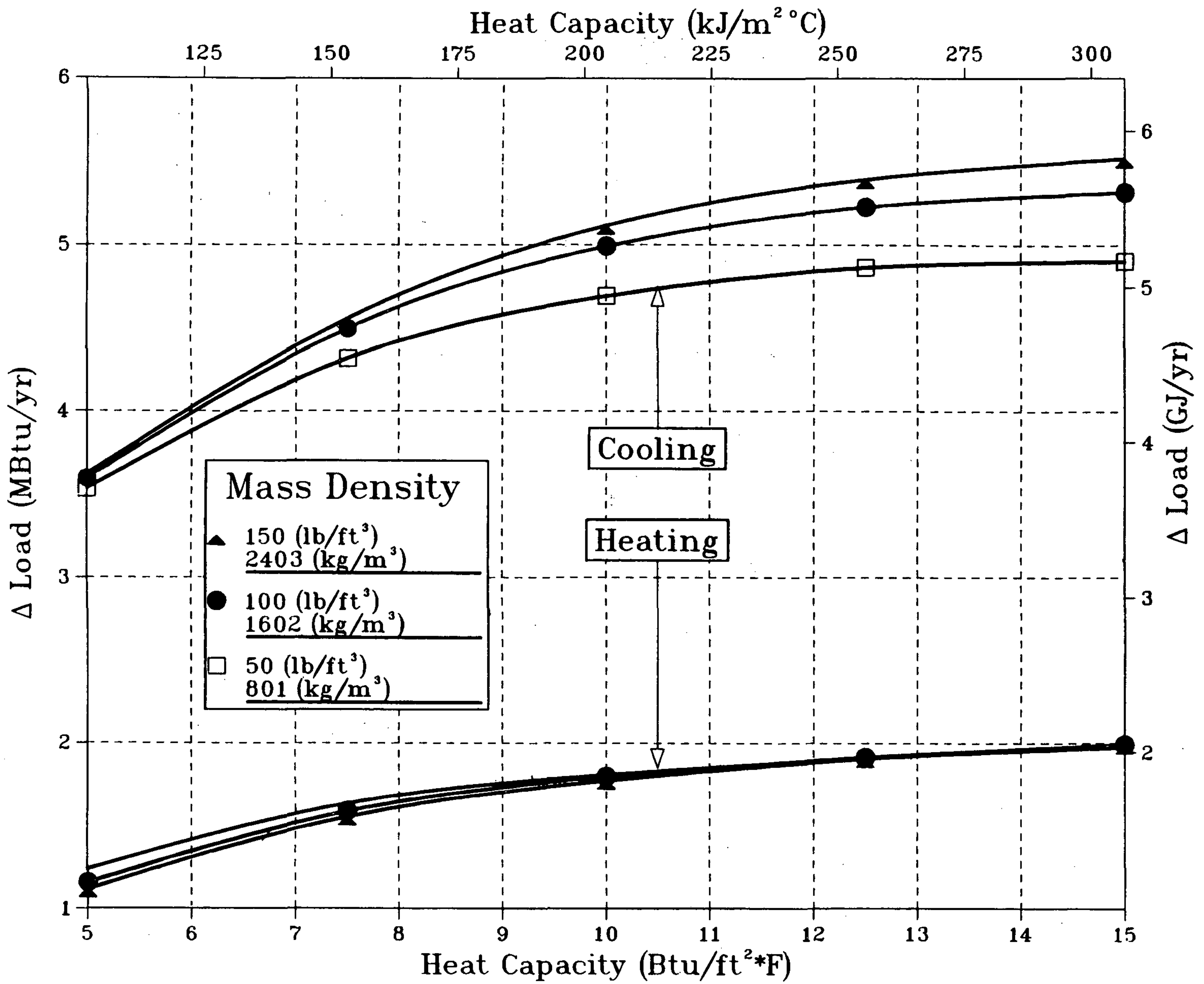


Figure 5: Annual delta heating and cooling loads (Phoenix, AZ) as a function of mass heat capacity for walls with three levels of mass density and with insulation outside of the mass layer.

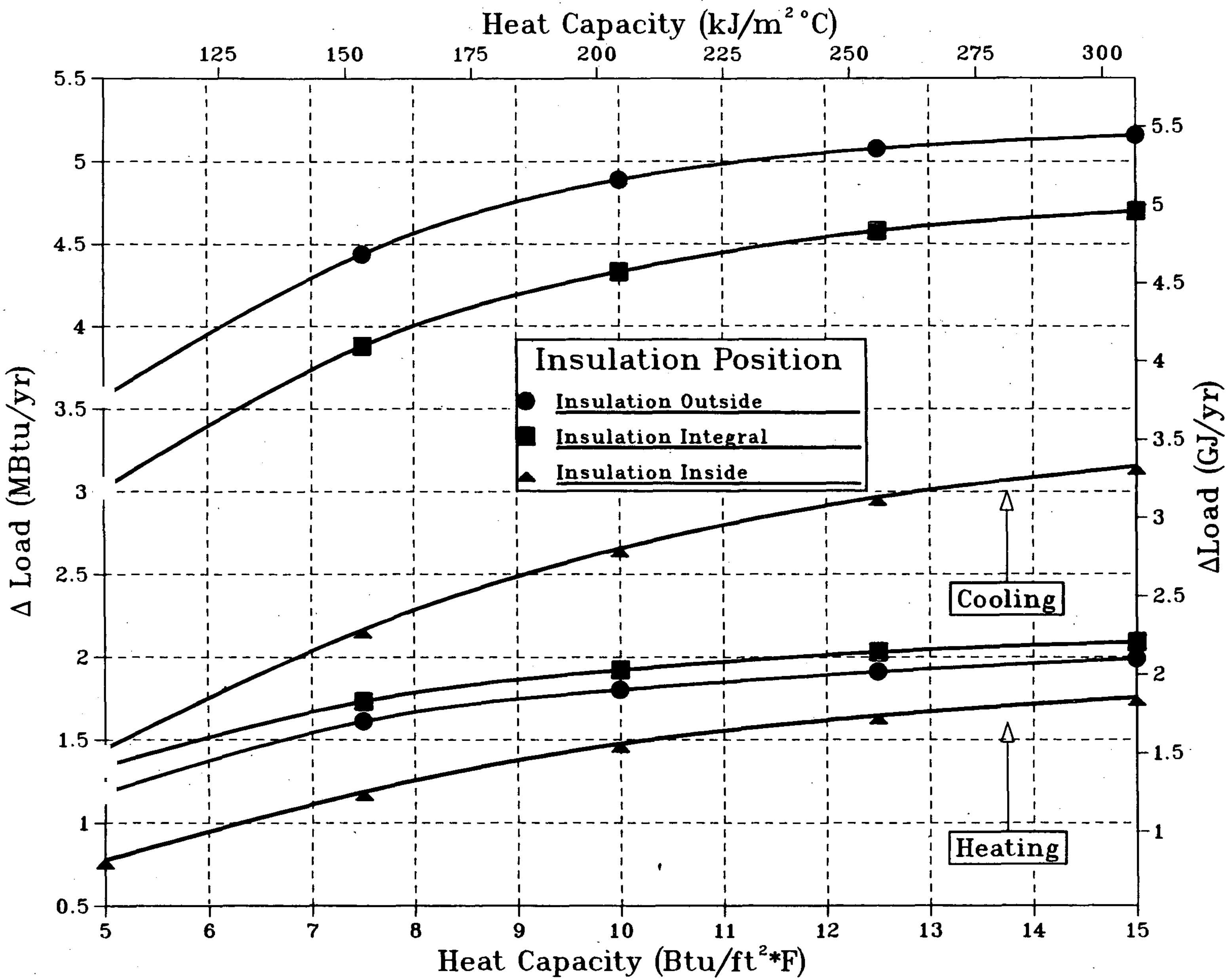


Figure 6: Annual delta heating and cooling loads (Phoenix, AZ) as a function of mass heat capacity for three wall insulation locations.

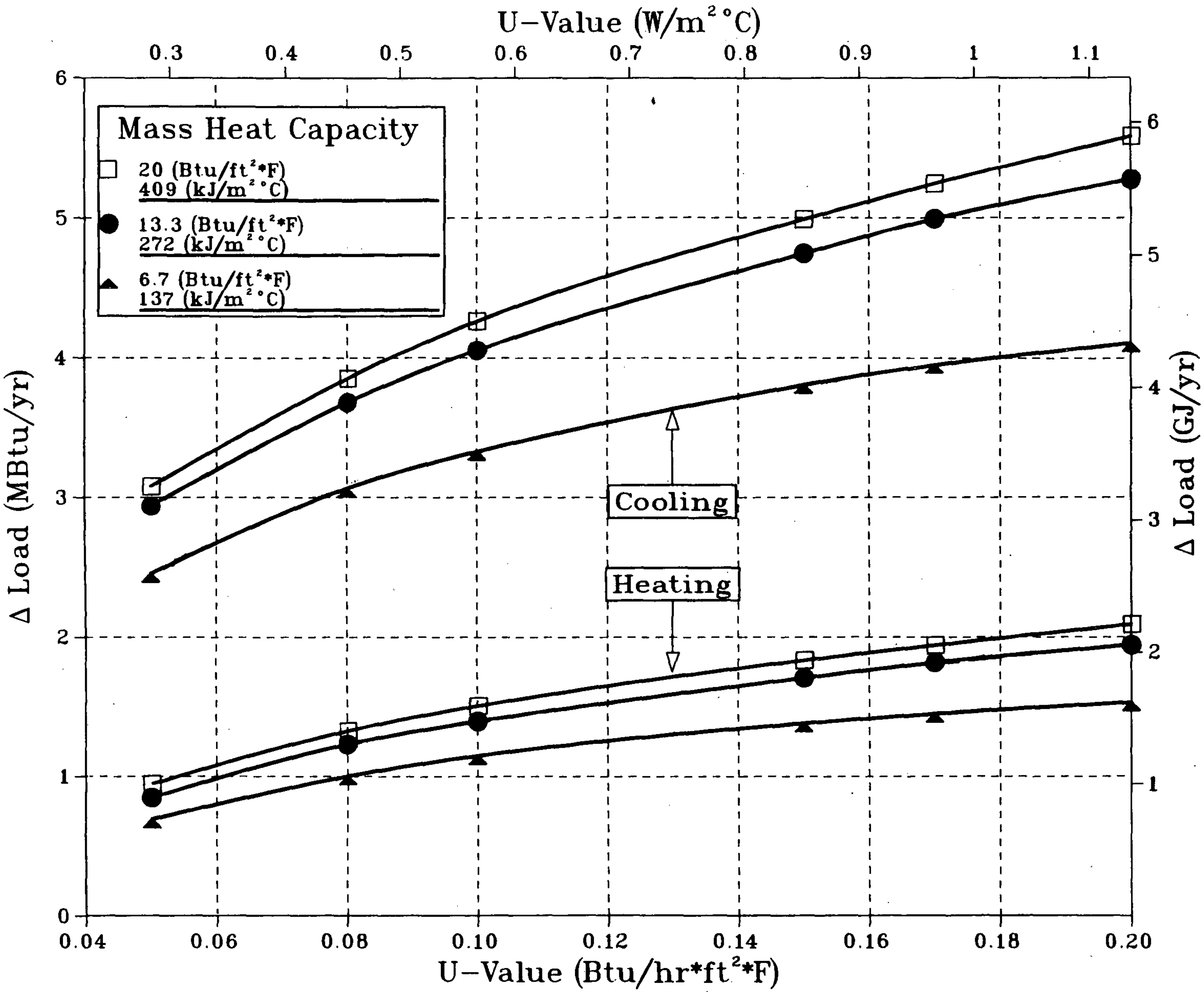


Figure 7: Annual delta heating and cooling loads (Phoenix, AZ) as a function of wall U-value for walls with three levels of mass heat capacity and with insulation outside of the mass layer.

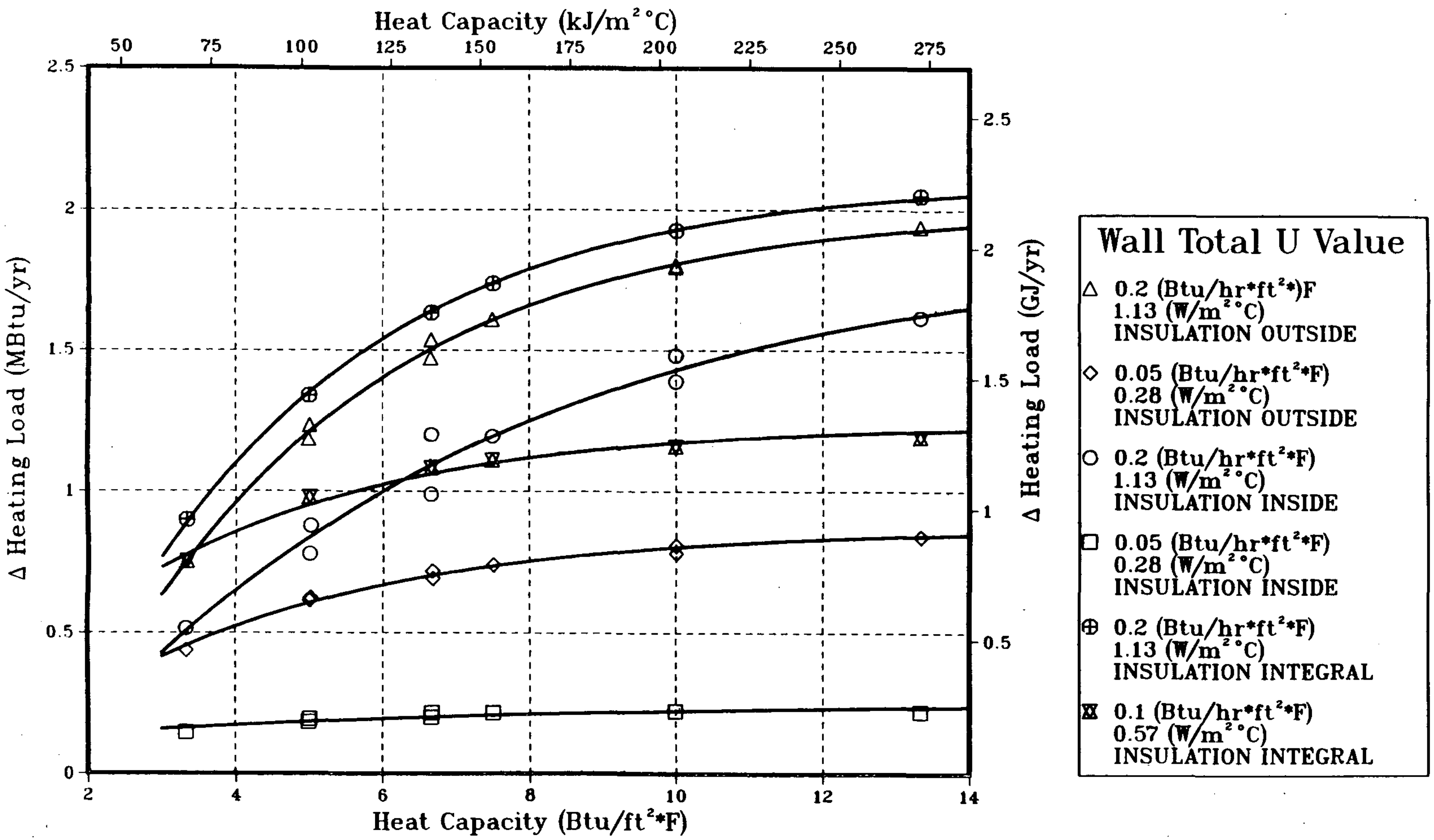


Figure 8a: Annual delta heating load (Phoenix, AZ) determined by DOE-2.1C and by regression equations for several wall configurations.

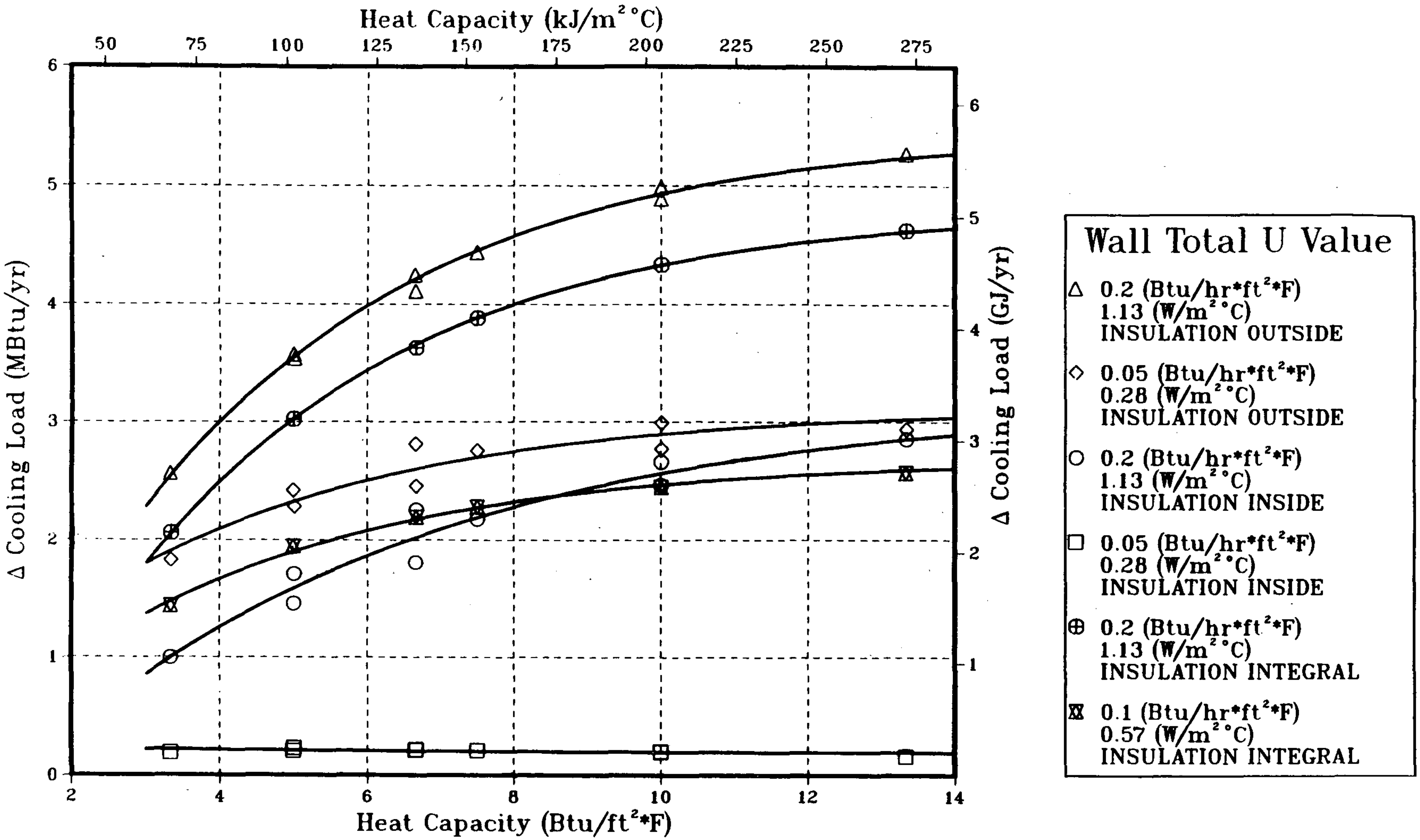


Figure 8b: Annual delta cooling load (Phoenix, AZ) determined by DOE-2.1C and by regression equations for several wall configurations.

Figure 9a: Annual delta heating load (Phoenix, AZ) as a function of mass heat capacity and window shading coefficient for walls with insulation outside of the mass layer.

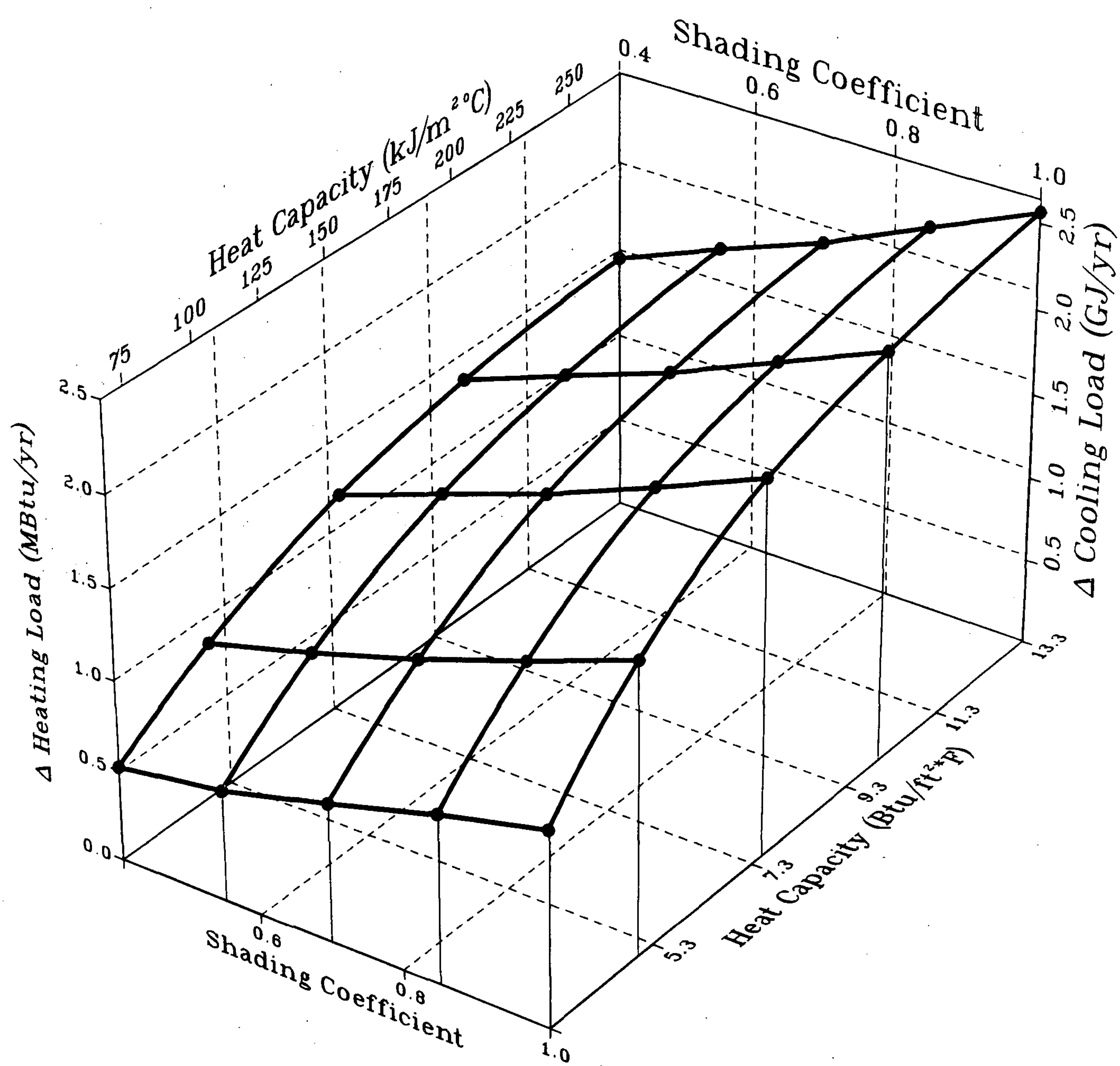


Figure 9b: Annual delta cooling load (Phoenix, AZ) as a function of mass heat capacity and window shading coefficient for walls with insulation outside of the mass layer.

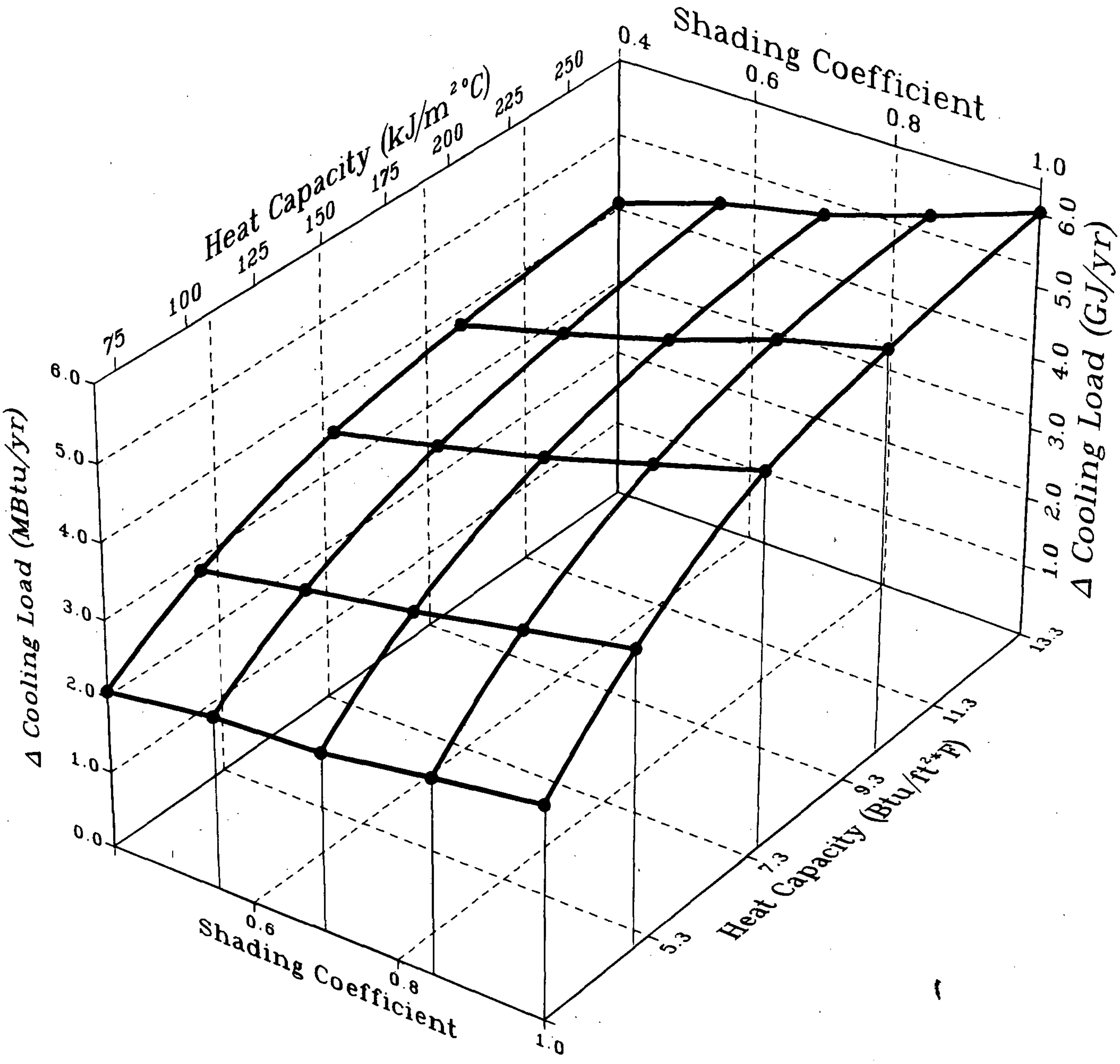


Figure 10: Monthly delta heating and cooling loads (Phoenix, AZ) as a function of window shading coefficient for a mass wall with insulation outside of the mass layer.

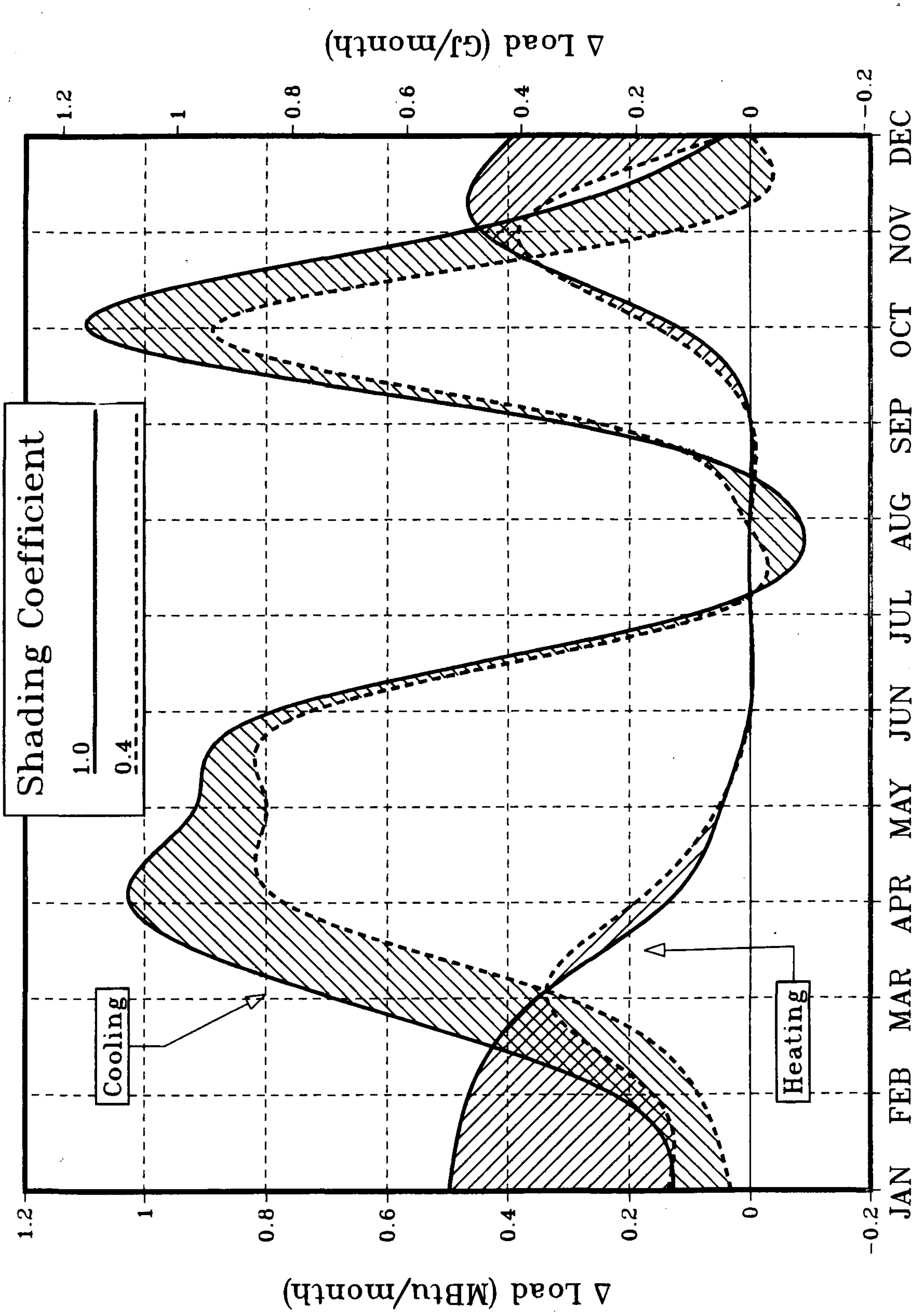
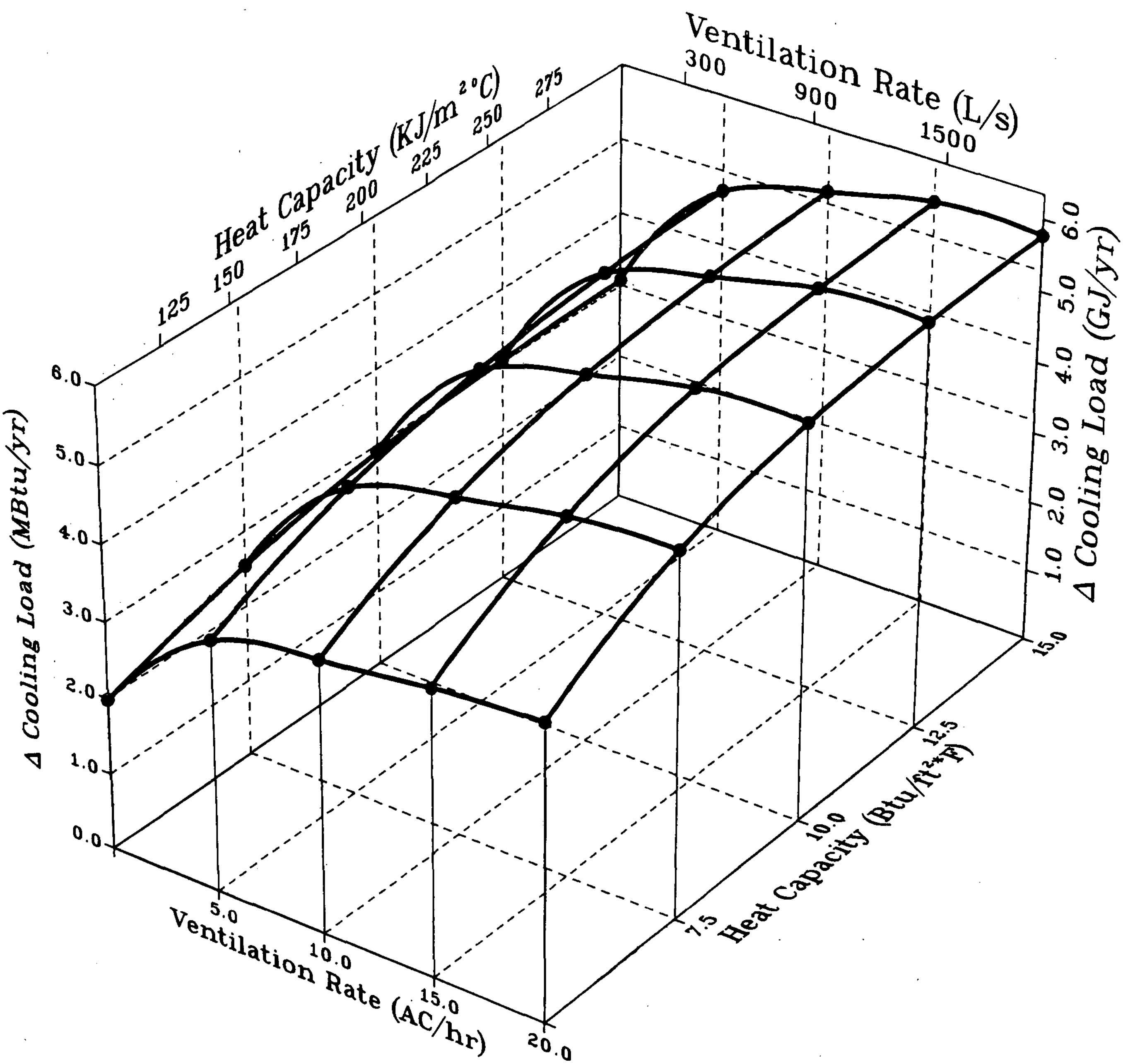


Figure 11: Annual delta cooling load (Phoenix, AZ) as a function of mass heat capacity and building ventilation rate for walls with insualtion outside of the mass layer.



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