Session II No. 2

Effect of Relative Placement of Thermal Mass and Insulation on Building Energy Use

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ABSTRACT

The purpose of this investigation was to determine how mass and insulation interact in building walls and roofs and what effect the relative placement of mass and insulation has on heat losses and gains through the structure. Consideration was given to three wall configurations:

1. Two-layer wall: concrete and insulation and reverse
2. Three-layer wall: alternating layers of concrete and insulation
3. Four-layer wall: alternating layers of concrete and insulation.

Outdoor temperatures and solar flux rates were altered to determine their effects.

Results show that three-layer walls with mass between two layers of insulation are more energy efficient than two- or four-layer constructions. Two-layer walls performed better with insulation on the outside, as was the case with four-layer construction. Altering the relative placement of mass and insulation was found to have a greater effect on cooling loads and energy requirements than on heating needs.

INTRODUCTION

Increased interest in building energy consumption has led to questions concerning the effect of relative placement of mass and insulation on building energy requirements. The greatest area of interest has been wall constructions. Dexter[1] points out that "Exterior walls offer unique opportunities for energy conservation.... The designers have greater control over wall loads than most other loads..." In addition, code-making bodies are paying attention to resistance insulation requirements of walls, without regard to mass effects.

The standard method of wall construction places insulation on the inner surface relative to the more massive portion of the wall. Kusuda[2] and others have suggested that reverse placement might reduce energy loads more effectively than standard construction. It has also been suggested that multiple-layer walls, having alternating layers of mass and insulation might also be more effective than the standard in some cases.

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It was the purpose of this project to determine how mass and insulation interact in building walls* and what effect the relative placement of mass and insulation has on heat losses and gains through the walls. Consideration was given to three wall configurations (Fig. 1):

1. Two-layer wall--mass and insulation
2. Three-layer wall--alternating layers of mass and insulation
3. Four-layer wall--alternating layers of mass and insulation

The study of energy loads in buildings is very complex because of the number of variables that can affect a given building. A complete analysis of the building envelope required that internal heat gains; losses through roofs, floors, and walls; the building operating schedule; yearly weather conditions, etc.; be taken into account.

As a simplification, this project treats walls as isolated structures rather than as a part of the entire building envelope, permitting observation of how wall constructions alone affect heat losses and gains and offering insight into their performance when considered as part of the total building envelope.

Yearly weather data for specific locations were not used in the project. Instead, outdoor temperatures and solar flux rates were altered to show, qualitatively, how particular conditions affect a specific construction.

METHODOLOGY

Closed-form analytical expressions can be developed for transient heat transfer, but they are generally very cumbersome and do not allow nonlinear boundary conditions such as solar radiation. As solar flux is an important parameter in the study of building walls, the use of closed-form analytical expressions is ruled out.

Another approach uses thermal response factors, or conduction transfer functions. This approach has become the standard method of modeling building-wall energy usage.

Although transfer functions are not difficult to work with, their determination is extremely complex. Because the transfer-function set is different for each type of wall, computer routines have been developed to calculate them. Kusuda[3] has developed the most extensive program. His program can be used to determine the transfer-function set for multilayered spheres, cylinders, and slabs. Peavy[4] has, more recently, developed a program for the determination of transfer functions for multilayered slabs only. For work dealing with multilayered slabs, the chief advantage of Peavy's program over Kusuda's is reduced computer time. Peavy's program, with minor modifications, was used as a subroutine for the main program.

With a means of determining heat-conduction rates in a slab available, it is now necessary to add boundary conditions to make the model correspond more closely to an actual building wall. Two types of boundaries are possible with a building wall--convective and radiative.

Convective heat transfer between the slab and the indoor and outdoor ambient conditions can result from natural convection or forced convection (winds). In this project, it was assumed that the indoor and outdoor convection heat-transfer coefficients were constants for any given hour, n. At any time, n, the inner and outer wall surface temperatures are denoted by $\theta_{1,n}$ and $\theta_{2,n}$, respectively. Therefore, the heat transfer rate per unit area from convection for the inner surface can be denoted by

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*Also applicable to ceiling/roof combinations.

$$C_{1,n} = h_i(T_{1,n} - \theta_{1,n}) \tag{1}$$

<u>where</u>

$C_{1,n}$ = heat-transfer rate at inner surface

h_i = inner heat convection coefficient

$T_{1,n}$ = indoor ambient temperature at time n

Similarly, for the outer surface

$$C_{2,n} = h_0(T_{2,n} - \theta_{2,n}) \tag{2}$$

<u>where</u>

$C_{2,n}$ = heat-transfer rate at outer surface

h_0 = outer heat convection coefficient

$T_{2,n}$ = outdoor ambient temperature at time n

In addition to convection, radiation can be included at the boundary surfaces. In this study it was assumed that all radiation striking the wall was absorbed. It was also assumed that the only source of radiation was solar flux on the outer wall surface.

Denoting the solar flux at time n as S_n and adding conduction and convection, the energy balances for indoor and outdoor wall surfaces become

$$C_{1,n} - q_{1,n} = 0 \tag{3}$$

$$S_n + C_{2,n} + q_{2,n} = 0 \tag{4}$$

<u>where</u>

$q_{i,n}$ and $q_{2,n}$ are inner and outer fluxes, respectively, and are determined as

$$q_{1,n} = \sum_{j=0}^{\infty} \theta_{1,n-j}X_j - \sum_{j=0}^{\infty} \theta_{2,n-j}Y_j \tag{5}$$

and

$$q_{2,n} = \sum_{j=0}^{\infty} \theta_{2,n-j}Z_j + \sum_{j=0}^{\infty} \theta_{1,n-j}Y_j \tag{6}$$

with X, Y, and Z the coefficients for the conduction transfer functions. Using the expressions for $q_{1,n}$, $q_{2,n}$, $C_{1,n}$ and $C_{2,n}$ and rearranging results in

$$-(h_i - X_0)\theta_{1,n} + Y_0\theta_{2,n} + h_iT_{1,n} = \sum_{j=1}^{K} \theta_{1,n-j}X_j - \sum_{j=1}^{K}\theta_{2,n-j}Y_j \tag{7}$$

and

$$(-h_0 - Z_0)\theta_{2,n} + Y_0\theta_{1,n} + h_0T_{2,n} = S_n + \sum_{j=1}^{K} \theta_{2,n-j}Z_j - \sum_{j=1}^{K} \theta_{1,n-j}Y_j \tag{8}$$

When solved simultaneously, Eqs 7 and 8 yield the inner and outer wall temperatures at any time, n. Once $\theta_{1,n}$ and $\theta_{2,n}$ have been determined, the flux rates $q_{1,n}$ and $q_{2,n}$ can be readily determined. As the focus of this project is energy usage in buildings, the flux at the inner wall surface, $q_{1,n}$, is the flux of interest.

To determine which flux rates to use, the initial wall temperatures $\theta_{1,n}$ and $\theta_{2,n}$ are needed. Since they are generally not known, the calculations are started with an estimated value several hours in advance of the time for which a solution is required. The further back in time a thermal environment is, the less influence it will have. Therefore, if calculations are started far enough in advance, the initial conditions will have little effect on the solution.

Two general types of exterior load conditions were imposed on the walls studied. These conditions were set up as pulses. The first (Fig. 2a), intended to model cooling load performance, places the exterior temperature below that of the interior during the night. During the day, the outdoor temperature is increased above that of the interior and a solar flux is introduced, allowing observation of how a particular wall responds to a cooling load. This temperature profile was used with flux and temperature pulse durations of 4, 9, and 14 hours. Two magnitudes of solar flux were modeled: 200 Btu/hr·ft^2 (631 W/m^2) and 2000 Btu/hr·ft^2 (6310 W/m^2). The majority of the cases used the 200 Btu/hr·ft^2 (631 W/m^2) flux rate as this value approximates an actual solar load. The 2000 Btu/hr·ft^2 case (6310 W/m^2), although much higher than a solar flux rate, was useful in determining whether altering the flux magnitude would change the optimum mass and insulation placement (i.e., is one construction better in some cases and the reverse construction better for other cases?).

To model heating effects, the same technique was used (Fig. 2b). The temperature pulse magnitude was set at 60°F (15.6°C). Pulse durations of 4 and 9 hours were modeled. A larger duration would not be expected during the winter. A solar flux magnitude of 200 Btu/hr·ft^2 (631 W/m^2) was used.

The exterior load conditions are given to the computer program hourly. For very massive constructions, the program must take load conditions from many previous days into account. Therefore, the program was set up to run a variable number of days, depending on how massive a structure was being modeled. For any number of hours selected, the exterior load conditions followed the profiles shown in Figs. 2a and 2b.

To model thermal mass and insulation, the following typical values were selected: (1) heavy concrete (144 lb/ft^3 [2300 kg/m^3]) and (2) insulation having a thermal conductivity of 0.022 Btu/hr·ft°F (0.037 W/m°C).

Table 1 shows the combinations of wall constructions and environmental conditions modeled. The column titled "placement" indicates the ordering of the mass and insulation layers in the wall. Each wall can have two possible orders. The numbers refer to Fig. 1. For example, a three-layer wall with a placement of "1,2" indicates that both three-layer constructions shown in Fig. 1 were modeled.

RESULTS

Cooling

Two-Layer Wall. In this segment of the study, two-layer walls were modeled to determine the optimum placement of mass and insulation. Figure 3 shows the percentage of improvement for an externally insulated wall relative to an internally insulated wall when both are subjected to a solar-flux magnitude of 200 Btu/hr·ft^2 (631 W/m^2) for 9 hours. In this case, having mass on the outer surface results in a substantial improvement. The insulation thickness has little effect on the results. A peak improvement is observed between 0.4 and 0.5 ft (0.12-0.15 m) of concrete.

Figure 4 shows the effect of increasing the solar flux to 14 hours. Again, the results show better performance for the externally insulated wall. However, the magnitude of the improvement has decreased. Insulation level has virtually no effect on the results. A peak improvement is noted for walls having approximately 0.3 ft (0.09 m) of concrete.

Figure 5 shows the effect of increasing the solar flux magnitude to 2000 Btu/hr·ft^2 (6310 W/m^2) for 9 hours. The externally insulated wall is slightly better than the internally insulated one. Insulation level has little effect. Comparing these results with those in Fig. 3, in which the walls were exposed to solar flux of 200 Btu/hr·ft^2 (631 W/m^2) for 9 hours, indicates that increasing the flux magnitude decreases the relative benefit of the externally insulated wall over the opposite construction.

In general, the results from this section suggest that, for cooling loads, two-layer walls with insulation on the outer surface are most efficient. The actual magnitude of improvement is dependent on weather conditions and mass thickness.

The externally insulated two-layer wall will be used for comparisons in the remainder of this report. Hence, "two-layer wall" will be referring to this construction.

Three-Layer Wall. The three-layer constructions were first compared to one another to determine which placement of mass and insulation was most efficient for cooling loads. The best of the three-layer walls was then used for comparisons with two-layer and four-layer walls.

Figure 6 shows one of the comparisons made of three-layer constructions. The results are for 200 Btu/hr·ft^2 (631 W/m^2) of solar flux for 9 hours. The insulation level is 0.1 ft (0.03 m). The three-layer construction with mass between two insulation layers is more efficient than the opposite construction. This trend was observed in general. Therefore, the three-layer construction with mass sandwiched between two insulation layers was selected for further comparisons with two-layer and four-layer walls. For the remainder of this report, "three-layer wall" will be referring to this construction.

Figure 7 presents results for two levels of insulation. The percentage of improvement of the three-layer over the two-layer construction is considerable. For concrete thicknesses of less than 1.0 ft (0.3 m), the three-layer wall performs substantially better than the two layer type with an increased insulation level.

Results of this section indicate that three-layer constructions with mass between two layers of insulation are, in general, better than two-layer constructions having insulation on the outer surface. The degree of improvement is dependent on weather and amounts of mass and insulation.

Four-Layer Wall. Comparisons were made to determine which ordering of mass and insulation in four-layer walls is most efficient. It was found that the construction having insulation on the outer surface is preferable to the opposite ordering.

Figure 8 shows a comparison of four-layer constructions. The daily flux rate, or cooling load, is less for the construction having insulation on the outer surface. This trend was observed in general. Therefore, the externally insulated four-layer construction was used for comparisons with two-layer and three-layer constructions.

Figure 9 shows the effect of changing the insulation level for walls exposed to solar flux of 200 Btu/hr·ft^2 (631 W/m^2) for 9 hours. The results show the percentage of improvement of the three-layer wall over the four-layer wall. The three-layer wall shows considerable improvement over the four-layer one, especially at the lower mass levels.

From these results, it can be concluded that, in general, three-layer walls are most efficient than four-layer walls for cooling. Again, as in the other cases, the amount of improvement is very dependent on the actual structure and its environment.

In addition, comparisons were made between two-layer and four-layer constructions. It was found that the four-layer construction was more efficient than the two-layer wall. Figure 10 shows the percentage of improvement of the four-layer construction relative to the two-layer type when both are exposed to a solar load of 200 Btu/hr·ft^2 (631 W/m^2) for 9 hours.

Heading

Two-Layer Wall. Figure 11 compares the percentages of improvement of externally and internally insulated two-layer walls. A solar flux of 200 Btu/hr·ft^2 (631 W/m^2) of 9 hours duration is used. Virtually no improvement is shown for the externally insulated wall.

Three-Layer Wall. Two-layer and three-layer constructions exposed to 200 Btu/hr·ft^2 (631 W/m^2) for 9 hours are compared in Fig. 12(a). The figure shows the percentages of improvement of the three-layer and the two-layer constructions. For low levels of mass, the three-layer wall is more efficient. For higher levels of mass, the walls perform equally.

Four-Layer Wall. Figure 12(b) presents the percentages of improvement of the three-layer and four-layer constructions. The figure gives the percentages of improvement for both. For low levels of mass, the three-layer construction is slightly better than the four layer type.

CONCLUSIONS

Based on the results of this project, the following conclusions can be made:

1. A three-layer wall with mass sandwiched between two insulation layers is more efficient than any two-layer or four-layer construction.
2. Two-layer walls are more efficient when insulation is placed on the exterior surface.
3. The relative placements of mass and insulation has a much greater effect on cooling loads than on heating loads.
4. The actual improvement of one construction over another will depend on a number of parameters--mass and insulation thicknesses, weather conditions, etc.
5. A certain thickness of mass often results in a peak improvement of one construction over another.
6. The effects of altering the placement of mass and insulation should be accounted for in a complete building energy analysis.

REFERENCES

1. Michael E. Dexter, "Including Mass and Insulation in Building Walls," ASHRAE Journal 22:3 (March, 1980), p. 35-38.

2. T. Kusuda, "Use of Simulation Models of Buildings in Assessing Energy Conservation Strategies," Energy Conservation Strategies in Buildings, ed. A. J. Stolwijk (John B. Pierce Foundation of Connecticut, Inc., 1978), p. 143-156.

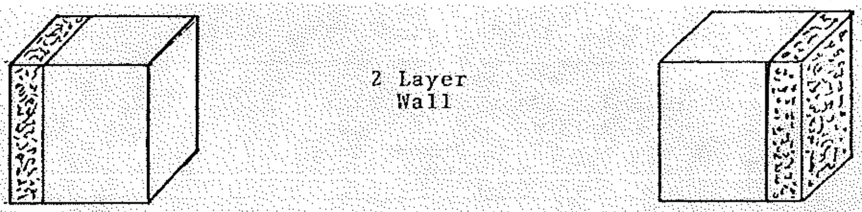
3. T. Kusuda, "NBSLD, The Computer Program for Heating and Cooling Loads in Buildings," NBS Building Science Series 69, (Washington, D.C.: U.S. Government Printing Office, 1976).

4. U.S. National Bureau of Standards, Determination and Verification of Thermal Response Factors for Thermal Conduction Applications, NBSIR 77-1405 by B. A. Peavy (Washington, D.C.: National Bureau of Standards, April 1978).

TABLE 1

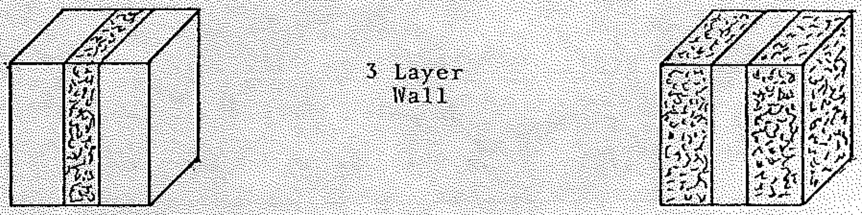
Wall Constructions And Environmental Conditions Modeled

	Layers	Placement	Solar Flux Duration, hr	Solar Flux Magnitude, Btu/hr·ft^2 (W/m^2)	Insulation Level, ft (m)
<u>Cooling</u>					
	2	1, 2	4, 9, 14	200(631)	0.1, 0.3, 0.5 (0.03, 0.09, 0.15)
	2	1, 2	9	2000(6310)	0.1, 0.3, 0.5 (0.03, 0.09, 0.15)
	3	1, 2	4, 9, 14	200(631)	0.1, 0.3, 0.5 (0.03, 0.09, 0.15)
	3	2	9	2000(6310)	0.1, 0.3, 0.5 (0.03, 0.09, 0.15)
	4	1, 2	4, 9, 14	200(631)	0.1, 0.3, 0.5 (0.03, 0.09, 0.15)
	4	2	9	2000(6310)	0.1, 0.3, 0.5 (0.03, 0.09, 0.15)
<u>Heating</u>					
	2	1, 2	4, 9	200(631)	0.1, 0.3, 0.5 (0.03, 0.09, 0.15)
	3	2	4, 9	200(631)	0.1, 0.3, 0.5 (0.03, 0.09, 0.15)
	4	2	4, 9	200(631)	0.1, 0.3, 0.5 (0.03, 0.09, 0.15)



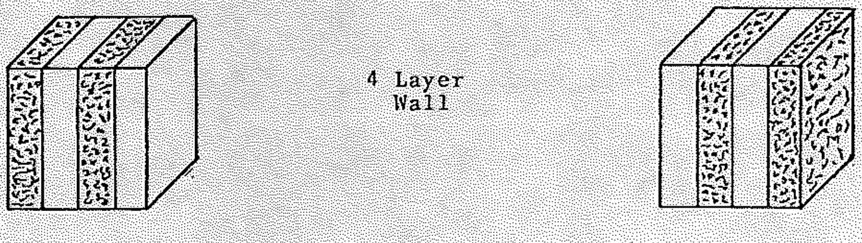
1. Insulation In

2. Insulation Out



1. Insulation In

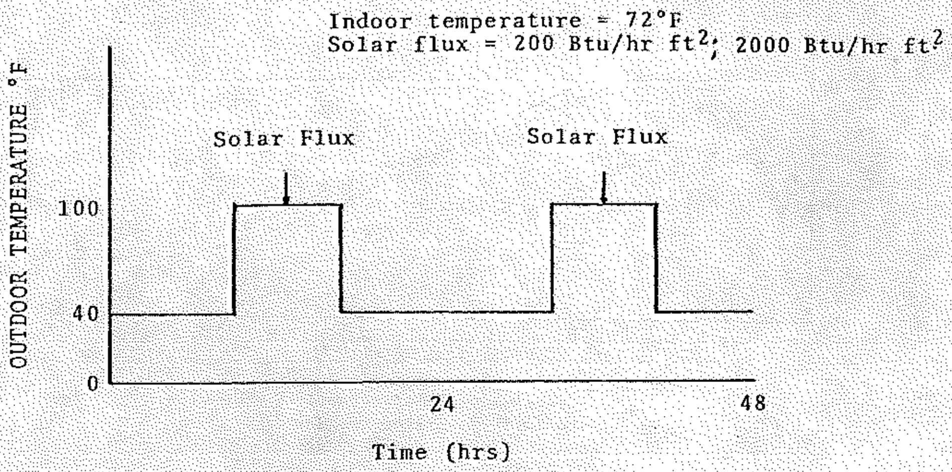
2. Mass In



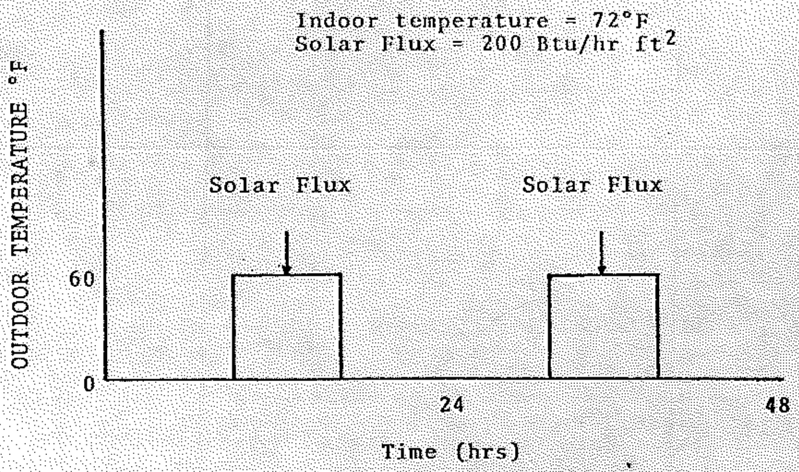
1. Mass Out

2. Insulation Out

Figure 1. Wall configurations modeled



(a) COOLING



(b) HEATING

Figure 2. Exterior load conditions

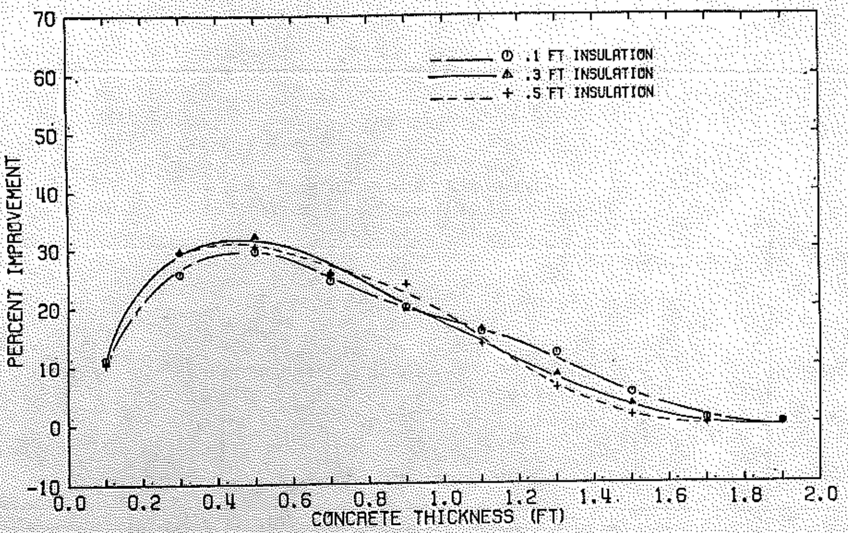


Figure 3. *Percent improvement (cooling) of externally insulated over internally insulated two-layer wall when exposed to 200 Btu/hr·ft^2 for nine hours*

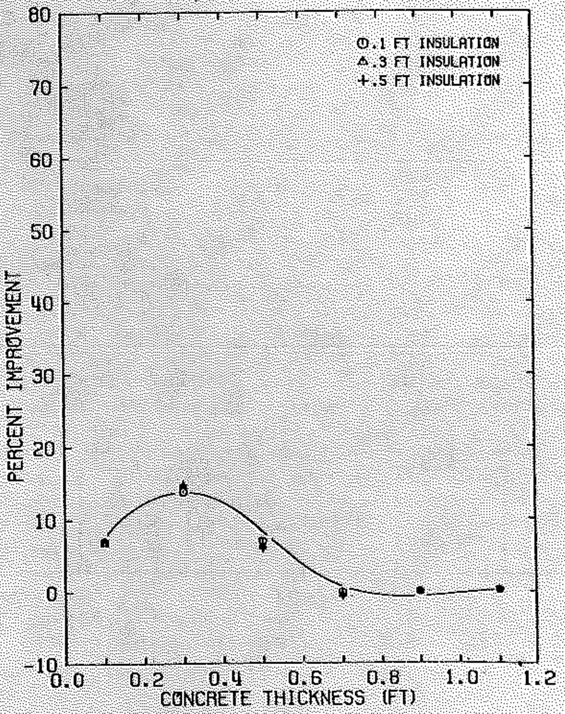


Figure 4. *Percent improvement (cooling) of externally insulated over internally insulated two-layer wall when exposed to 200 Btu/hr·ft^2 for 14 hours*

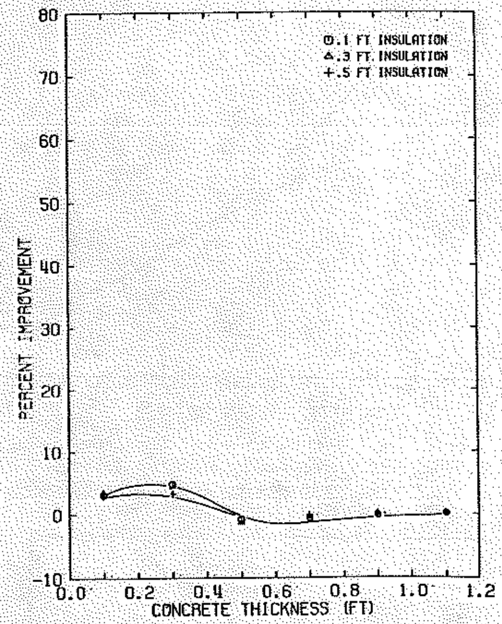


Figure 5. Percent improvement (cooling) of externally insulated over internally insulated two-layer wall when exposed to 200 Btu/hr·ft^2

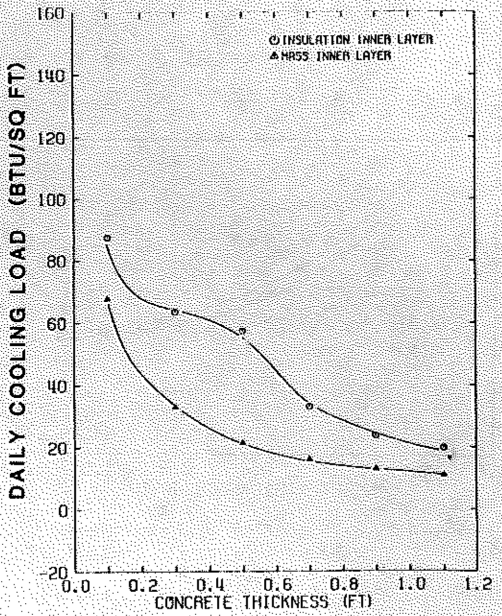


Figure 6. Daily cooling loads for three-layer walls with 0.1-foot insulation exposed to 200 Btu/hr·ft^2 for nine hours

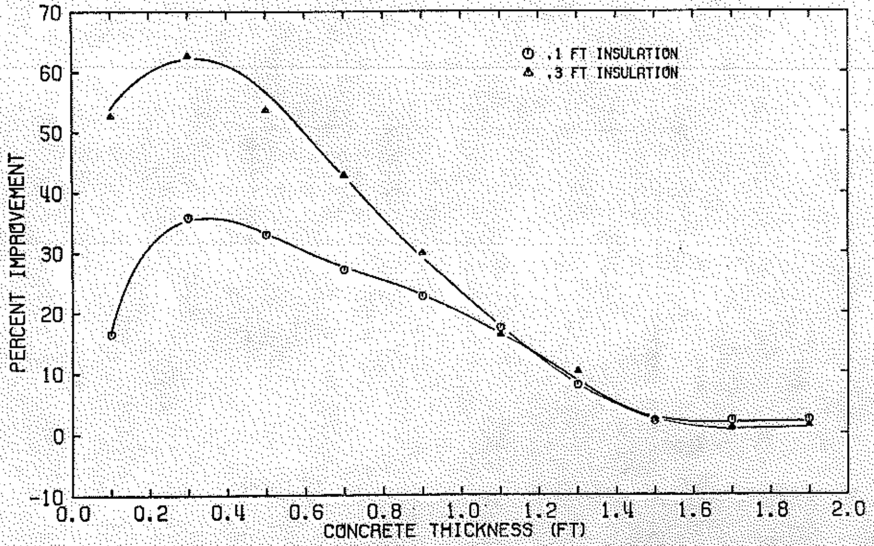


Figure 7. Percent improvement (cooling) of three-layer over two-layer wall exposed to 200 Btu/hr·ft^2 for nine hours

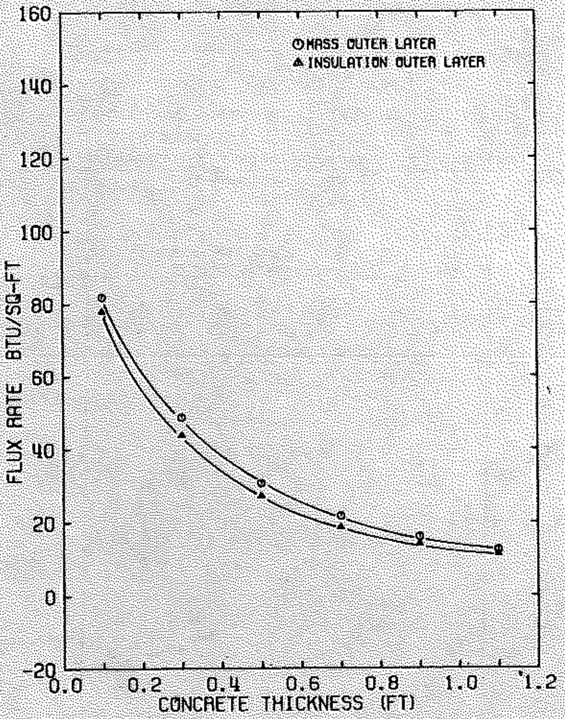


Figure 8. Daily cooling loads for four-layer walls with 0.1 foot of insulation exposed to 200 Btu/hr ft^2 for nine hours

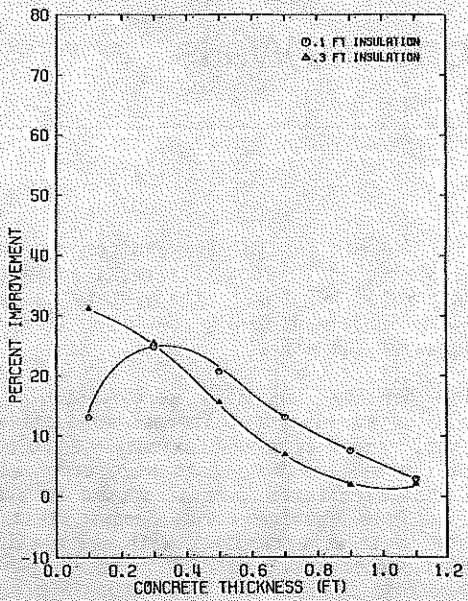


Figure 9. Percent improvement (cooling) of three-layer over four-layer wall when exposed to 200 Btu/hr ft^2 for nine hours

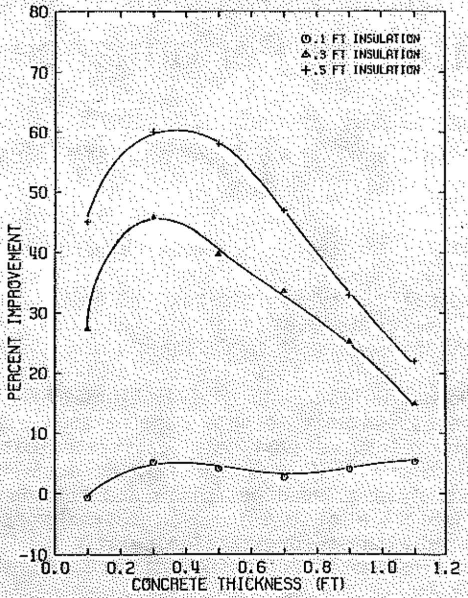


Figure 10. Percent improvement (cooling) of four-layer over two-layer wall when exposed to 200 Btu/hr·ft^2 for nine hours

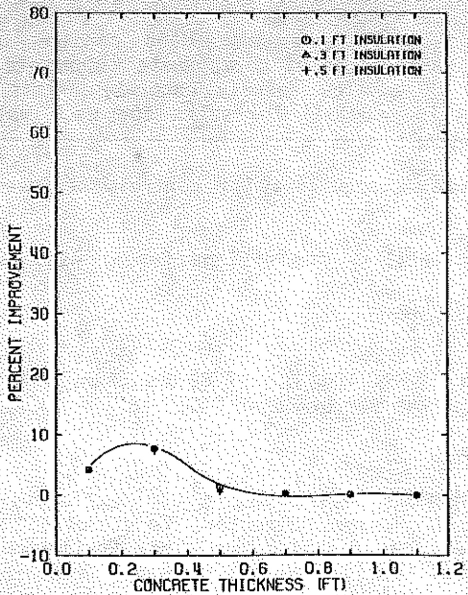


Figure 11. Percent improvement (heating) of a two-layer externally insulated over a two-layer internally insulated wall exposed to 200 Btu/hr·ft^2 for nine hours

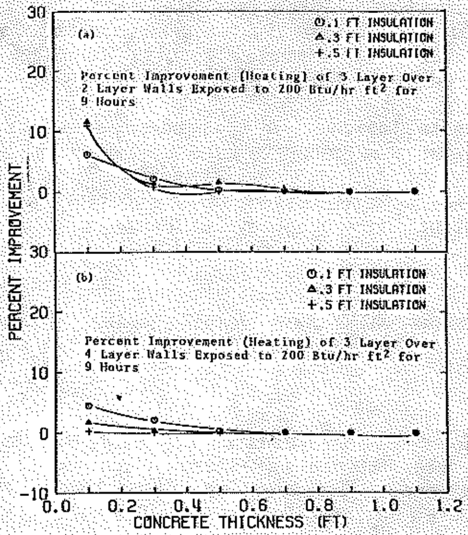


Figure 12. Improvement (heating) of three-layer over both two- and four-layer walls