ECONOMIC CONSIDERATIONS IN INSULATING MASONRY AND WOOD-FRAME WALLS OF SINGLE-FAMILY HOUSING

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ABSTRACT

Maximum economic levels of insulation in masonry walls are expected to be lower than those for wood-frame walls in many parts of the United States for two reasons: (1) insulation costs are significantly higher for masonry walls, and (2) energy savings are somewhat lower because of differences in the dynamic thermal performance of the two wall types. This report examines the impact of both of these factors in determining economically optimal insulation levels for several types of wall construction used in single-family housing, over a wide range of geographic locations. The NBSLD computer program is used to calculate reductions in annual heating and cooling requirements due to several levels of insulation in each of four wall variations examined. Economically optimal insulation levels (based on life-cycle cost analysis) are calculated for a wide range of assumptions related to climate, energy prices, insulation costs, and present worth factors.

Key words: Insulation, building economics, energy conservation, load calculation, mass, exterior walls, building design

INTRODUCTION

Considerable controversy has continued in recent years regarding the superior dynamic thermal performance of masonry walls in buildings relative to lighter construction materials having the same steady-state thermal performance characteristics. It is generally acknowledged that walls built of masonry materials have an advantage over wood-frame construction in terms of dynamic thermal performance because of their ability to dampen the effects of the daily temperature cycle, thus reducing peak heating and cooling loads[1,2]. However, there has been considerably less agreement regarding the effects of mass in reducing actual energy requirements over the course of the heating and cooling seasons[1-6].

As a result, energy conservation standards and guidelines have not generally differentiated between masonry (or other massive building materials) and wood-frame construction in specifying maximum allowable steady-state heat transmission coefficients (U) for walls in new buildings [7,8]. At the same time, representatives of the masonry industry have proposed that such steady-state requirements be modified to reflect equivalent thermal performance measured in a dynamic environment[1].

The purpose of this paper is to shift the focus of this controversy away from the concept of thermal performance, per se, suggesting instead that guidelines and standards for insulating masonry and wood-frame walls in single-family housing be differentiated on the basis of life-cycle-cost performance. Specifically, this paper suggests that the economically optimal level of insulation in masonry walls in many cases is less than that for wood-frame walls. Thus, to require the same level of performance for each wall will result in a suboptimal allocation

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of energy conservation investment. In such cases, the reallocation of this investment to other energy conservation opportunities in buildings (e.g., improved glazing or increased attic insulation) will provide greater energy savings for the same total expenditure.

Economically optimal levels of insulation in masonry walls are likely to be lower than those for wood-frame walls for two distinct reasons:

(1) the cost of insulating masonry walls is often two to three times higher than that of insulating wood-frame walls to equivalent U-values; and

(2) the reduction in annual energy requirements due to an equivalent reduction in the wall U-value is generally somewhat lower for masonry walls than for wood-frame walls, since the dynamic thermal performance of the two wall types is different.

Both of these factors are considered in this paper in order to determine economically optimal levels of insulation for these two basic wall types in new residential construction. In addition, climate factors, current and projected energy costs, discount rates, and expected useful insulation lifetimes are incorporated into the analysis. Based on the analytical results derived herein, an index number method is developed for use by architects, builders, homebuyers, and building researchers in determining the economically optimal level of insulation for four wall construction variations common in new residential construction. This paper does not examine economic factors other than those related to energy conservation that should be considered in the selection of construction materials and techniques to be used.

THERMAL ANALYSIS

A large number of simulations of annual space heating and cooling requirements for a prototypical single-story house were made using the National Bureau of Standards Load Determination Program (NBSLD)[9] and an expanded output version of that program.[10] Hourly climate data for eleven cities were taken from Test Reference Year (TRY) records.

The prototypical house used in these simulations is based on the three-bedroom, 110 m^2 (1176 ft^2) ranch house suggested by Hastings[11]. The outside dimensions measure 12.8 x 8.5 m (42 x 28 ft) with the longer walls facing south and north. Of the 11.8 m^2 (127 ft^2) of glass area, 6.7 m^2 (72 ft^2) face south and the remainder north. The net opaque wall area, excluding the glass area and a 1.9 m^2 (20 ft^2) door, is 90.4 m^2 (973 ft^2). The house was modeled as a single room in order to better simulate the single heating zone of a typical one-story house. However, a well insulated 9070 kg (20,000 lb) concrete floor was modeled in order to represent the thermal storage characteristics of partition walls and furnishings. Air changes average approximately 0.6 per hour during the heating season and approximately 0.5 per hour during cooling periods.

No modifications were made to the prototypical house other than wall construction and wall insulation level for any given climatic region. However, ceilings and windows were insulated in accordance with the 1978 HUD Minimum Property Standards[8] so that the overall building envelope is thermally tighter in the colder climates than in the warmer climates in order to better reflect regional differences in overall thermal design.

The thermostat setting for heating periods was 20°C (68°F) during the day and 15.5 °C (60°F) between 11:00 p.m. and 7:00 a.m. The air-conditioning thermostat setting was 25.5°C (78°F). Between these settings, the inside temperature was allowed to float with no heating or cooling supplied. (Conservative thermostat settings, including night setback, were used in order to estimate the energy savings from insulation that can be expected in a house operated in a reasonably energy conserving manner.) Two adults and two children were assumed to occupy the house. Heat output from the occupants, lights, and appliances were scheduled hourly.* Cooling requirements were calculated both for windows closed at all times and for windows opened for natural ventilation when the outdoor dry-bulb temperature (t_o) is below 25.5°C (78°F).

* The actual operational profile and heat release schedule used, as well as supporting computational data, are reported in Petersen, Barnes, and Peavy, Determining Cost-Effective Insulation Levels for Masonry and Wood-Frame Walls in New Single-Family Housing[12].

Three basic wall types were simulated in the prototypical house: a 200 mm (8 in) hollow concrete block wall weighing 185 kg/m^2 (38 lbs/ft^2) of net wall area, a 100 mm (4 in) brick and 100 mm (4 in) hollow concrete block wall weighing 303 kg/m^2 (62 lbs/ft^2), and a 38 x 89 mm (2 x 4 in) wood-frame wall, 30 kg/m^2 (6 lbs/ft^2). Insulation was simulated both on the inside surface and in the cavity of the brick and block wall, resulting in four wall variations considered. While rigid foam insulation was simulated in the actual NBSLD analysis of the masonry walls, the results will be nearly identical for any relatively lightweight insulation material of the same total resistance placed in the same position in the wall.

Two basic cross sections were modeled for each wall type: (1) for walls having hollow concrete cores, the cross sections with the hollow core were modeled separately from the web cross sections, and (2) for wood-frame walls, the cross sections with the stud space (i.e., cavity) were modeled separately from the stud cross sections. (Initial NBSLD computer simulations made for this report showed that modeling such walls as homogeneous in thermal resistance and weight exaggerates the dynamic thermal response characteristics of the wall.)

The base wall in all cases was covered with 13 mm (1/2 in) gypsum wallboard on the inside; 19 mm (3/4 in) furring stripes were used when the wallboard was used over masonry. The masonry walls were untreated on the outside. The wood-frame walls were covered with 13 mm (1/2 in) fiberboard sheathing and 19 mm (3/4 in) wood siding. The exterior surface of all the walls was assumed to have the same solar absorptance (0.5), typical of medium coloring, in order to provide a consistent basis for comparison of the thermal performance of the different wall types.

The NBSLD computer program was used to estimate the annual heating requirements (AHR) and annual cooling requirements (ACR) of the prototype house with each wall type modeled at a minimum of three insulation levels. For the masonry walls, R-0, R-metric 0.66 (R-3.75), and R-metric 1.98 (R-11.25) insulation were examined. For wood-frame walls, R-0, R-metric 1.94 (R-11), and R-metric 3.17 (R-18) insulation were examined. (R-metric 3.17 (R-18) is the approximate resistance of a 150 mm (6 in), R-metric 3.35 (R-19) mineral wool blanket compressed into a 140 mm (5 1/2 in) stud space.) Eleven TRY locations were used in the analysis of the 200 mm (8 in) block wall and the wood-frame wall. Eight of these same TRY locations were analyzed for the brick and block walls.

Figure 1 shows the results of the NBSLD simulation of the prototypical house with each of the four wall variations for Washington, D.C., which is near average in terms of continental U.S. heating and cooling climates. AHR and ACR for the 110 m^2 (1176 ft^2) house are plotted on the vertical axis in gigajoules (million Btu), corresponding to a range of (opaque) wall U-values on the horizontal axis. Two ACR curves are shown: (1) total cooling requirements calculated with windows closed at all times (ACR^T), and (2) net cooling requirements calculated only for hours when $t_o \geq 25.5°C$ (78°F) (ACR$^+$). No attempt is made to add AHR and ACR together, since these represent space conditioning requirements only. Actual energy usage requires consideration of heating and cooling equipment efficiencies as well. Moreover, if energy costs for heating and cooling are different, total annual heating and cooling costs will not be proportional to total energy usage.

Interpolation between the data points actually calculated in the NBSLD analysis to normalize for differences in U-values for the different wall variations allows a direct comparison of the effects of wall weight alone on AHR and ACR. In general, the heavier walls perform slightly better than the wood-frame walls in the heating mode, with the difference being somewhat more significant in the cooling mode. Results for the other ten locations examined show similar results, although the relative effects of wall weight tend to be greater in milder heating or cooling climates and relatively less in more severe heating or cooling climates. For the brick and block wall, the thermal performance of the wall was improved significantly when the insulation was moved from the inside surface to the cavity.

More important than the magnitude of these curves (which is greatly influenced by the thermal integrity of the overall envelope) is the slope of the curves. It is the slope which indicates the actual rate of reduction (or increase) in space heating or cooling requirements, and thus measures the effectiveness of the wall insulation. In general, a given size reduction in the wall U-value has a very significant effect in reducing AHR, while its effect in reducing ACR is both small and mixed. That is, if air conditioning is only used when the outside temperature is equal to or greater than 25.5°C (78°F) (equivalent to the ACR$^+$ curves in Figure 1) and natural ventilation is used below that temperature, there will be a small reduction in ACR due to an increase in wall insulation. On the other hand, if no natural ventilation is used (as in the case of the ACR^T curves in Figure 1) more wall insulation will actually increase ACR. Since houses are typically operated somewhere between these two extremes, with windows more likely to be opened in spring and fall and closed during summer months, the expected change in ACR can be expected to be zero or insignificant.

Similar results in terms of net change in ACR were found in all locations examined, except Phoenix, where a significant reduction in ACR was found, even if windows were closed at all times. This result for Phoenix is attributable to the extremely high daytime temperatures and the relatively large difference between daytime and nighttime temperatures during the cooling season. As a result, no change in ACR will be considered as attributable to wall insulation except in climatic regions like that of the Phoenix area.

A useful result of the NBSLD simulations is the linear relationship between wall U-values and AHR. This relationship implies that the ΔAHR will be directly proportional to the ΔU throughout the general range of the U-values considered. Table 1* shows the reduction in AHR per square metre (square foot) of net wall area that results from a 0.5 reduction in the wall U-value (0.1 reduction in customary U-value), as calculated from the results of the NBSLD simulations for each wall variation in each location examined. Table 1 also lists the heating degree days calculated for the traditional base 18.3°C, $HDD_{18.3°C}$ (65°F, $HDD_{65°F}$), and for base 12.8°C, $HDD_{12.8°C}$ (55°F,$HDD_{55°F}$), in both cases computed from the same TRY climate data used in the simulations. In general, the relationship between wall U-values and ACR is not as linear as that for AHR. However, since the ΔACR tends to be insignificant except in the case of the Phoenix-type climate, this result is not critical to the methodology being developed. The reduction in ACR due to the same reduction in wall U-value is also shown in Table 1 for Phoenix only.

In order to develop a general relationship between the ΔAHR data shown in Table 1 and local climate conditions, a number of linear regressions were computed using several HDD bases. The highest coefficient of determination, R^2, (0.997) was obtained for $HDD_{12.8°C}$ ($HDD_{55°F}$); thus, the $HDD_{12.8°C}$ ($HDD_{55°F}$) data is shown in Table 1. Figure 2 shows the graphical relationship between the ΔAHR for the 200 mm (8 in) block wall and the $HDD_{12.8°C}$ ($HDD_{55°F}$) data for 11 cities from Table 1. Regression equations were developed for all four wall variations with equally good results:

<u>200 mm (8 in) Block Wall</u>

$$\Delta AHR\ (MJ/m^2) = \Delta U_M(6.12 + 0.0994\ HDD_{12.8°C})$$ or, in customary units,

$$\Delta AHR\ (10^3\ Btu/ft^2) = \Delta U_C(3.06 + 0.027\ HDD_{55°F}) \qquad (1)$$

<u>Brick and Block Wall (insulation inside)</u>

$$\Delta AHR\ (MJ/m^2) = \Delta U_M(2.72 + 0.1019\ HDD_{12.8°C})$$ or,

$$\Delta AHR\ (10^3\ Btu/ft^2) = \Delta U_C(1.36 + 0.0283\ HDD_{55°F}) \qquad (2)$$

<u>Brick and Block Wall (cavity insulation)</u>

$$\Delta AHR\ (MJ/m^2) = \Delta U_M(7.14 + 0.1019\ HDD_{12.8°C})$$ or,

$$\Delta AHR\ (10^3\ Btu/ft^2) = \Delta U_C(3.57 + 0.0283\ HDD_{55°F}) \qquad (3)$$

<u>Wood-Frame Wall</u>

$$\Delta AHR\ (MJ/m^2) = \Delta U_M(14.08 + 0.0976\ HDD_{12.8°C})$$

$$\Delta AHR\ (10^3\ Btu/ft^2) = \Delta U_C(7.04 + 0.0271\ HDD_{55°F}) \qquad (4)$$

A $HDD_{55°F}$ map of the United States, based on long-term weather data, is shown in Figure 3, as provided by the National Climatic Center. Thus, the approximate ΔAHR for any given

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* Separate tables for metric and customary units are provided for all tables (except Table 2).

ΔU (in the general range of opaque wall U-values between 0.25 and 1.5 (in customary units, 0.05 and 0.25)) corresponding to any of the four wall variations shown can be computed for most locations in the United States, using the above equations. While the data base is calculated using a single zone, 110 m^2 (1176 ft^2) house, with thermostat settings of 20°C (68°F) (day) and 15.5°C (60°F) (night setback), these equations should provide reasonable estimates for other houses as well, if they are operated similarly.

ECONOMIC ANALYSIS

While the reduction in annual heating requirements due to insulating exterior walls may be significant, the extent to which insulation is a worthwhile investment is a matter to be determined by economic analysis. Specifically, life-cycle cost analysis is used to evaluate the incremental costs and savings due to additional increments of insulation in order to determine the total insulation level with the greatest net present-value savings over the useful life of the insulation, i.e., total life-cycle savings (LCS) less total cost (K).

In general, the costs of wall insulation are primarily increased first costs and thus there is no need to evaluate recurring or replacement costs in the future. Energy savings are assumed to recur each year, however, and to escalate in value each year as the price of energy increases. At the same time, these annual dollar savings must be discounted to present value over the expected useful life of the insulation in order to compare savings with costs on a time-equivalent basis.

Both the projected annual escalation rate for energy prices (E) and the discount rate (D) can be considered simultaneously for any given insulation life (L, in years) in order to develop a modified uniform present worth factor (UPW*) that is useful in determining present-value, life-cycle energy savings in dollar terms:

$$UPW^* = \left(\frac{1+E}{D-E}\right)\left[1-\left(\frac{1+E}{1+D}\right)^L\right] \quad \text{if } D \neq E, \text{ or} \tag{5a}$$

$$UPW^* = L \qquad \text{if } D = E. \tag{5b}$$

Table 2 provides UPW* factors calculated for several values of E and L, based on a ten percent discount rate. Multiplication of the UPW* by the annual energy savings valued in current energy prices will result in present-value, life-cycle savings.

In order to determine the economically optimal insulation level in any given application, the increase in life-cycle savings (LCS) due to each additional increment of insulation considered must be calculated. The size of these insulation increments is generally determined by the difference in the successive thicknesses (or corresponding thermal resistances) of commonly available insulation materials (e.g., customary R-11, R-19, R-22 and R-30 mineral wool blankets).

In general, the net present-value savings due to additional insulation will increase as long as its incremental life-cycle savings (ΔLCS) are greater than the incremental cost (ΔK) of that additional insulation. The economically optimal level of insulation is defined as that level with the greatest net savings; any additional insulation will have incremental savings less than incremental costs. Therefore, additional insulation is cost effective as long as:

$$\Delta K < \Delta LCS. \tag{6}$$

If both heating and cooling savings are to be calculated, the ΔLCS can be calculated as follows:

$$\Delta LCS = \left(\frac{\Delta AHR}{\eta_H}\right)\left(P_H\right)\left(UPW^*_H\right) / 1000 + \left(\frac{\Delta ACR}{\eta_C}\right)\left(P_C\right)\left(UPW^*_C{}'\right) / 1000 \tag{7}$$

where:

ΔAHR and ΔACR are the change in annual heating and cooling requirements in MJ (10^3 Btu), respectively, due to an increase in insulation,

η_H is the seasonal furnace efficiency,

η_C is the seasonal air conditioner coefficient of performance (COP),

P_H is the price in dollars per GJ (million Btu) for heating energy,

P_C is the price in dollars per GJ (million Btu) for cooling energy,

UPW^*_H is the modified present worth factor for heating energy savings, and

UPW^*_C is the modified present worth factor for cooling energy savings.

If only heating savings are attributed to additional wall insulation, this same criterion can be expressed as:

$$1000\Delta K < \left(\frac{\Delta AHR}{\eta_H}\right)\left(P_H\right)\left(UPW^*_H\right) \tag{8}$$

or

$$\frac{1000\Delta K}{\Delta AHR} < I, \tag{9}$$

where $$I = \left(P_H\right)\left(UPW^*_H / \eta_H\right) \tag{10}$$

Equations 9 and 10 are useful because they provide the basis of an index number (I) and breakpoint ratio ($1000\Delta K/\Delta AHR$) for determining whether additional wall insulation is cost effective. Assuming that η_H is approximately constant as the wall insulation level is increased, the index number remains constant for any given house, while the breakpoint ratio grows larger for each additional increment of insulation. (In general, the breakpoint ratio for each subsequent increment of insulation evaluated will increase. If the incremental insulation cost per resistance unit drops sharply, this ordering may be temporarily violated. In such a case, the size of the last increment before the decrease in the breakpoint ratio should be increased so that it includes all increments with lower breakpoint ratios immediately subsequent to it.) The maximum cost-effective level of insulation is the highest increment considered which has a breakpoint ratio less than or equal to the appropriate index number.

The index number, I, can be calculated quite easily using equation 10 and Table 2. Equations 1 through 4 provide estimates of ΔAHR per m^2 (ft^2) as a function of HDD and ΔU. Thus, all that remains to be estimated is the ΔU corresponding to the increments of insulation to be evaluated and $1000\Delta K$, the incremental insulation cost per square metre (foot) of net wall area multiplied by the scalar "1000" (to avoid small decimal numbers).

The incremental cost of insulation depends on the type of insulation used and the method of installation. In general, the insulation system with the lowest installed cost per resistance unit will be used, provided that it satisfies the general performance requirements for insulating materials. Mineral wool batts or blankets are generally the most cost-effective materials for insulating wood-frame walls up to approximately R-13. Higher insulation levels are achieved either by increasing the stud dimensions and adding more mineral wool, or by using rigid foam insulated sheathing (e.g., polystyrene or polyisocyanurate), or a combination of both. Foam insulation materials (e.g., polystyrene, polyurethane, or polyisocyanurate) are frequently used in masonry wall construction because of their relatively low conductivity and rigidity. However, their installed costs tend to be significantly higher than those for mineral wool blankets installed in free standing 38 x 64 mm (2 x 3 in) framing, 610 mm (24 in) on center, on the inside of the masonry wall, even after adjusting for the loss of interior space.* As a result, interior framing and conventional mineral wool blankets appear to be a more cost-effective system for insulating masonry walls in new constuction than rigid foams. Moreover, additional mineral wool insulation can be installed by moving the framing farther from the wall, resulting in incremental costs for insulation levels above R-metric 1.94

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* The cost per additional square metre (foot) of interior space is based on the cost of extending the end wall of the house to maintain equivalent inside area. This cost has been calculated to be approximately $54.00 per additional square metre ($5.00 per square foot) of floor area for the prototype house examined in this report. Inside finishing costs are unchanged except for trim around windows and doors. The use of 38 x 64 mm (2 x 3 in) free standing framing with masonry walls is not a widespread practice but is an acceptable construction method for increasing insulation levels in masonry walls.

(R-11) much lower than those for rigid foam. Rigid foam insulation is typically used for insulating the cavity of a brick and block wall. While this approach is thermally superior to insulating the inside wall surface to the same overall U-value, it appears that this higher thermal performance level can be achieved at less cost by insulating with mineral wool to a lower U-value on the inside surface.

Analysis of poured insulation in hollow cores of the concrete blocks used in the two masonry walls examined has shown that this insulation system is generally more costly than adding an equivalent level of insulation to the inside wall surface[13] and thus has not been considered further. In addition, it was found that mineral wool insulation levels less than R-metric 1.94 (R-11) are not generally as cost-effective as the R-metric 1.94 (R-11) level in new construction, so that intermediate levels have also not been considered.

Table 3 provides representative incremental cost data for both rigid foam and mineral wool insulation in masonry walls and for mineral wool only in conventional wood-frame walls, along with corresponding reductions in U-values. This data base can be used to calculate ΔK and ΔU for each incremental level to be considered.

For example, the index number for gas heat with η_H of 0.7, a cost of \$2.85 per GJ (\$3.00 per million Btu), and a UPW* of 30 is 122 (= (2.85)(30)/(0.7)) (129 = (3.00)(30)/(0.7) for customary units). In order to calculate the breakpoints corresponding to R-metric 0.53, 1.94 and 3.35 (R-3, R-11 and R-19) mineral wool insulation for a 200 mm (8 in) block wall in a 110 $HDD_{12.8°C}$ (2000 $HDD_{55°F}$) climate, the ΔK, ΔU and corresponding ΔAHR per square metre (foot) must be calculated. Based on the data in Table 3 and equation 1 these are as follows:

Insulation Level	ΔU W/(m²·K) (Btu/(ft²·h·°F))	ΔK \$/m² (\$/ft²)	ΔAHR MJ/m² (10³Btu/ft²)	$\frac{1000\Delta K}{\Delta AHR}$
R-metric 0.53 (R-3)	0.454 (0.080)	\$1.11 (0.10)	52.9 (4.66)	21.0 (21.5)
R-metric 1.94 (R-11)	0.494 (0.087)	4.70 (0.46)	57.5 (5.07)	81.7 (90.7)
R-metric 3.35 (R-19)	0.159 (0.028)	2.60 (0.24)	18.5 (1.63)	140.4 (147.2)

The breakpoint ratio ($1000\Delta K/\Delta AHR$) for R-metric 1.94 (R-11) is less than 122 (129) while the breakpoint ratio for R-metric 3.34 (R-19) is greater than 122 (129). The maximum cost-effective level of insulation in this example is R-metric 1.94 (R-11), although an intermediate level of insulation (e.g., R-metric 2.29 (R-13)) may be economically justified if it were evaluated.

Based on the insulation costs shown in Table 3 and the preceding analysis, maximum economic levels of insulation are estimated for several $HDD_{12.8°C}$ ($HDD_{55°F}$) values and two index numbers, 142 and 236 (150 and 250), which correspond to a range of current energy prices and UPW*s. These maximum economic insulation levels are shown in Tables 4 and 5.

It should be noted that the levels of insulation examined are meant to be representative of commonly available insulation resistances. Other levels could be considered as well, if they are available to the user. The levels used will provide reasonable guidelines for maximum economic levels of insulation, but should be recognized as being approximate.

CONCLUSIONS

In general, insulation costs for masonry walls are considerably higher than those for wood-frame walls, especially if rigid foam insulation is used in the masonry walls. In addition, equal reductions in U-value tend to save less energy in masonry walls than in wood-frame walls, especially in the southern and southwestern regions of the United States. As a result, the maximum economic level of insulation tends to be lower for masonry walls than for wood-frame walls, at least in the milder heating regions. Where a minimum of R-metric 1.94 (R-11) mineral wool insulation in wood-frame walls is cost effective in nearly every region of the continental U.S. (except southern Florida), the equivalent level of rigid foam insulation in masonry walls is not generally cost effective anywhere in the southern half of the United States.

The use of free-standing 38 x 64 mm (2 x 3 in) framing on the inside surface of masonry walls, together with conventional fiberglass insulation, is a cost-effective alternative to rigid foam insulation. While the cost of the framing is substantial, the expense of furring strips is avoided. Moreover, the framing can be moved out farther from the wall to accommodate more insulation at little increase in carpentry costs. Equivalent interior areas can be maintained by extending the end walls slightly during construction. With the use of this mineral wool insulating system, higher R-values than were found for rigid foam insulation are cost-effective. Still, the maximum economic level of insulation in masonry walls in southern, southwestern, and west coast regions tends to be significantly lower (often R-metric 0.53 (R-3)) than that for wood-frame walls, especially where natural gas or heat pumps are used in heating.

It was found that the addition of insulation to either wood-frame or masonry walls reduced cooling loads insignificantly, except in the case of the Phoenix climatic region. As a result, the simplified index number methodology developed in this paper is applied to heating savings only.

While the insulation of the inside wall surfaces negates some of the beneficial effects of thermal mass on exterior walls, the reduced rate of heat loss through those walls more than compensates for this negative effect. Since insulation on inside surfaces can be significantly less expensive than exterior insulation, serious doubts about the economic efficiency of exterior insulation are raised.

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Table 1 (Metric Units). $\Delta AHR/m^2$ due to $\Delta U = 0.5$[a] for Four Wall Variations in Selected Locations

Location	$HDD_{18.3°C}$	$HDD_{12.8°C}$	ΔAHR (MJ/m^2): 200 mm Block Wall	Brick & Block Wall: Insulation Inside	Brick & Block Wall: Insulation In Cavity	Wood-Frame Wall
Albany	3954	2577	128.6	NA	NA	130.4
Albuquerque	2443	1338	65.3	67.0	71.8	71.9
Atlanta	1644	761	43.7	42.7	46.0	47.0
Indianapolis	3270	2066	108.4	107.6	109.1	109.4
Jackson	1307	569	34.0	NA	NA	37.7
Jacksonville	688	182	11.0	9.9	12.1	14.6
Madison	4062	2647	134.6	133.3	135.3	136.0
Phoenix	873	224	12.1	10.2	12.8	17.9
(ΔACR^T)[b]			(16.2)	(11.4)	(17.8)	(28.0)
(ΔACR^+)			(27.1)	(21.7)	(24.1)	(40.9)
Salt Lake City	3453	2182	110.4	NA	NA	113.1
Tampa	255	32	2.8	2.4	2.9	4.0
Washington, D.C.	2312	1214	67.9	67.7	69.1	69.8

[a] Reduction in metric U-value from 0.80 to 0.30.

[b] Reduction in Annual Cooling Requirements (ΔACR) is only significant in Phoenix. ΔACR^T is calculated with windows closed at all times; ΔACR^+ is for cooling only when $t_o \geq 25.5°C$.

[c] NA means AHR data base was not available.

Table 1 (Customary Units). ΔAHR/ft^2 due to $\Delta U = 0.1$[a] for Four Wall Variations in Selected Locations

Location	$HDD_{65°F}$	$HDD_{55°F}$	ΔAHR (10^3 Btu/ft^2)			
				Brick & Block Wall		
			8" Block Wall	Insulation Inside	Insulation In Cavity	Wood-Frame Wall
Albany	7118	4638	12.86	NA	NA	13.04
Albuquerque	4397	2408	6.53	6.70	7.18	7.19
Atlanta	2959	1370	4.37	4.27	4.60	4.70
Indianapolis	5886	3719	10.84	10.76	10.91	10.94
Jackson	2352	1025	3.40	NA	NA	3.77
Jacksonville	1239	327	1.10	0.99	1.21	1.46
Madison	7311	4765	13.46	13.33	13.53	13.60
Phoenix	1571	404	1.21	1.02	1.28	1.79
(ΔACR^T)[b]			(1.62)	(1.14)	(1.78)	(2.80)
(ΔACR^+)			(2.71)	(2.17)	(2.41)	(4.09)
Salt Lake City	6216	3928	11.04	NA	NA	11.31
Tampa	459	57	0.28	0.24	0.29	0.40
Washington, D.C.	4162	2185	6.79	6.77	6.91	6.98

a Reduction in U-value from 0.15 to 0.05.

b Reduction in Annual Cooling Requirements (ΔACR) is only significant in Phoenix. ΔACR^T is calculated with windows closed at all times; ΔACR^+ is for cooling only when $t_o \geq 78°F$.

c NA means AHR data base was not available.

Table 2. Modified Uniform Present Worth Factors (UPW*) for Energy Savings[a]

(10% Discount Rate)

Projected Energy Price Escalation Rate	Life (years) 20	30	40
0.04	11.69	14.11	15.49
0.05	12.72	15.80	17.73
0.06	13.87	17.78	20.48
0.07	15.15	20.11	23.87
0.08	16.59	22.86	28.08
0.09	18.20	26.12	33.36
0.10	20.00	30.00	40.00
0.11	22.02	34.62	48.42
0.12	24.30	40.15	59.13

[a] Multiply appropriate factor by annual dollar energy savings based on initial year energy prices to get present-value, life-cycle savings. UPW* based on equation 5a or 5b.

Table 3 (Metric Units). ΔU-Values and Representative Cost Data[a] for Selected Walls and Insulation Systems

A. Mineral Wool Insulation in Masonry Walls[b]

Insulation R	ΔU		Δ Cost
	200 mm Block	Brick & Block	($/m^2)
0.53 (RAS only[c])	0.454	0.335	$1.11
1.94	0.494	0.403	4.70
3.35	0.159	0.148	2.60

B. Rigid Foam in Masonry Walls (including reflective air space)[d]

Insulation R	ΔU		Δ Cost
	200 mm Block	Brick & Block	($/m^2)
0.53 (RAS only[c])	0.454	0.335	$1.11
1.36	0.379	0.324	4.33
1.64	0.062	0.057	0.84
2.18	0.097	0.079	2.04
2.73	0.057	0.057	1.86
3.28	0.045	0.040	2.09

C. Mineral Wool in Wood-Frame Walls[e]

Insulation R	ΔU	Δ Cost ($/m^2)
0.53 (RAS only[c])	0.346	$1.11
1.94	0.420	1.38
3.17	0.142	2.21

[a] Cost data for rigid foam insulation and inside framing based on Means.[(13)] Cost data for mineral wool insulation obtained by telephone conversation with Arthur Johnson of Insulation Contractors Association, Washington, D.C.

[b] U-metric for uninsulated 200 mm hollow block wall = 1.36, for brick and block wall = 1.14. (This includes gypsum wallboard and a 2 mm air space.)

[c] RAS = reflective air space in furring (stud) space, removed when mineral wool insulation is installed. R-metric 0.53 is the approximate thermal resistance of air space with reflective surface on one side.[(14)]

[d] Rigid foam on inside surface of wall or in cavity.

[e] U-metric for uninsulated wood-frame wall = 1.19.

Table 3 (Customary Units). ΔU-Values and Representative Cost Data[a] for Selected Walls and Insulation Systems

A. Mineral Wool Insulation in Masonry Walls[b]

Insulation R	ΔU		Δ Cost
	8" Block	Brick & Block	($\$/ft^2$)
3 (RAS only[c])	0.080	0.059	$0.10
11	0.087	0.071	0.46
19	0.028	0.026	0.24

B. Rigid Foam in Masonry Walls (including reflective air space)[d]

Insulation R	ΔU		Δ Cost
	8" Block	Brick & Block	($\$/ft^2$)
3 (RAS only[c])	0.080	0.059	$0.10
7.7	0.070	0.057	0.40
9.3	0.011	0.010	0.08
12.4	0.017	0.014	0.19
15.5	0.010	0.010	0.17
18.6	0.008	0.007	0.19

C. Mineral Wool in Wood-Frame Walls[e]

Insulation R	ΔU	Δ Cost ($\$/ft^2$)
3 (RAS only[c])	0.061	$0.10
11	0.074	0.13
18	0.025	0.20

[a] Cost data for rigid foam insulation and inside framing based on Means.[13] Cost data for mineral wool insulation obtained by telephone conversation with Arthur Johnson of Insulation Contractors Association, Washington, D.C.

[b] U for uninsulated 8" hollow block wall = 0.24, for brick and block wall = 0.28. (This includes gypsum wallboard and 3/4" air space.)

[c] RAS = reflective air space in furring (stud) space, removed when mineral wool insulation is installed. R-3 is the approximate thermal resistance of air space with reflective surface on one side.[14]

[d] Rigid foam on inside surface of wall or in cavity.

[e] U for uninsulated wood-frame wall = 0.21.

Table 4 (Metric Units). Maximum Economic Insulation Levels[a]: I = 142[b]

	Insulation and Wall Type				
	Mineral Wool			Rigid Foam[d]	
HDD[c] 12.8°C	200 mm Block	Brick & Block	Wood-Frame	200 mm Block	Brick & Block
280	R-0.53	R-0.53	R-1.94	R-0.53	R-0.53
560	R-0.53	R-0.53	R-1.94	R-0.53	R-0.53
830	R-1.94	R-1.94	R-1.94	R-1.36	R-0.53
1110	R-3.35	R-1.94	R-3.17	R-1.64	R-1.64
1670	R-3.35	R-3.35	R-3.17	R-2.18	R-1.64
2780	R-3.35	R-3.35	R-3.17	R-2.73	R-2.73
2890	R-3.35	R-3.35	R-3.17	R-3.28	R-3.28

a Based on insulation levels and costs detailed in Table 3.

b I = 142 corresponds (approximately) to:

Natural Gas @\$3.32/GJ, $\eta_H = 0.70$, PWF = 30 (L = 30, D = .10, E = .10)
Oil @\$3.32/GJ, $\eta_H = 0.70$, PWF = 30 (L = 30, D = .10, E = .10)
Electric
Resistance @\$7.10/GJ, $\eta_H = 1.0$, PWF = 20 (L = 30, D = .10, E = .07)
Heat Pump @\$12.07/GJ, $\eta_H = 1.7$, PWF = 20 (L = 30, D = .10, E = .07)

c See Figure 3 for a Heating Degree Day (base 55°F) map of the U.S.

d Rigid foam resistances include R-metric 0.53 reflective air space.

Table 4 (Customary Units). Maximum Economic Insulation Levels[a]: I = 150[b]

HDD[c] 55°F	Insulation and Wall Type: Mineral Wool, 8" Block	Mineral Wool, Brick & Block	Mineral Wool, Wood-Frame	Rigid Foam[d], 8" Block	Rigid Foam[d], Brick & Block
500	R-3	R-3	R-11	R-3	R-3
1000	R-3	R-3	R-11	R-3	R-3
1500	R-11	R-11	R-11	R-8	R-3
2000	R-19	R-11	R-18	R-9	R-9
3000	R-19	R-19	R-18	R-12	R-9
5000	R-19	R-19	R-18	R-16	R-16
7000	R-19	R-19	R-18	R-19	R-19

a Based on insulation levels and costs detailed in Table 3.

b I = 150 corresponds (approximately) to:

Natural Gas @35¢/therm, η_H = 0.70, PWF = 30 (L = 30, D = .10, E = .10)
Oil @49¢/gallon, η_H = 0.70, PWF = 30 (L = 30, D = .10, E = .10)
Electric
Resistance @2.6¢/kwh, η_H = 1.0, PWF = 20 (L = 30, D = .10, E = .07)
Heat Pump @4.4¢/kwn, η_H = 1.7, PWF = 20 (L = 30, D = .10, E = .07)

c See Figure 3 for a Heating Degree Day (base 55°F) map of the U.S.

d Rigid foam resistances include R-3 reflective air space and are rounded to nearest integer.

Table 5 (Metric Units). Maximum Economic Insulation Levels[a]: I = 236[b]

$HDD^{c}_{12.8°C}$	Insulation and Wall Type				
	Mineral Wool			Rigid Foam[d]	
	200 mm Block	Brick & Block	Wood-Frame	200 mm Block	Brick & Block
280	R-0.53	R-0.53	R-1.94	R-0.53	R-0.53
560	R-1.94	R-1.94	R-3.17	R-1.64	R-1.36
830	R-3.35	R-3.35	R-3.17	R-2.18	R-1.64
1110	R-3.35	R-3.35	R-3.17	R-2.18	R-2.18
1670	R-3.35	R-3.35	R-3.17	R-2.73	R-2.73
2780	R-3.35	R-3.35	R-3.17	R-3.28	R-3.28
3890	R-3.35	R-3.35	R-3.17	R-3.28	R-3.28

a Based on insulation levels and costs detailed in Table 3.

b I = 236 corresponds (approximately) to:

Natural Gas @$5.50/GJ, η_H = 0.70, PWF = 30 (L = 30, D = .10, E = .10)
Oil @$5.50/GJ, η_H = 0.70, PWF = 30 (L = 30, D = .10, E = .10)
Electric
Resistance @$11.80/GJ, η_H = 1.0, PWF = 20 (L = 30, D = .10, E = .07)
Heat Pump @$20.06/GJ, η_H = 1.7, PWF = 20 (L = 30, D = .10, E = .07)

c See Figure 3 for a Heating Degree Day (base 55°F) map of the U.S.

d Rigid foam resistances include R-metric 0.53 reflective air space.

Table 5 (Customary Units). Maximum Economic Insulation Levels[a]: I = 250[b]

$HDD^{c}_{55°F}$	Insulation and Wall Type				
	Mineral Wool			Rigid Foam[d]	
	8" Block	Brick & Block	Wood-Frame	8" Block	Brick & Block
500	R-3	R-3	R-11	R-3	R-3
1000	R-11	R-11	R-18	R-9	R-8
1500	R-19	R-19	R-18	R-12	R-9
2000	R-19	R-19	R-18	R-12	R-12
3000	R-19	R-19	R-18	R-16	R-16
5000	R-19	R-19	R-18	R-19	R-19
7000	R-19	R-19	R-18	R-19	R-19

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[a] Based on insulation levels and costs detailed in Table 3.

[b] I = 250 corresponds (approximately) to:

Natural Gas @58¢/therm, η_H = 0.70, PWF = 30 (L = 30, D = .10, E = .10)
Oil @82¢/gallon, η_H = 0.70, PWF = 30 (L = 30, D = .10, E = .10)
Electric
Resistance @4.3¢/kwh, η_H = 1.0, PWF = 20 (L = 30, D = .10, E = .07)
Heat Pump @7.3¢/kwh, η_H = 1.7, PWF = 20 (L = 30, D = .10, E = .07)

[c] See Figure 3 for a Heating Degree Day (base 55°F) map of the U.S.

[d] Rigid foam resistances include R-3 reflective air space and are rounded to nearest integer.

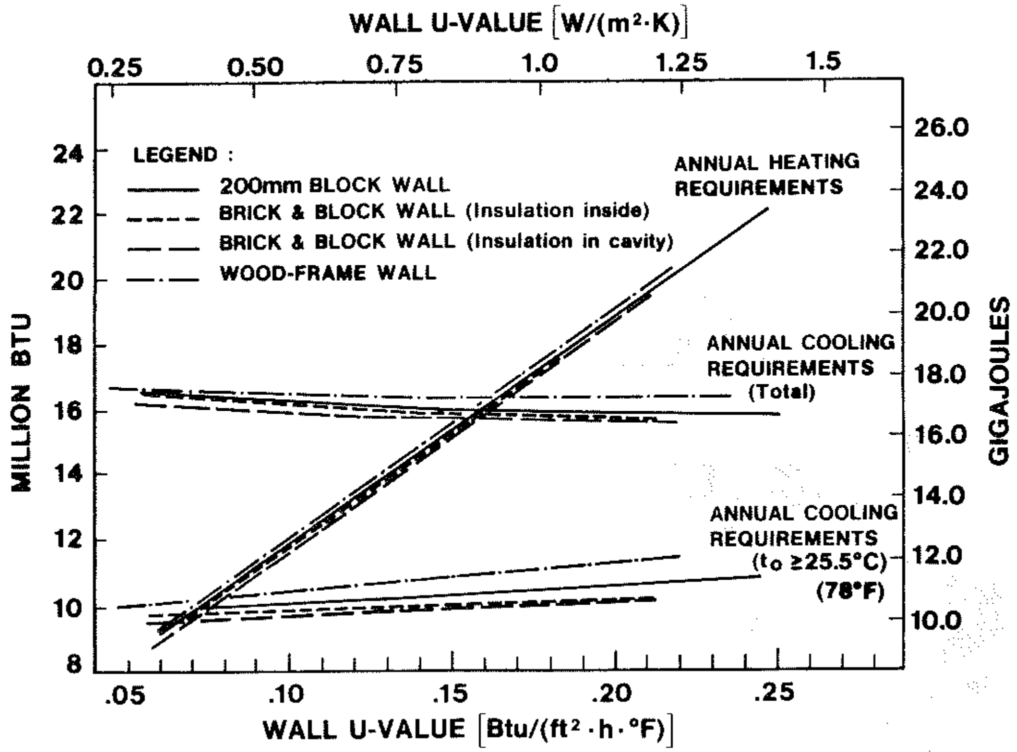

Fig. 1. Annual Heating and Cooling Requirements for a 110 m^2 (1176 ft^2) House in Washington, D.C. by Wall U-value

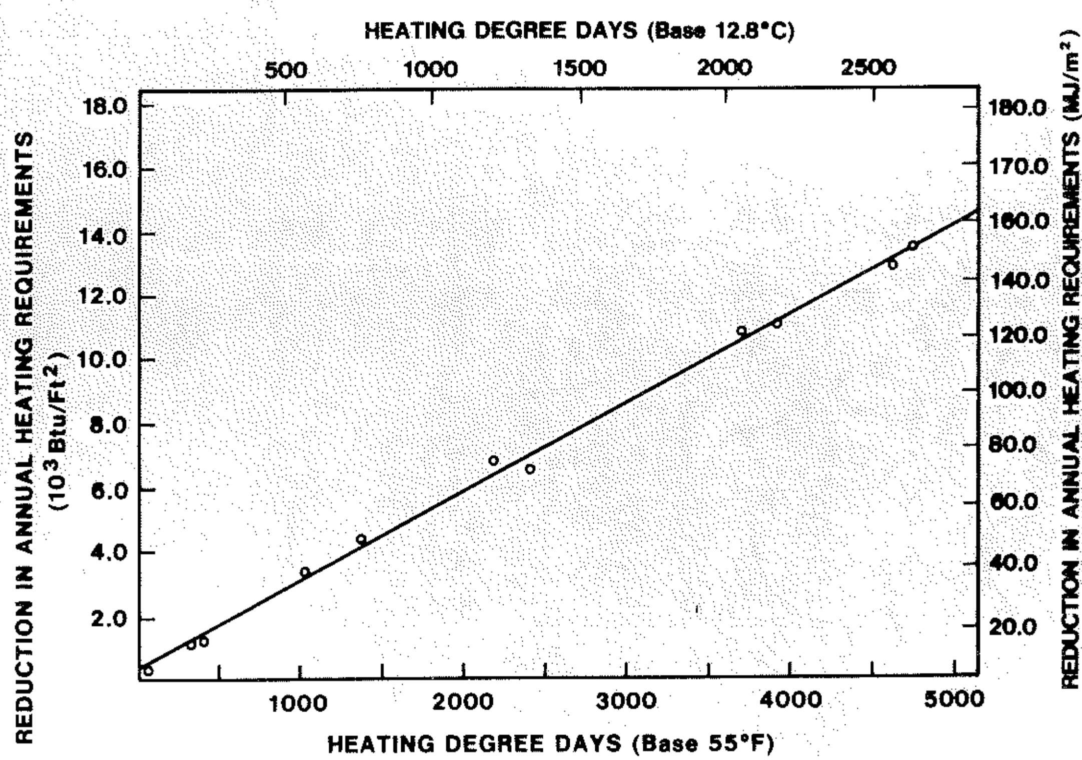

Fig. 2. Reduction in Annual Heating Requirements as a Function of Heating Degree Days (Base 12.8°C (55°F)) For the 200 mm (8") Block Wall

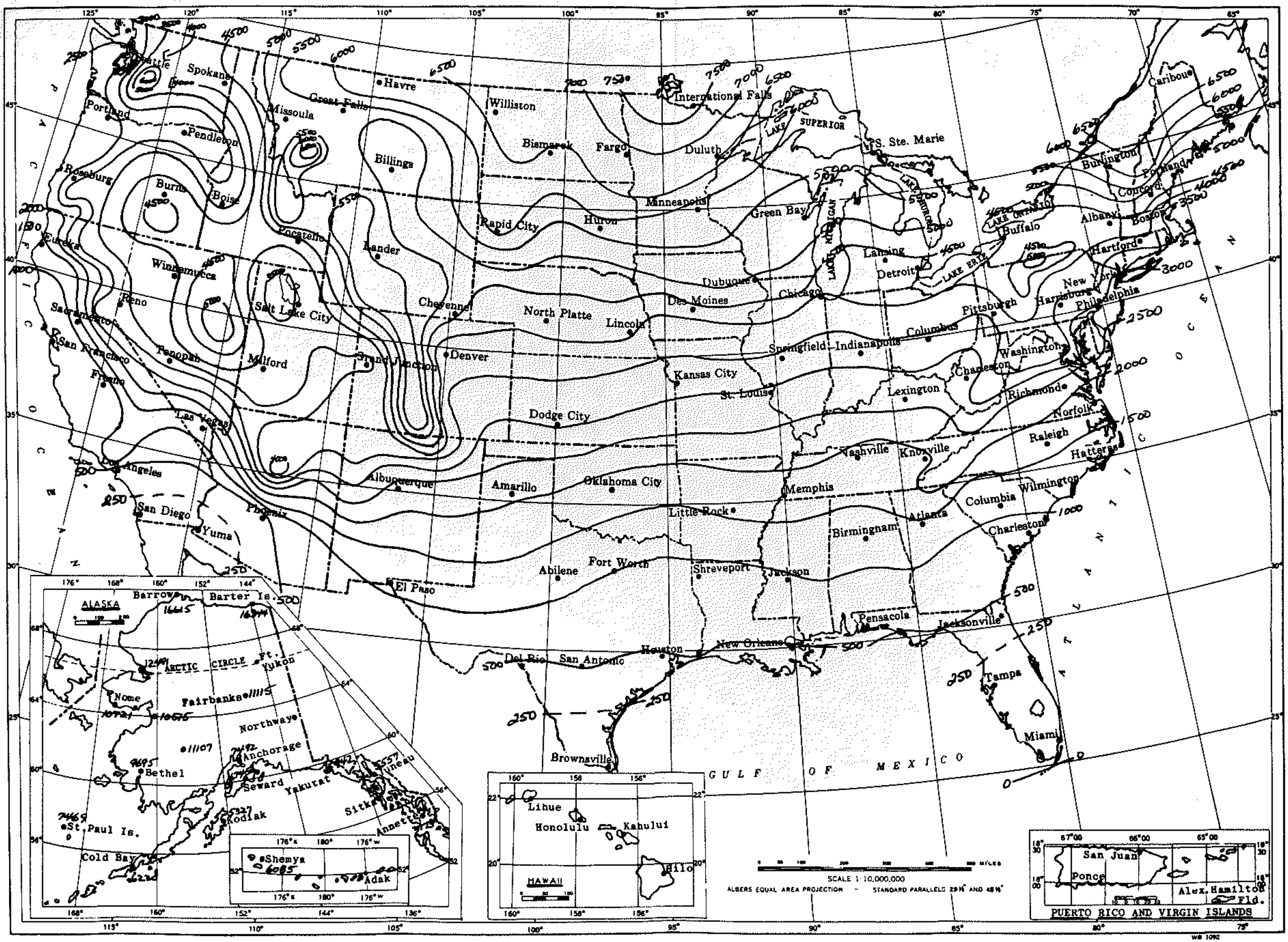

Fig. 3. Normal Seasonal Heating Degree Days - Base 55°F