NBS BUILDING SCIENCE SERIES 134

Determining Cost-Effective Insulation Levels for Masonry and Wood-Frame Walls in New Single-Family Housing

U.S. DEPARTMENT OF COMMERCE • NATIONAL BUREAU OF STANDARDS

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ABSTRACT

Economically optimal insulation methods and resistance levels for three different types of walls in a one-story, single-family residence are calculated for a wide range of geographic locations, energy prices, heating and cooling equipment efficiencies, and financial evaluation criteria. The three basic wall types examined are 8-in concrete block walls, brick and block walls, and wood-frame walls with lightweight siding. Changes in annual heating and cooling requirements for an 1176 ft^2 prototype house resulting from several different insulation resistances in each wall type are calculated using the NBS Load Determination program and Test Reference Year climate data for a number of geographic locations. Changes in heating requirements are correlated with heating degree days to provide estimates of energy savings in all geographic regions of the continental United States. Cooling requirements are not found to vary significantly with the thermal resistance of the walls under a typical operating profile except in the southwestern desert. An index number system is developed to quickly determine insulation levels based on the data generated in the report.

Key words: building design; building economics; energy conservation; exterior wall; HVAC calculations; insulation; life-cycle cost analysis; masonry; mass.

Cover: *In residential construction, the economically optimal level of insulation for masonry walls is likely to be different from that for wood-frame walls.*

PREFACE

The work in this report was conducted as an interdisciplinary research project by the Building Economics and Regulatory Technology Division and the Building Thermal Performance Division within the Center for Building Technology, National Engineering Laboratory, at the National Bureau of Standards. This effort was supported by the Department of Energy (DoE) under Interagency Agreement No. 77-A-01-6010, Task Order A008-BCS.

This report extends to additional wall types and climatic areas the work reported in NBSIR 79-1789, Economic Analysis of Insulation in Selected Masonry and Wood-Frame Walls. That report was sponsored by the Department of Housing and Urban Development and built upon concurrent research in economic analysis of insulation in masonry walls sponsored by DoE.

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SI CONVERSION

In view of the presently accepted practice of the building industry in the United States and the structure of the NBS Load Determination computer program used in this report, common U.S. units of measurement have been used throughout this report. In recognition of the position of the United States as a signatory to the General Conference of Weights and Measures, which gave official status to the metric SI system of units in 1960, appropriate conversion factors have been provided in the table below. The reader interested in making further use of the coherent system of SI units is referred to:

> NBS SP330, 1972 Edition, "The International System of Units" E380-72
> ASTM Metric Practice Guide (American National Standard Z210.1).

Metric Conversion Factors

Length:	1 inch (in) = 25.4 millimeters (mm) 1 foot (ft) = 0.3048 meter (m)
Area:	1 ft^2 = 0.092903 m^2
Volume:	1 ft^3 = 0.028317 m^3
Fluid Capacity:	1 gallon (gal) = 3.78541 litres (L)
Temperature:	1°F = 9/5°C + 32
Temperature Interval:	1°F = 5/9°C or K
Mass:	1 pound (lb) = 0.453592 kilogram (kg)
Mass per unit length:	1 lb/ft = 1.48816 kg/m
Mass per unit area:	1 lb/ft^2 = 4.88243 kg/m^2
Mass per unit volume:	1 lb/ft^3 = 16.0185 kg/m^3
Energy:	1 Btu = 1.05506 kilojoules (kJ)
Heat flow rate:	1 Btu/h = 0.293071 Watt (W)
Specific heat:	1 Btu/(lb)(°F) = 4.1868 kJ/(kg)(K)
U-value:	1 Btu/(ft^2)(h)(°F) = 5.67826 W/(m^2)(K)
R-value:	1 (ft^2)(h)(°F)/Btu = 0.176110(m^2)(K)/W

EXECUTIVE SUMMARY

This report examines both the energy and dollar-value savings and the additional costs attributable to thermal insulation in the exterior walls of new masonry and wood-frame single-family housing. Based on these savings and costs, economically optimal insulation methods and corresponding thermal resistance (R) values are determined. Economically optimal insulation methods and R-values are defined as those having the greatest present-value, life-cycle, net savings of all the alternatives considered. Since net savings are determined in part by climate and energy costs, optimal insulation methods and R-values for exterior walls can vary significantly with both geographic location and the space heating equipment used. In addition, significant differences in insulation costs between masonry and wood-frame walls and somewhat smaller differences to the potential energy savings may result in differences in the optimal method and R-value between wall types as well.

Three distinct wall types are examined in this report: (1) 8-in concrete block walls; (2) brick and block cavity walls; and (3) wood-frame walls. All three walls are evaluated in an otherwise identical 1176 square-foot (28 ft x 42 ft) single-story house. An expanded output version of the National Bureau of Standards Load Determination program (NBSLD) and hourly Test Reference Year (TRY) climate data for each location are used to calculate the annual heating and cooling requirements (AHR, ACR) of the house and reductions in those requirements due to increasing levels of insulation.

Thermal performance data are generated for 11 locations for wood-frame and 8-in block walls and 8 locations for brick and block walls:

	8-in Block	Brick & Block	Wood Frame
Albany, New York	X		X
Albuquerque, New Mexico	X	X	X
Atlanta, Georgia	X	X	X
Indianapolis, Indiana	X	X	X
Jackson, Mississippi	X		X
Jacksonville, Florida	X	X	X
Madison, Wisconsin	X	X	X
Phoenix, Arizona	X	X	X
Salt Lake City, Utah	X		X
Tampa, Florida	X	X	X
Washington, D.C.	X	X	X

Based on these results, generalized relationships between reductions in overall wall U-values and reductions in AHR are developed and correlated with heating degree days. Sensitivity analyses with regard to exterior wall color and wall density are made for the 8-in block walls. The effects of changing the position of the insulation from the inside surface to the cavity of the brick and block walls on AHR and ACR are also calculated.

Representative costs for the most common insulating methods are estimated in 1980 dollars for a wide range of commonly available R-values using Means

Building Construction Cost Data for 1980. A methodology is outlined for determining the present dollar value of energy savings from each additional level of insulation, sensitive to energy prices, projected energy price escalation rates, a discount rate, and the expected useful life of the insulation. An index number system is devised to assist the reader in determining optimal insulation levels for each wall type and geographic location, as well as for different economic factors, with a minimum of computational requirements.

Some of the conclusions reached in this study may be of considerable interest to the building community and could have a significant impact on insulation practices in new home construction.

(1) Because of the higher cost of insulating masonry walls relative to wood-frame walls, the economically optimal level of insulation in much of the South and Southwest is no more than R-3 (a reflective air space provided by furring and foil-backed wall board). R-11 or R-13 mineral wool insulation is generally cost effective in similar houses with wood-frame walls in the same locations (with the exception of a gas-heated house in southern Florida).

(2) Free-standing framing on the inside of masonry walls with 2 x 3-in studs, insulated with mineral wool batts or blankets, is generally a more cost-effective method of reducing heat loss than the use of furring strips and rigid foam insulation. If rigid foam insulation is used, optimal insulation levels in masonry walls tend to be significantly lower than those for wood-frame walls insulated with mineral wool. If framing and mineral wool are used in masonry walls, optimal insulation levels tend to be quite similar to those for wood-frame walls, except in the mildest heating climates (i.e., the South and Southwest). In the colder climates, the optimal insulation level may be as high as R-23 if high cost heating fuels are used.

(3) Reductions in annual heating requirements due to insulating exterior walls are similar for both wood-frame and masonry walls in regions with more than 3000 heating degree days (base 65°F). In milder regions, the reductions tend to be less for the insulation in masonry walls. However, these differences are generally small in absolute terms.

(4) Changes in annual cooling requirements due to increasing insulation levels in exterior walls tend to be insignificant except in extremely hot climates like the Arizona desert. In fact, cooling requirements may increase if the house is kept closed up, especially in the spring and fall. Small reductions in annual cooling requirements may occur if air conditioning is only used when the outdoor dry bulb temperature is higher than the thermostat setpoint. These reductions or increases in annual cooling requirements are not generally large enough to have any effect on the optimal level of insulation except in the mildest heating climates (especially southern Arizona).

(5) In climates typified by mild winter or summers, increased mass in exterior walls can significantly improve the thermal performance of those walls.

However, in these regions, heating or cooling requirements tend to be small to begin with and thus absolute energy savings are small. As more severe climates are encountered, the advantages of mass in terms of reducing annual energy usage are sharply reduced.

(6) Insulation in the cavity of a brick and block wall generally performs significantly better than the same insulation placed on the inside surface of the same wall. If the installed cost per resistance unit of cavity insulation is approximately the same or less than for insulation on the inside surface, cavity insulation is generally more cost effective.

(7) Insulation in the core of concrete blocks is generally less cost effective than mineral wool insulation installed on the inside wall surface, primarily because of thermal bridging effects and a higher first cost per equivalent R-value.

(8) The color of the exterior surface of walls may have more effect on annual heating and cooling requirement than mass. However, unless the location of the house is clearly dominated by either heating or cooling loads, the advantage of a given color in one season will be offset by the disadvantage of the same color in the opposite season.

Facing page: *Past guidelines for insulation in residential buildings were based in large part on the analysis of energy savings and costs for insulation in wood-frame housing.*

1. INTRODUCTION

1.1 STATEMENT OF PROBLEM

Life-cycle cost analysis has been frequently used to demonstrate that the increased use of thermal insulation in residential construction is generally a cost-effective means of reducing the impact of rapidly rising energy prices.[1] As a result, Government Agencies and industry sources have significantly upgraded their standards and/or recommendations for insulation usage in new and existing housing.[2] Where R-30 attic insulation and R-19 wall insulation were virtually unheard-of ten years ago, both of these have become common practice in many parts of the United States today.[3]

Current guidelines and standards for residential insulation are based in large part on the analysis of energy savings and insulation costs in wood-frame housing. While such guidelines and standards tend to be differentiated by climate and fuel type (in order to recognize differences in the dollar values of the energy savings accrued), little attention has been given to differentiation by construction type. For example, while R-30 or R-38 insulation may be economically justified in open attics, such resistance levels will be considerably more costly and thus inappropriate in some flat roofs and cathedral-type ceilings. Similarly, R-11 or R-19 wall insulation may be justified in a conventional wood-frame wall, while somewhat different resistance levels may be more appropriate for masonry wall construction.

The purpose of this report is to develop economic guidelines for insulating load-bearing masonry and wood-frame walls in single-family residences.[4] Economically optimal insulation guidelines for load-bearing masonry walls are likely to be different from those for wood-frame walls in residential construction for two distinct reasons:

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[1] For examples of this, see the following: U.S. Department of Energy, Office of Conservation and Solar Energy, Economic Analysis, Energy Performance Standards for New Buildings, Doc. 9568.00 (Washington, D.C.: U.S. Department of Energy, November 1979); Stephen R. Petersen, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, NBS BSS 64 (Washington, D.C.: National Bureau of Standards, December 1974); and J. E. Snell, P. R. Achenbach, and S. R. Petersen, "Energy Conservation in New Housing Design," Science, Vol. 192, June 25, 1976, pp. 1305-1311.

[2] For examples of recently published standards, see: U.S. Department of Agriculture, Farmers Home Administration, "Thermal Performance Standards" (Washington, D.C., 1979); and U.S. Department of Housing and Urban Development, "Minimum Property Standards for One- and Two-Family Dwellings" (Washington, D.C., 1979).

[3] NAHB Research Foundation, Inc., "Annual Builder Practices Survey," Rockville, Md. 20850.

[4] It is assumed that the type of wall construction to be used has already been selected at this point. This report does not compare the costs of alternative methods of wall construction.

(1) The cost of insulating a load-bearing masonry wall is substantially more expensive than insulating a wood-frame wall to the same U-value because there is no stud space suitable for installing relatively low-cost blanket or batt insulation materials.

(2) The greater weight of the masonry wall relative to the wood-frame wall gives it some natural advantage in terms of dampening the effects of the diurnal climate on space heating and cooling loads. As a result, the potential reduction in energy requirements due to insulation in masonry walls may be somewhat different than the equivalent thermal resistance value in wood-frame walls, especially if the insulation is located toward the outer surface of the wall.

Both of these differences will be examined in some detail in this report in order to provide a suitable basis for a life-cycle cost analysis of insulation in masonry walls.

1.2 SCOPE

In this report, economic guidelines for insulating load-bearing masonry walls and wood-frame walls are developed, based on a life-cycle cost analysis of the increased construction costs and corresponding energy savings related to the increased use of insulation. Two basic types of masonry construction are examined: 8-in concrete masonry units,[1] typical of masonry construction in Florida and the Southwest, and a composite (or cavity) construction made of 4-in face brick and 4-in blocks,[2] more typical of load-bearing masonry wall construction in other parts of the United States. (While brick veneer walls are not explicitly examined, implications for these walls are discussed in subsections 4.1.1 and 5.3.) For the 8-in block wall, insulation will be considered both in the hollow cores of the blocks and on the inside wall surface, covered with 0.5-in gypsum wallboard. For the brick and block wall, insulation is considered both on the inside wall surface and in the cavity between the brick and block. Economic guidelines for insulation in conventional wood-frame wall construction are developed using the same methodology.

Annual space heating and cooling requirements are calculated for an 1176 square-foot, one-story house, with each wall type examined individually over a

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[1] For the remainder of this paper concrete masonry units will be simply referred to as "blocks."

[2] When insulation is placed between the brick and block, this composite wall type will be refer~ed to as "cavity wall" construction. The term "brick and block" will be used to describe the general wall construction.

range of insulation levels. An expanded output version of the National Bureau of Standards Load Determination computer program (NBSLD),[1] and Test Reference Year weather data[2] are used in calculating these requirements.

In general, only the least costly means of insulating a wall to different levels of thermal performance need be considered in determining the optimal insulation level, provided that other (non-thermal) performance criteria are satisfied. However, in this report, alternative means of insulating masonry and wood-frame walls are considered in order to provide a broader basis for evaluating insulation methods.

Calculations of annual space heating and cooling requirements were made for 11 widely dispersed locations for the prototype house with 8-in block and wood-frame walls, and in 8 of those 11 locations for the prototype house with the brick and block walls. Based on these calculations, a method for calculating heating and cooling requirements in other locations throughout the continental United States is developed. Some sensitivity analyses related to both the weight of the wall and the solar absorptivity of its exterior surfaces are made for the 8-in block wall.

The two basic insulation materials considered for increasing the thermal resistance of load-bearing masonry walls were rigid foam and mineral wool blanket. In addition, loose-fill insulation poured into the hollow cores of 8-in blocks is examined. However, the methodology presented is flexible enough to allow the reader to consider many variations in insulating materials, based on their thermal resistance characteristics and general suitability for installation in sidewalls.

1.3 APPROACH

Incremental changes in annual space heating and cooling requirements due to increased levels of thermal resistance in exterior walls are calculated for each wall type in a wide range of climates for a 1176 square-foot, single-story house. The present-dollar values of life-cycle energy savings corresponding to these changes are then calculated, based on current and projected energy costs, equipment efficiencies, a discount rate, and the expected lifetime of the insulation. Initial costs of the different insulation types and resistance values examined are also estimated, based on current (1980) construction cost data.

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[1] For a description of NBSLD, see T. Kusuda, NBSLD, The Computer Program for Heating and Cooling Loads in Buildings, NBS BSS 69 (Washington, D.C.: National Bureau of Standards, 1976). For a description of the expanded output version, see Stephen R. Petersen and James P. Barnett, Expanded NBSLD Output for Analysis of Thermal Performance of Building Envelope Components, NBSIR 80-2076 (Washington, D.C.: National Bureau of Standards, July 1980).

[2] See E. Stamper, "Weather Data," ASHRAE Journal, February 1977, p. 47.

Incremental savings and costs due to increased insulation usage are compared on a present-value, life-cycle basis in order to determine the economically optimal level of insulation, i.e., that insulation method and resistance value which has the greatest cumulative net savings in any given installation. An indexing format is developed which allows the user to quickly determine the optimal insulation method and resistance value for each of the wall types examined.

1.4 ORGANIZATION

This report has six sections in addition to this introductory section. Section 2 begins by detailing the wall types and insulation methods to be considered. Section 3 outlines the thermal analysis procedures used to calculate the reduction in annual heating and cooling requirements attributable to increased insulation usage in each wall type. The prototype house and operational profile used in the analysis are described. In addition, the climatic variations used in the analysis are discussed. Section 4 provides the results of the thermal analysis in terms of calculated annual heating and cooling requirements for the prototype house, varied by wall type, wall U-value, and geographic location. The changes in annual heating and cooling requirements attributable to a reduction in U-value of 0.1 Btu/$(ft^2)(h)(°F)$ are calculated for each wall type, insulation method, and climate. Regression equations are then calculated based on heating degree days to allow interpolation of the thermal analyses to other geographic regions.

In section 5, the economic criteria for determining optimal insulation levels are presented. Three example problems are solved in order to demonstrate the calculation procedures. In section 6 an index number calculation procedure is introduced in order to facilitate the computation process, so that optimal insulation methods and resistance levels can be quickly identified. Finally, a summary, conclusions, and recommendations for further research are presented in section 7.

This report also contains three appendices which are intended to provide additional information related to the material covered in the main body of the report. Appendix A contains a glossary of selected technical terms used in this report. Appendix B provides graphical representations of the results of the thermal analysis described in section 4 for the 11 cities used in that analysis. Appendix C contains a brief guide to the relationship between the surface color and solar absorptance of various exterior wall coverings.

Facing page: *The thermal performance of a masonry wall can be expected to vary with concrete density, wall weight, the specific heat of its components, and the relative placement of the insulation within the wall.*

2. WALL TYPES EXAMINED AND INSULATION METHODS CONSIDERED

2.1 DESCRIPTION OF WALL TYPES EXAMINED

Basic descriptions of the three wall types modeled in this report are provided in table 1 for the 8-in concrete block wall, table 2 for the brick and block wall, and table 3 for the wood-frame wall. The descriptions include the thickness, specific heat, thermal resistance, and weight of each wall component and the resistance, thermal transmission coefficient (U), weight, and thermal mass of the overall wall on a square-foot basis.

Table 1. Base 8-in Block Wall Description[a]

A. 100 lb/ft^3 Concrete Block Wall

Component Description	Specific Heat Btu/(lb °F)	Overall Wall R	Overall Wall lb/ft^2	Core Area (71%) R	Core Area (71%) lb/ft^2	Web Area (29%) R	Web Area (29%) lb/ft^2
Outside air film[b]	-	0.17	-	0.17	-	0.17	-
8-in block	0.21	1.88	36.2	1.79	25.0	2.11	63.5
0.75-in air space[c]	-	0.96	-	0.96	-	0.96	-
0.50-in gypsum board	0.20	0.45	2.1	0.45	2.1	0.45	2.1
Inside air film	-	0.68	-	0.68	-	0.68	-
Total		4.14	38.3	4.05	27.1	4.37	65.6
U = 1/R		0.242		0.247		0.229	
Thermal Mass (Btu/ft^2 °F)		8.02		5.67		13.76	

B. 80 lb/ft^3 Block Wall

Component Description	Specific Heat Btu/(lb °F)	Overall Wall R	Overall Wall lb/ft^2	Core Area (71%) R	Core Area (71%) lb/ft^2	Web Area (29%) R	Web Area (29%) lb/ft^2
Outside air film[b]	-	0.17	-	0.17	-	0.17	-
8-in block	0.21	2.39	28.9	2.16	20.0	3.05	50.8
0.75-in air space[c]	-	0.96	-	0.96	-	0.96	-
0.50-in gypsum board	0.20	0.45	2.1	0.45	2.1	0.45	2.1
Inside air film	-	0.68	-	0.68	-	0.68	-
Total		4.65	31.0	4.42	22.1	5.31	52.9
U = 1/R		0.215		0.226		0.188	
Thermal Mass (Btu/ft^2 °F)		6.49		4.62		11.09	

C. 120 lb/ft^3 Concrete Block Wall

Component Description	Specific Heat Btu/(lb °F)	Overall Wall R	Overall Wall lb/ft^2	Core Area (71%) R	Core Area (71%) lb/ft^2	Web Area (29%) R	Web Area (29%) lb/ft^2
Outside air film[b]	-	0.17	-	0.17	-	0.17	-
8-in block	0.21	1.52	43.4	1.54	30.0	1.47	76.2
0.75-in air space[c]	-	0.96	-	0.96	-	0.96	-
0.50-in gypsum board	0.20	0.45	2.1	0.45	2.1	0.45	2.1
Inside air film	-	0.68	-	0.68	-	0.68	-
Total		3.78	45.5	3.80	32.1	3.73	78.3
U = 1/R		0.265		0.263		0.268	
Thermal Mass (Btu/ft^2 °F)		9.53		6.72		16.42	

[a] Actual thickness of 8-in block is 7.625 in. Total thickness of wall is 8.875 in.

[b] Winter design value (wind speed = 15 miles/hour).

[c] 0.75-in air space between block and gypsum board includes 0.75-in wood furring strips, 24 inches on center, having approximately the same resistance value as the air space.

Table 2. Base Brick and Block Wall Description[a]

Component Description	Specific Heat Btu/(lb °F)	Overall Wall R	Overall Wall lb/ft^2	Core Area (72.6%) R	Core Area (72.6%) lb/ft^2	Web Area (27.4%) R	Web Area (27.4%) lb/ft^2
Outside air film[b]	-	0.17	-	0.17	-	0.17	-
4-in brick (130 lb/ft^3)	0.19	0.40	39.3	0.40	39.3	0.40	39.3
2-in air space	-	0.96	-	0.96	-	0.96	-
4-in block (100 lb/ft^3)	0.21	1.36	20.3	1.51	16.6	1.01	30.2
0.75-in air space[c]	-	0.96	-	0.96	-	0.96	-
0.50-in gypsum board	0.20	0.45	2.1	0.45	2.1	0.45	2.1
Inside air film	-	0.68	-	0.68	-	0.68	-
Total		4.98	61.7	5.13	58.0	4.63	71.6
U = 1/R		0.201		0.195		0.216	
Thermal Mass (Btu/ft^2 °F)		12.15		11.37		14.23	

[a] Actual thickness of 4-in brick or block is 3.625 in. Total thickness of wall is 10.5 in.

[b] Winter design value (wind speed = 15 miles/hour).

[c] See footnote c in table 1.

Table 3. Base Wood-Frame Wall Description[a]

Component Description	Specific Heat Btu/(lb °F)	Overall Wall R	Overall Wall lb/ft^2	Cavity Area (85%) R	Cavity Area (85%) lb/ft^2	Stud Area (15%) R	Stud Area (15%) lb/ft^2
Outside air film[b]	-	0.17	-	0.17	-	0.17	-
0.50-in wood siding	0.28	0.82	1.3	0.82	1.3	0.82	1.3
0.50-in sheathing	0.31	1.31	0.8	1.31	0.8	1.31	0.8
3.50-in stud space[c]	0.33	1.27	1.4	0.94	-	4.36	9.3
0.50-in gypsum board	0.20	0.45	2.1	0.45	2.1	0.45	2.1
Inside air film	-	0.68	-	0.68	-	0.68	-
Total		4.70	5.6	4.37	4.2	7.79	13.5
U = 1/R		0.213		0.228		0.128	
Thermal Mass (Btu/ft^2 °F)		1.49		1.03		4.10	

a Wall thickness is 5.0 in.

b Winter design value (wind speed = 15 miles/hour).

c Studs are assumed to be placed on 16-in centers.

Component weights, thermal resistances, and specific heats are based on the _ASHRAE Handbook of Fundamentals_.[1] Three different concrete densities are examined in the description of the 8-in block wall: 80 lb/ft^3 (lightweight), 100 lb/ft^3 (medium weight), and 120 lb/ft^3 (heavyweight). However, an initial sensitivity analysis of the thermal performance of these three densities shows little difference after adjustment for differences in the overall U-value.[2] As a result, the 100 lb/ft^3 concrete is used as the base case for both the 8-in block wall and brick and block wall. Detailed drawings of each wall type examined are shown in figure 1.

The three basic wall types examined in this report range widely in weight, from approximately 5.6 lb/ft^2 of wall area for the wood-frame wall to 61.7 lb/ft^2 for the brick and block wall. The 8-in block wall (100 lb/ft^3 concrete) is approximately halfway between these two extremes at 38.3 lb/ft^2. Such a wide variation in weight per unit wall area can be useful in determining the relationship between wall weight and thermal performance for walls with identical U-values. For example, the 5.6 lb/ft^2 of wall area for the wood-frame wall is based on the use of lightweight siding (e.g., wood or aluminum). If brick veneer is used, the resulting wall weight is nearly identical to the 8-in block wall. Thus, the thermal analysis of the latter wall system provides a good basis for estimating the thermal performance of brick veneer walls.[3] While the use of a stucco exterior on masonry or wood-frame walls is not explicitly analyzed, the effect of stucco on the thermal performance of walls is primarily related to a change in wall U-value rather than wall weight.[4]

The thermal performance of the wall can also be expected to vary with the specific heat of its components and the relative placement of the insulation in the wall. The "thermal mass" of the wall, which is the sum of the weight of each component multiplied by its specific heat, is a better indicator of the ability of the wall to store and release heat in a dynamic operating environment than weight alone. No parametric measure has been defined to include the effects of the relative placement of the insulation within the wall. As will be seen, insulation placement can have a significant impact on the actual thermal performance of a wall design.

The solar absorptance (α) of the exterior wall surface, which is a function of its color, is also an important variable in the analysis of the thermal performance of wall constructions. For this reason, the same value for solar absorptance is used for establishing the basic performance data for each wall variation examined in this report. This base value is 0.5, which corresponds

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[1] _ASHRAE Handbook of Fundamentals_ (New York: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1972).

[2] See section 4.1.3.

[3] See section 4.1.1.

[4] See section 4.1.3.

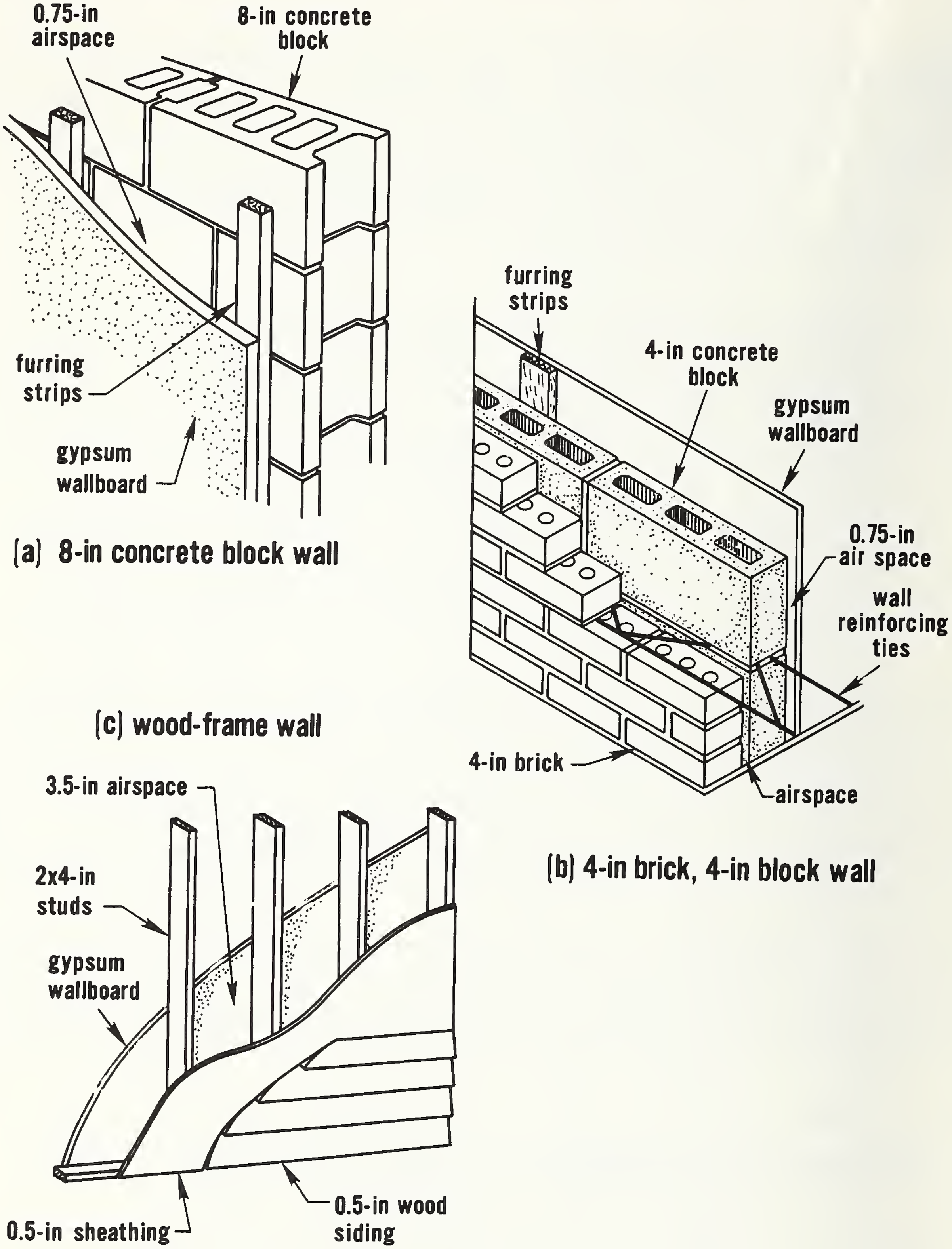

Figure 1. Details of three major wall types examined.

to a medium coloring (i.e., buff or beige). Appendix C contains a short guide to the relationship between surface color and solar absorptance. A limited sensitivity analysis is performed for the 8-in block wall in order to demonstrate the extent of variation in wall performance due to a higher (0.75) and lower (0.25) solar absorptance.

In tables 1 to 3, the core and web cross sections of the block walls are described separately. Similarly, in the wood-frame walls, the stud space and studs are described separately. Preliminary investigation into alternative modeling techniques showed that modeling the core (stud space) and web (stud) cross sections separately is more realistic than modeling the wall as homogeneous in mass and thermal resistance. This latter approach is easier and faster but exaggerates the thermal response characteristics of the wall in terms of dampening wall heat losses and gains over the heating and cooling seasons, respectively.

2.2 INSULATION METHODS

Practical insulation methods for exterior walls vary both by wall type and by the level of overall thermal resistance desired. Since the placement of the insulation vis a vis the thermal mass in masonry walls can have a significant effect on the dynamic thermal performance of those walls, this factor should be considered as well. In this subsection, several approaches to the insulation of both masonry walls and wood-frame walls will be briefly examined. For all wall types, the base case (i.e., uninsulated) wall is assumed to be covered with 0.5-in gypsum wallboard enclosing a non-reflective air space (R-value ≈ 0.96 $(ft^2)(h)(°F)/Btu$[1]).

For each insulation method discussed, an estimated installed cost (in 1980 dollars) is given. All costs include contractor overhead and profit. These costs are based on the 1980 Means Building Construction Cost Data.[2] In all cases where the use of increased insulation reduces usable floor space and/or increases window and door framing costs, these factors are included in estimating the installed insulation cost. The implicit cost of reduced inside floor space can be estimated by calculating the cost per incremental square foot of floor area (rather than average cost per square foot) in a new house. Extending the end wall of a house 28 feet wide (the width of the house studied in this report) by 2 feet will result in approximately 52 square feet of

[1] ASHRAE Handbook of Fundamentals, p. 358.

[2] Means Building Construction Cost Data, 1980 (Duxbury, Mass.: Robert Snow Means Company, Inc., 1979).

increased floor space at a cost of approximately $260, or $5 per square foot.[1] This provides a cost adjustment factor for insulation methods which increase the thickness of a wall beyond the base design value.

In general, for all masonry walls insulated on the inside surface and for wood-frame walls, the first increase in thermal resistance considered in this report is the use of foil-backed gypsum board together with the existing air space formed by the furring strips or studs. This reflective foil backing on one side of the air space has an emissivity of approximately 0.05, which results in an R-value of approximately 3.0 $(ft^2)(h)(°F)/Btu$.[2] The foil-backed gypsum board is generally considered first in this report because of its relatively low cost per resistance unit. However, if the air space is filled with conventional insulating materials in order to further increase the thermal resistance of the wall, the foil backing is no longer considered since it has no thermal resistance value without an adjoining air space.

2.2.1 Insulation in Masonry Walls

2.2.1.1 Insulation on the Inside Surface

Both concrete block and brick and block walls can be insulated on the inside surface before covering the wall with gypsum wallboard. Two basic methods are referenced here:

(1) Rigid foam insulation over, between, or beneath furring strips.[3] Rigid foam insulation beneath 0.75-in furring strips is preferred in this report because it reduces insulation cutting and fitting time,

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[1] This cost is for the structural modifications only since the actual inside finished area is assumed to remain constant. Based on Means Building Construction Cost Data, 1980, this cost includes the extension of footings, slab, walls, and roof.

[2] ASHRAE Handbook of Fundamentals, p. 358. In fact, this R-value varies between 2.8 and 3.6 $(ft^2)(h)(°F)/Btu$ depending on the mean temperature of the air space and the temperature differential across the air space. However, dynamic changes in the resistance of the air space cannot currently be modeled by the NBSLD computer program. Convection currents (i.e., air circulation) within the furring (stud) space can significantly reduce the effective resistance of any insulating method. The extent to which convection currents reduce the effective resistance of the reflective foil is not known.

[3] Alternatively, the furring strips can be eliminated (except at the top and bottom of the wall), and the wallboard can be glued directly to the foam insulation. This will reduce the cost of insulating with rigid foam but may reduce wall performance over time and increase wiring costs. As a result, it is not considered further in this report.

reduces thermal bridging, and provides an air space that can be used with foil-backed gypsum board, thereby reducing costs and increasing wall performance relative to the other two approaches. This approach is currently finding widespread use in Florida.

(2) Framing with free-standing 2 x 3-in studs in place of furring strips and insulating with mineral wool batts. While this second approach may appear redundant (in terms of creating a second "wall"), it is generally less costly than the first approach for two reasons: (i) mineral wool insulation materials (in standard sizes, e.g., R-11, R-19) are much less expensive than rigid foam insulation materials per unit of thermal resistance; and (ii) much of the cost of the framing is offset by omitting the furring strips. Typically, R-11 mineral wool insulation would be the smallest insulation resistance used with this approach since the cost differential above lower R-values (e.g., R-7) is relatively small. In such a case, the interior framing would stand away from the block wall approximately 1 inch in order to accomodate the standard 3.5-in, R-11 insulation batts without compression. By moving the framing out further from the wall, R-19 or greater resistances can be used in a similar manner.

Table 4 shows several levels of thermal resistance for both methods used with 8-in block walls, along with corresponding U-values and estimated installed costs. Table 5 shows similar data for brick and block walls.

2.2.1.2 Insulation in Cavity (Brick and Block Walls)

Only rigid foam insulation is considered for insulating the cavity area of a brick and block wall in this report. A 1-in air space between the insulation and the outer wall is recommended to avoid moisture penetration from the outside wall.[1] (Moisture-resistant, loose-fill insulating materials are also sometimes poured into the cavity. However the R-value per inch for these loose-fill materials is typically less than half that of rigid foam insulation, with a higher cost per unit of resistance.) Maximum cavity width depends on the wall design. However, 4.5 -in is considered to be a practical maximum.[2] Thus, with a rigid foam insulation having an R-value per inch of approximately 5.25 $(ft^2)(h)(°F)/Btu$ (e.g., extruded polystyrene), a maximum practical insulation R-value would be approximately R-18. (Some rigid foam insulation materials have R-values per inch as high as 7.0 $(ft^2)(h)(°F)/Btu$.) Since this insulation is located toward the outside of much of the wall mass, its thermal performance can be expected to be somewhat greater than the same insulation resistance on the inside surface of the wall.

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[1] "BIA Technical Notes on Brick Construction - 21," Brick Institute of America, McLean, Va.

[2] Ibid.

Table 4. Insulation Levels Examined and Cost Data for Insulation in 8-in Block Walls

Description	Insulation Resistance $(ft^2)(h)(°F)/Btu$	U-value $Btu/(ft^2)(h)(°F)$	Cost/ft^2
Base Case (0.75-in air space and 0.5-in wallboard)	–	0.242	0
Foil-backed wallboard	R-3	0.162	$0.10
Mineral Wool in 2 x 3-in framing[a]	R-11	0.074	$0.75
	R-13	0.066	$0.80
	R-19	0.046	$1.00
Rigid Foam on Inside Surface (R-value includes R-3 foil-backed wallboard)	R-7	0.098	$0.61
	R-9	0.082	$0.76
	R-12	0.066	$1.00
	R-15	0.055	$1.23
	R-18	0.047	$1.46
Loose fill in cores	R-12.5	0.112	$0.63

[a] Framing or furring area equals approximately 10 percent of net wall area. Costs include adjustment for decreased floor area.

Table 5. Insulation Levels Examined and Cost Data for Insulation in Brick and Block Walls

Description	Insulation Resistance $(ft^2)(h)(°F)/Btu$	U-value $Btu/(ft^2)(h)(°F)$	Cost/ft^2
Base Case (0.75-in air space and 0.5-in wallboard)	-	0.201	0
A. Insulation on Inside			
Foil-back wallboard	R-3	0.142	$0.10
1. Mineral Wool in 2 x 3-in framing	R-11	0.070	$0.75
	R-13	0.062	$0.80
	R-19	0.045	$1.00
2. Rigid Foam (R-value includes R-3 foil-back wallboard)	R-7	0.091	$0.61
	R-9	0.077	$0.76
	R-12	0.062	$1.00
	R-15	0.053	$1.23
	R-18	0.045	$1.46
B. Insulation in Cavity			
1. Rigid Foam	R-4	0.111	$0.51
	R-6	0.091	$0.66
	R-9	0.071	$0.90
	R-12	0.059	$1.13
	R-15	0.050	$1.36
	R-18	0.043	$1.57

Insulation resistance levels in the cavity of a brick and block wall that are examined in this report are shown in part B of table 5, along with estimated 1980 insulation cost data.

2.2.1.3 Insulation in Cores (Concrete Block Walls)

Loose-fill insulation (e.g., perlite or vermiculite) can be poured into the hollow cores of concrete blocks during construction. However, the effectiveness of such an insulating technique is somewhat limited because of the thermal bridging between cores. (Approximately 29 percent of the cross section of the 8-in block wall modeled is solid concrete.) Perlite has a somewhat higher resistance value per inch of thickness than vermiculite (approximately 2.7 vs. 2.2 $(ft^2)(h)(°F)/Btu$) and thus the former is modeled in the thermal analysis. While poured insulation may be practical in the cores of 8-in blocks, it is not considered practical in the smaller cores of the 4-in blocks used in brick and block walls because of its relatively high cost per effective resistance unit (R).

A cost of $\$0.63/ft^2$ of wall area is estimated for poured insulation in 8-in block walls, based on Means.[1] The use of perlite insulation reduces the U-value of an otherwise uninsulated 8-in block wall from approximately 0.242 to 0.112 $Btu/(ft^2)(h)(°F)$.[2] Note, however, that a greater reduction in U-value can be achieved at lower cost by insulating the wall on the inside. Table 5 shows that a U-value of 0.091 $Btu/(ft^2)(h)(°F)$, using rigid foam insulation plus reflective foil wallboard, costs only about $0.58 per square foot.

Rigid foam inserts which can be placed in the cores of 8-in blocks are also available. However, insufficient thermal performance data are available at this time to adequately model the use of such inserts. Thus these inserts are not evaluated in this report.

2.2.1.4 Insulation on the Outside Surface

Rigid foam insulation can be placed on the outer surface of a masonry wall in order to enhance the thermal storage characteristics of the walls.[3] However, this requires that the insulation be covered with a weatherproof covering (e.g., stucco or aluminum siding) at considerable additional cost. Since a major benefit of masonry walls is low exterior maintenance, this additional covering serves little purpose other than to protect the insulation. In such a case, exterior insulation is difficult to justify on a cost effectiveness basis relative to the insulation methods discussed above, despite its somewhat

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[1] Means Building Construction Cost Data, 1980.

[2] See table 4.

[3] See B. Peavy, F. Powell and D. Burch, Dynamic Thermal Performance of an Experimental Masonry Building, NBS BSS 45 (Washington, D.C.: National Bureau of Standards, 1972).

enhanced thermal performance.[1] For this reason it has not been explicitly evaluated in this report. (Some insight into the superior performance of insulation on the outside wall surface can be gained from examination of the cavity-insulated brick and block wall.)

2.2.2 Insulation in Wood-Frame Walls

As mentioned in the introduction, wood-frame walls have a natural advantage over load-bearing masonry walls when insulation is considered because of the empty stud space between the exterior sheathing and inside paneling. Since this stud space is open during construction, mineral wool insulation batts can be easily and relatively inexpensively installed at that time. Typically, R-11 mineral wool insulation is used in a nominal 2 x 4-in stud space because it has been engineered to fit snugly into a 3.5-in stud space having 16- or 24-in stud centers. A denser R-13 mineral wool batt is also produced to fit into the same space. In general, no less than R-11 insulation is recommended for use in wood-frame walls for two reasons: (1) if the stud space is not filled, convection currents tend to degrade the actual performance of the wall;[2] and (2) the extra cost involved in using R-11 mineral wool insulation relative to some lower level (e.g., R-7) is usually quite small so that the R-11 insulation tends to be more cost effective (in terms of reducing energy costs) than the lower level.

In order to increase the thermal resistance of a wood-frame wall beyond R-13, two basic options are available:

(1) The use of nominal 2 x 6-in studs in place of 2 x 4-in studs, which allows the use of a thicker insulation batt. (The additional framing cost can be minimized if the 2 x 6-in studs are placed 24-in on center, which also reduces thermal bridging.) Typically, a 6-in, R-19 mineral wool batt is used in this case. However, since the actual stud space is only 5.5 in, this results in a slight compression of the batt, thereby reducing its effective thermal resistance to R-18.[3]

(2) The use of rigid foam insulation (e.g., polystyrene or polyisocyanurate) instead of the more conventional asphalt-impregnated fiberboard sheathing. This rigid insulation is available in several thicknesses and

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[1] If the exterior covering is justified primarily for aesthetic, rather than protective, purposes (i.e., it would have been used whether or not the exterior wall was to be insulated), this approach would more likely be preferred to the use of rigid foam insulation on the inside wall surface.

[2] G. J. Tietsma and B. A. Peavy, The Thermal Performance of a Two-Bedroom Mobile Home, NBS BSS 102 (Washington, D.C.: National Bureau of Standards, 1978).

[3] Based on private correspondence with a representative of the Owens-Corning Fiberglas Corporation.

resistance values. It can be used in conjunction with 2 x 4-in studs and mineral wool insulation to achieve a total insulation resistance approximately equivalent to that using 2 x 6-in studs and R-19 mineral wool batts. Or it can be used with 2 x 6-in studs and R-19 mineral wool batts to increase the total insulation resistance significantly beyond the 2 x 6-in stud wall with conventional sheathing (e.g., R-23 to R-27).

Rigid foam insulation typically costs three or four times more per resistance unit than mineral wool batts (although the substitution for the conventional sheathing reduces its effective cost in this application somewhat). At the same time, the increased cost of 2 x 6-in studs instead of 2 x 4-in studs must be attributed to the insulation cost if R-19 mineral wool batts are used. As a result, the cost per unit of resistance above R-13 is typically significantly higher than the unit cost below R-13.

Table 6 shows five alternative levels of insulation for wood-frame walls examined in this report, along with the corresponding overall wall U-value and representative 1980 insulation costs. In table 6, the R-18 insulation level is based on R-13 mineral wool plus R-5 rigid foam sheathing, since the cost of this system is shown to be less than using 2 x 6-in studs and R-19 mineral wool. However, in some cases, the latter system may have a cost advantage over the former. For either case, the resulting U-value for the net wall area is approximately the same.

Table 6. Insulation Levels Examined and Cost Data for Insulation in Wood-Frame Walls

Description	Insulation Resistance $(ft^2)(h)(°F)/Btu$	U-value $Btu/(ft^2)(h)(°F)$	Cost
Base Case (3.5-in air space)		0.213	$ 0
Foil-backed wallboard	R-3	0.152	$0.10
Mineral Wool	R-11	0.078	$0.30
	R-13	0.071	$0.35
	≈R-19[a]	0.055	$0.55
Mineral Wool (R-18 plus Rigid Foam Sheathing (R-5))	≈R-23	0.045	$0.90

[a] R-19 mineral wool in a nominal 2 x 6-in stud wall compresses to R-18.

Facing page: *To calculate the thermal response of walls of significantly different weights and construction types, a dynamic simulation program such as NBSLD was needed.*

3. THERMAL ANALYSIS PROCEDURES

In this section, the basic modeling procedures used to calculate the reduction in space heating and cooling loads attributable to the various levels of insulation examined are discussed. This includes a description of the prototypical house used in the thermal analysis, the NBSLD computer program used to calculate space heating and cooling loads, and the climate data used to represent different geographic locations.

3.1 DESCRIPTION OF SINGLE-FAMILY HOUSE PROTOTYPE

In order to calculate accurately the effects of wall insulation on annual heating and cooling requirements, it is necessary to model the building in which the walls to be insulated are located. Table 7 provides the basic specifications of an 1176 ft^2, one-story, single-family house used in the NBSLD simulation of space heating and cooling requirements. This house, shown in figure 2, is modeled after the "compact" ranch-style house proposed by S. R. Hastings[1] as typical of one-story, single-family houses built in the United States, although it is somewhat smaller than the average house size of approximately 1500 ft^2. (However, the average figure includes multistory houses as well.) The house is modeled as one room, as it has been determined through previous analysis at NBS[2] that this method more closely approaches the actual thermal performance of a single-story house than modeling uncoupled rooms within the house. (Thermal coupling of rooms is a difficult problem and has not yet been incorporated into the NBSLD computer program.) The ceiling is modeled with an insulated attic; the level of insulation depends on the climatic location examined. The floor is modeled as a concrete slab weighing 20,000 lb and is essentially adiabatic (i.e., does not transmit heat into the ground).[3] This floor weight was selected to represent the internal mass of the house, including internal partitions, fixtures, and furnishings, rather than an actual slab on grade. As a result, the building modeled is more representative of a house over a heated basement or well-insulated crawlspace than a house actually built on a concrete floor slab. The house has approximately 0.6 air changes per hour at an outdoor temperature of 45°F and a wind speed of 7.5 miles per hour. However, the actual air change rate in any hour is dependent upon the inside-outside temperature differential and wind speed.

The base house is oriented with the long walls facing north and south. Of the 127 ft^2 of glass area, 72 ft^2 face south and 55 ft^2 face north. (The glass to gross wall area ratio is approximately 11 percent.) The south-facing glass includes a sliding glass door.

Operational assumptions are shown in table 8. Note that a night setback from 68° to 60°F is assumed during the heating season. This night setback, together with the internal mass and south-facing windows, gives the house some advantage from a "passive" solar aspect. The hourly internal heat release profile is also shown in table 8.

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[1] S. R. Hastings, Three Proposed Typical House Designs for Energy Conservation Research, NBSIR 77-1309 (Washington, D.C.: National Bureau of Standards, 1977).

[2] See S. R. Petersen and J. P. Barnett, Expanded NBSLD Output for Analysis of Thermal Performance.

[3] This is accomplished by modeling a very high thermal resistance beneath the slab in order to isolate it from the ground temperature.

Table 7. Prototype House Parameters[a]

Floor and ceiling areas = 1176 ft^2

Glass area = 127 ft^2 (72 ft^2 south, 55 ft^2 north)

Wall area: gross (including windows and doors) = 1120 ft^2
net = 973 ft^2

Wood door (1) = 20 ft^2

Outside dimensions = 28 ft x 42 ft

Solar absorptance of exterior walls = 0.50

Floor weight = 20,000 lb[b]

Shading coefficients for glass: single = 0.8, double = 0.7, triple = 0.6.

[a] Based on ranch house design in S. R. Hastings, Three Proposed Typical House Designs.

[b] Representative of interior mass of house.

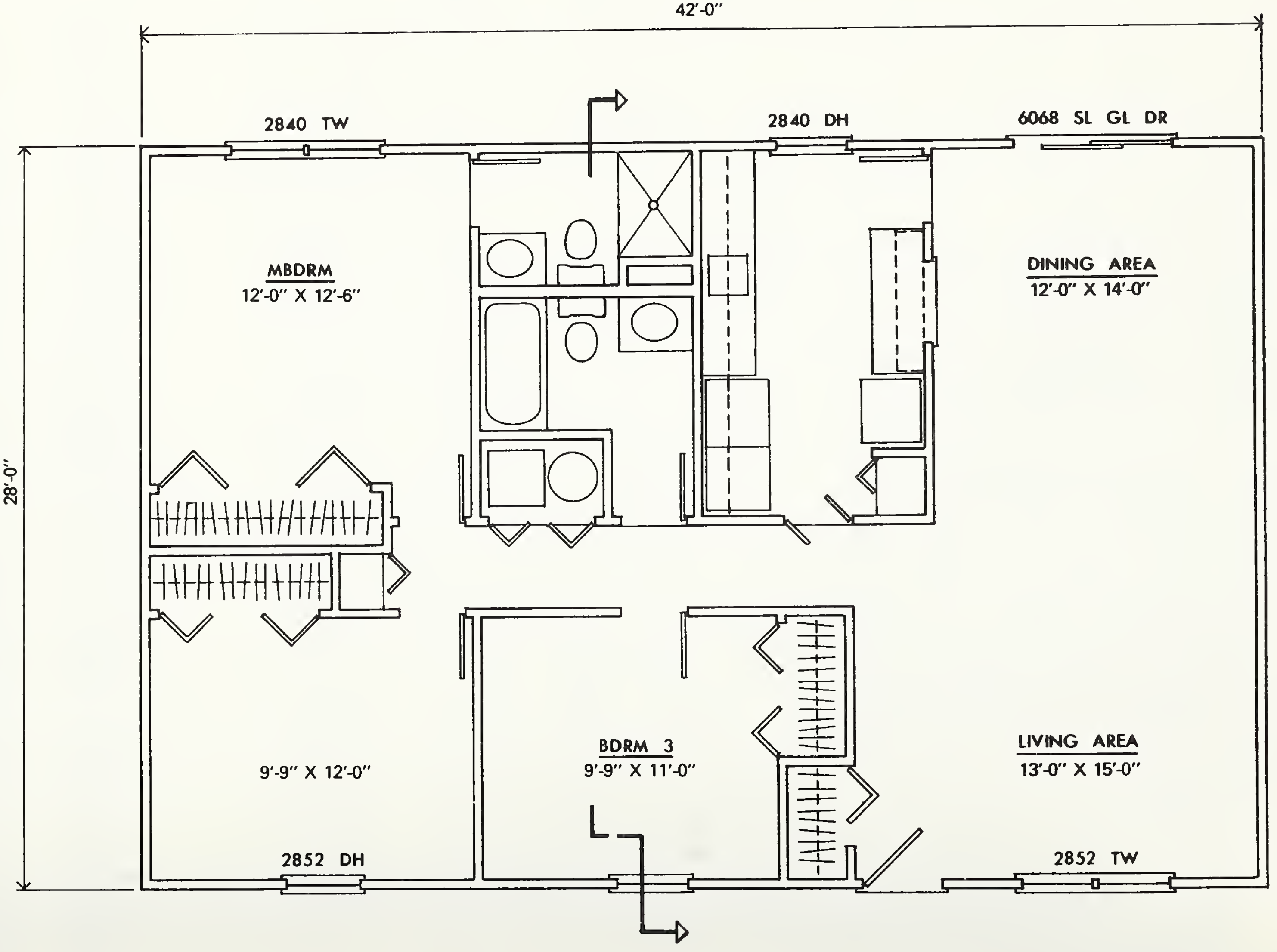

Figure 2. Floor plan of 1176 ft^2 single-family house used in analysis.
Source: S. R. Hastings, Three Proposed Typical House Designs.

Table 8. Operational Profile of Prototype House

Thermostat settings:[a]

Heating Periods: 68°F day
60°F night (11 p.m. - 7 a.m.)
Cooling Periods: 78°F

Relative Humidity:[b]
Lower Bound 20%
Upper Bound 60%

Occupants: 2 adults, 2 children

Hourly Lighting, Equipment, and Occupant Heat Release Schedule (Btu/h)

Hour	Lights	Equipment	Occupants
1	0	703	1200
2	0	703	1200
3	0	703	1200
4	0	703	1200
5	0	703	1200
6	0	1984	1200
7	2088	2935	1200
8	2088	3927	1200
9	48	2356	480
10	48	2522	480
11	48	2356	480
12	48	3638	480
13	48	2563	480
14	48	1984	480
15	48	1984	480
16	48	2108	828
17	48	1984	828
18	48	2687	1200
19	48	2894	1200
20	1044	3349	1200
21	1044	4134	1200
22	2088	2563	1200
23	2088	2894	1200
24	2088	1984	1200

[a] No cooling or heating is required when indoor temperature is between heating and cooling thermostat settings.

[b] Humidification is assumed during heating periods only, dehumidification is assumed during cooling periods only.

Since this study is limited to the analysis of wall insulation, the specification of the other shell components was held constant for each of the 11 geographic locations examined in this report. However, attic insulation levels and window glazing specifications (e.g., single, double, triple) were adjusted in each location in order to conform approximately with 1978 HUD Minimum Property Standards[1] for those locations. Table 9 provides these specifications for each of the 11 locations considered in this report. Details regarding the selection of these 11 locations are provided in section 3.3.

3.2 THERMAL MODELING PROCEDURES

NBSLD-XO,[2] an expanded output version of the National Bureau of Standards Load Determination Program, NBSLD,[3] was used to simulate the heating and cooling loads of the prototype house with its various wall modifications on an hourly basis for an entire year. Test Reference Year (TRY)[4] weather tapes were used to provide typical hourly climate data for the locations considered, consistent with the requirements of the basic NBSLD program. The annual heating requirements and annual cooling requirements reported represent the thermal energy output to the conditioned space from the heating and cooling equipment. Actual purchased energy requirements are calculated outside of the NBSLD simulation, based on estimates of seasonal heating and cooling equipment efficiencies.

Because NBSLD can calculate the thermal response of walls of significantly different weights and construction types to a relatively high degree of accuracy, this program is well suited for the thermal analyses needed for a study of this nature. In addition, it has been successfully validated in a number of studies at NBS and elsewhere.[5]

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[1] U.S. Department of Housing and Urban Development, "Minimum Property Standards for One- and Two-Family Dwellings."

[2] S. R. Petersen and J. P. Barnett, Expanded NBSLD Output for Analysis of Thermal Performance.

[3] T. Kusuda, NBSLD, The Computer Program for Heating and Cooling Loads.

[4] E. Stamper, "Weather Data."

[5] NBS studies include: B. Peavy, F. Powell and D. Burch, Dynamic Thermal Performance of an Experimental Masonry Building; and B. Peavy, D. Burch, F. Powell and C. M. Hunt, Comparison of Measured and Computer-Predicted Thermal Performance of a Four Bedroom Wood-Frame Townhouse, NBS BSS 57 (Washington, D.C.: National Bureau of Standards, 1973). Other studies include Roberts, Nall, Rogers and Greenburg, "Comparison of Computer-Predicted Thermal Loads with Measured Data from Three Occupied Townhouses," ASHRAE Transactions, Vol. 83, Part I (New York: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., 1978).

Table 9. Attic and Window Glazing Specifications by City

	Window Glazing	Attic Insulation
Albany	Double	R-30
Albuquerque	Double	R-30
Atlanta	Single	R-19
Indianapolis	Double	R-30
Jackson	Single	R-19
Jacksonville	Single	R-19
Madison	Triple	R-38
Phoenix	Single	R-19
Salt Lake City	Double	R-30
Tampa	Single	R-19
Washington, D.C.	Double	R-30

Three specific changes to the standard NBSLD program were made to improve the modeling of heating and cooling loads for the prototype house: (1) All glass areas of the house are assumed to be 50 percent shaded from May through September. (2) The direct solar heat gain is modeled so that 90 percent is distributed directly to the floor, with the remaining 10 percent evenly distributed to the other interior surfaces. This solar distribution in effect simulates the solar gain of interior partitions and furniture rather than of the inside of the exterior surfaces of the house when the house is modeled as a single room. (3) Cooling loads are divided into two parts: those cooling loads which occur when the outdoor temperature falls below the thermostat setting and those cooling loads which occur when the outdoor temperature is equal to or greater than the thermostat setting (78°F). This distinction is important because the direction of heat flow through the walls during cooling periods depends in part on whether the outdoor temperature is higher or lower than the inside temperature. When heat flow is outward during cooling periods, increased thermal resistance will increase cooling loads rather than reduce them. Moreover, when the outdoor temperature is lower than the indoor temperature, cooling loads can often be eliminated by increased natural ventilation.

3.3 CLIMATIC VARIATION CONSIDERATIONS

Eleven locations were selected for the NBSLD analysis of space heating and cooling loads. These locations are shown in table 10, along with heating degree day and cooling degree hour data calculated from the Test Reference Year weather tapes used in the analysis. (Two different calculation bases are shown for both heating degree days and cooling degree hours, as it will be shown in section 4.4 that the second calculation base in each case is useful in interpolating annual heating and cooling requirements to other locations in the United States.) Four of these eleven locations were selected because they are located in the south and southwest regions of the United States where the use of concrete block construction is common (Tampa, Jacksonville, Phoenix, and Albuquerque). The other locations were selected to provide a broader range of climate data for the thermal analysis. Even though it is recognized that load-bearing masonry wall construction is not common in single-family houses in many regions of the United States, the more complete data base that results may provide useful information to some potential users of this report, such as standards-making organizations.

The most comprehensive NBSLD analyses of the different wall parameters examined in this report, including changes in thermal resistance, mass, and color, were performed for the Washington, D.C. climate. This location was selected because it represents an approximate average heating climate and cooling climate in the United States.[1] For the brick and block walls, only 8 of the 11 locations were included in the analysis due to resource constraints. All calculations

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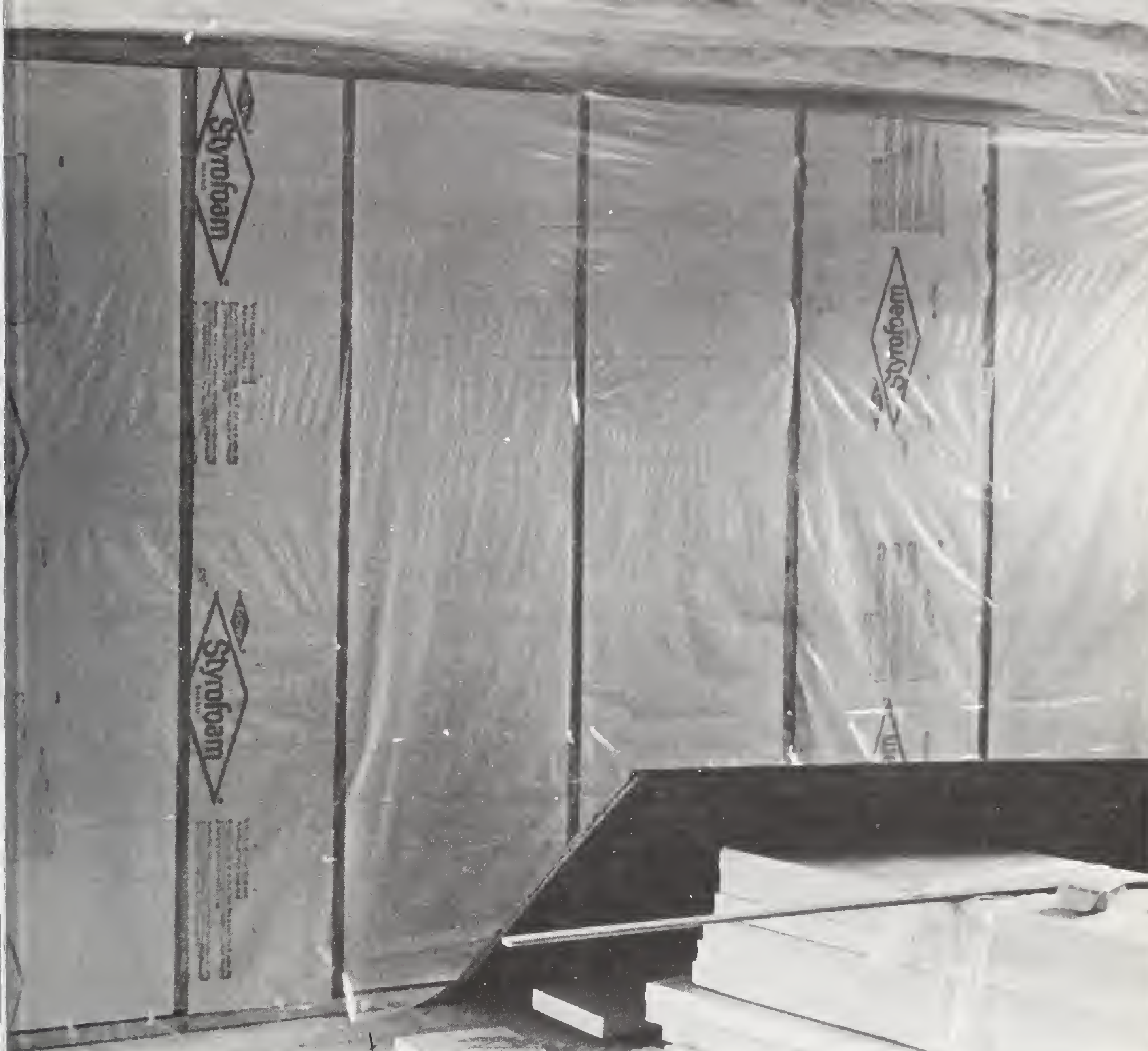
[1] Edward A. Arens and William L. Carroll, Geographical Variation in the Heating and Cooling Requirements of a Typical Single-Family House, and Correlation of These Requirements to Degree Days, NBS BSS 116 (Washington, D.C.: National Bureau of Standards, November 1978), p. 18.

Table 10. Heating Degree Days and Cooling Degree Hours Based on Test Reference Year (TRY) Data

Location	Heating Degree Days Base 65°F	Heating Degree Days Base 55°F	Cooling Degree Hours Base 65°F	Cooling Degree Hours Base 78°F
Albany	7118	4638	16742	1872
Albuquerque	4397	2408	35970	8054
Atlanta	2959	1370	36104	4525
Indianapolis	5886	3719	26320	3854
Jackson	2352	1025	59926	13547
Jacksonville	1239	327	65667	11827
Madison	7311	4765	15911	2239
Phoenix	1571	404	90743	37907
Salt Lake City	6216	3928	30367	7784
Tampa	459	57	76663	12904
Washington, D.C.	4162	2185	37589	7668

of annual heating and cooling requirements are based on the entire year of analysis and are not adjusted to remove heating or cooling requirements occuring out of season.

Facing page: *One of the types of insulation materials considered in this study was rigid foam.*



4. THERMAL ANALYSIS OF WALL INSULATION

In this section, the energy savings attributable to reductions in the U-value of each wall type described in section 3.1 are calculated using the NBS Load Determination (NBSLD) program and Test Reference Year (TRY) climate data. In order to reduce the total number of runs needed for a complete analysis of each case considered, and to provide a more generally useful data set, NBSLD runs were made only to establish the specific relationship between the thermal performance of the wall and wall U-values for each wall type and climate. Based on these specific relationships, the wall performance corresponding to any wall U-value (in the same general range) for a given wall type, climate, and insulation method can be accurately estimated.

A description of the U-values and corresponding insulation resistance levels actually analyzed using NBSLD, the resulting annual heating and cooling requirements, and some implications for wall design are discussed in this section.

4.1 INSULATION IN 8-IN BLOCK WALLS

4.1.1 Base Case (Open Cores, 100 lb/ft^3 Concrete, α =0.50)

Table 11 lists the annual heating and cooling requirements (AHR, ACR) of the single-family prototype house with the basic 8-in concrete block walls (i.e., open cores, 100 lb/ft^3 concrete density, solar absorptance of exterior surface = 0.50) for each of the 11 locations shown in table 10. In Washington, D.C., 5 different U-values were modeled; in the remaining 10 cities, 3 U-values were modeled. The U-values used were selected to establish a general relationship between AHR, ACR, and wall U-value. The AHR and ACR corresponding to intermediate U-values can be found by interpolation. In addition, moderate extrapolation to lower U-values will provide useful results.

The relationships between AHR and U-value and ACR and U-value are shown in figure 3 for the 8-in block wall in Washington, D.C. Note that AHR are characterized by a straight line, while there is a slight curvature in the ACR lines. The results for all 11 cities are shown graphically in figures B.1 through B.11 in appendix B. In general, they are also characterized by a linear AHR function and slightly curved ACR relationships.

As discussed in section 3.2, ACR are divided into two parts: ACR^+ include only cooling loads that occur when the outdoor temperature is equal to or greater than the air conditioner thermostat setting (78°F); ACR^- include only cooling loads that occur when the outdoor temperature is below the thermostat setpoint. These latter cooling requirements result when heat losses through the shell of the house are insufficient to offset the internal heat gain from occupants, lights, appliances, and solar heat gain through windows.

As the walls are better insulated, ACR^+ generally decrease, although only slightly in most cases. At the same time, ACR^- tend to increase, and generally offset any decrease in ACR^+, so that their sum, ACR^T, tends to increase as well. The only exception to the trends observed in the 11 locations examined is Phoenix, where the increase in wall insulation does result in a significant decrease in ACR^T, due to the extremely high daily temperatures during much of the cooling season in southwestern desert locations. When only the months of April through October are evaluated (i.e., assuming that the air conditioning equipment is not operating between November and March), ACR^T in Jackson, Jacksonville, and Tampa decrease as insulation levels in walls are increased. In the remaining cities studied, ACR^T increase slightly as the walls are better insulated.

If windows are assumed to be closed at all times, ACR^T better represent annual cooling requirements. If windows are opened for natural ventilation when the outdoor temperature (t_o) is below 78°F, ACR^+ are better. In fact, actual operating practices are usually somewhere between these two extremes. For example,

Table 11. Annual Heating and Cooling Requirements for Prototype House: 8-in Block Walls, No Insulation in Cores

Location	Overall Wall U-value Btu/$(ft^2)(h)(°F)$	R-value in Furring Space $(ft^2)(h)(°F)$/Btu	Annual Space Heating and Cooling[a] Requirements (million Btu) AHR	ACR^+	ACR^-	ACR^T
Albany	0.2417	0.96	51.33	3.10	3.13	6.23
	0.1443	3.75	39.46	3.11	3.86	6.97
	0.0693	11.25	30.07	3.16	4.73	7.89
Albuquerque	0.2417	0.96	21.89	9.06	3.94	13.00
	0.1443	3.75	15.28	8.72	4.69	13.40
	0.0693	11.25	10.33	8.55	5.61	14.15
Atlanta	0.2417	0.96	16.81	9.37	7.43	16.80
	0.1443	3.75	12.55	9.22	8.48	17.70
	0.0693	11.25	9.36	9.18	9.49	18.68
Indianapolis	0.2417	0.96	41.34	6.32	4.34	10.65
	0.1443	3.75	31.26	6.18	5.10	11.28
	0.0693	11.25	23.35	6.14	6.04	12.17
Jackson	0.2417	0.96	12.46	19.59	8.14	27.74
	0.1443	3.75	9.11	18.97	8.87	27.84
	0.0693	11.25	6.63	18.56	9.58	28.14
Jacksonville	0.2417	0.96	3.50	21.66	11.05	32.71
	0.1443	3.75	2.27	21.21	12.01	33.22
	0.0693	11.25	1.47	20.94	13.03	33.97
Madison	0.2417	0.96	48.71	3.17	2.20	5.37
	0.1443	3.75	36.23	3.17	2.95	6.12
	0.0693	11.25	26.41	3.21	3.97	7.18
Phoenix	0.2417	0.96	3.93	36.44	5.57	42.01
	0.1443	3.75	2.56	33.84	6.30	40.14
	0.0693	11.25	1.68	31.86	7.09	38.96
Salt Lake City	0.2417	0.96	39.82	7.91	2.84	10.76
	0.1443	3.75	29.51	7.76	3.33	11.09
	0.0693	11.25	21.45	7.73	3.92	11.65
Tampa	0.2417	0.96	0.82	24.26	13.91	38.16
	0.1443	3.75	0.47	23.79	15.15	38.94
	0.0693	11.25	0.28	23.51	16.29	39.80
Washington, D.C.	0.2417	0.96	21.53	10.70	4.97	15.67
	0.1618	3.00	16.10	10.34	5.53	15.86
	0.1443	3.75	14.92	10.26	5.68	15.94
	0.0936	7.50	11.55	10.06	6.20	16.27
	0.0693	11.25	9.96	9.98	6.52	16.49

[a] $ACR^T = ACR^+ + ACR^-$.

[b] Air space (0.75 in) has an R-value of approximately 0.96 $(ft^2)(h)(°F)$/Btu. Insulation density actually modeled is 2.2 lb/ft^2 with an R-value per inch of 5.0 $(ft^2)(h)(°F)$/Btu.

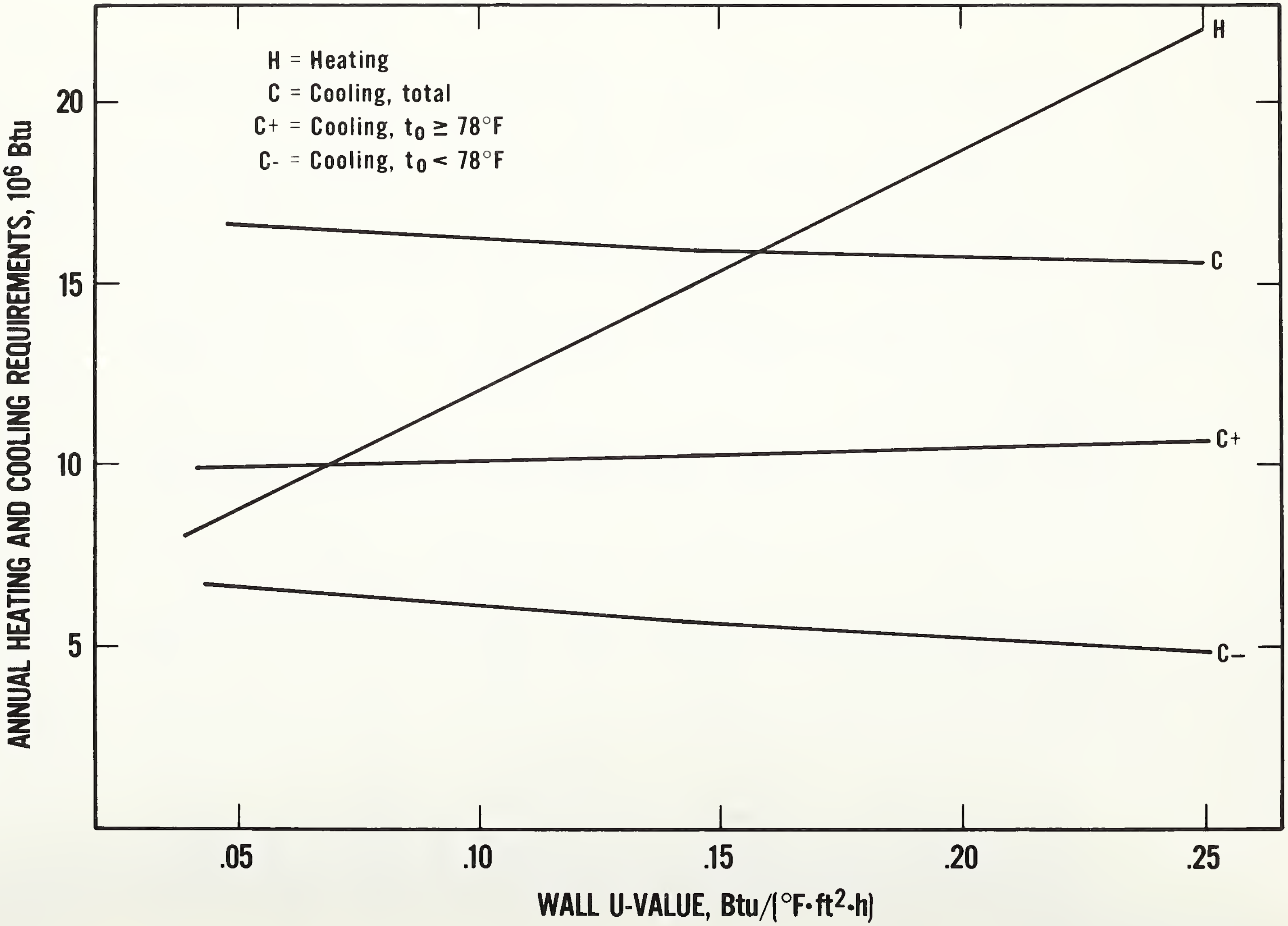


Figure 3. Relationship between AHR, ACR, and U-value: 8-in block walls (Washington, D.C.).

during spring and fall, windows and doors may be left open for natural ventilation more frequently than during the summer months. However, noise, humidity, air pollution, and security considerations may encourage leaving windows closed more than they might be otherwise, especially in urban areas. As a result, the net effect of increasing wall insulation in many houses is likely to be insignificant in terms of decreasing or increasing actual ACR, depending largely on how the house is operated by its occupants during the year.

Note that no simple summation of AHR and ACR to compute total space heating and cooling requirements is provided. Such a total would be relatively meaningless since it does not correspond to the actual purchased energy needed to satisfy these total requirements, due to differences in furnace and air conditioner efficiencies. Nor would such a total recognize the difference in price (nor resource energy requirements) if different energy types were used for heating and cooling (e.g., natural gas and electricity, respectively). The combined effects of both AHR and ACR are best quantified in terms of present-value, life-cycle dollar expenditures for energy used in space conditioning.[1]

Thermal insulation materials are generally of relatively low density (0.75 to 3.5 lb/ft^3 for most rigid foam and mineral wool insulating materials) compared to masonry materials. Variations in insulation density in this range will not have a significant effect on wall performance, given equal thermal resistance. Thus the AHR and ACR corresponding to other insulation types than the rigid foam insulation modeled can also be interpolated using the data in table 11, provided that the thermal resistance is known and its relative placement in the wall is the same.

Because the weight of the 8-in concrete block walls (38.3 lb/ft^2 of wall area) is nearly identical to the weight of brick veneer walls (4-in face brick on wood-frame walls), the AHR and ACR shown in table 11 will be appropriate to use for brick veneer walls as well.

4.1.2 Solar Absorptance Variations

The solar absorptance (α) of the exterior wall surface can have a significant effect on the thermal performance of walls. In general, one would expect that darker colored walls, having a higher solar absorptance, would lose less heat during the heating season and gain more heat during the cooling season than lighter colored walls. These expectations are borne out in the results of the additional thermal analysis of 8-in block walls with an α of 0.25 and 0.75, corresponding to a very light and a moderately dark colored wall, respectively. (Appendix C provides a short guide to the correspondence between surface color and solar absorptance.)

Table 12 provides the calculated AHR and ACR for the prototype house with exterior walls having an α of 0.25 for 8 of the 11 locations examined in

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[1] This will be discussed further in section 5.

Table 12. Annual Heating and Cooling Requirements for Prototype House: 8-in Block Walls, $\alpha = 0.25$

Location	Overall Wall U-value Btu/(ft^2)(h)(°F)	R-value in Furring Space (ft^2)(h)(°F)/Btu	Annual Space Heating and Cooling[a] Requirements (million Btu) AHR	ACR^+	ACR^-	ACR^T
Albuquerque	0.2417	0.96	23.01	8.27	3.37	11.64
	0.0693	11.25	10.59	8.33	5.34	13.66
Atlanta	0.2417	0.96	17.40	8.77	6.64	15.41
	0.0693	11.25	9.50	9.02	9.17	18.19
Indianapolis	0.2417	0.96	42.22	5.87	3.87	9.73
	0.0693	11.25	23.57	6.01	5.81	11.82
Jacksonville	0.2417	0.96	3.73	20.80	10.28	31.08
	0.0693	11.25	1.51	20.71	12.72	33.43
Madison	0.2417	0.96	49.76	2.90	1.81	4.71
	0.0693	11.25	26.68	3.14	3.76	6.90
Phoenix	0.2417	0.96	4.31	34.56	4.72	39.28
	0.0693	11.25	1.75	31.32	6.73	38.06
Tampa	0.2417	0.96	0.89	23.46	13.17	36.62
	0.0693	11.25	0.28	23.29	16.01	39.30
Washington, D.C.	0.2417	0.96	22.24	10.10	4.53	14.63
	0.1443	3.75	15.31	9.90	5.34	15.24
	0.0693	11.25	10.13	9.81	6.32	16.12

[a] $ACR^T = ACR^+ + ACR^-$.

this report. Table 13 provides the calculated AHR and ACR corresponding to an α of 0.75 for the same eight locations. Annual cooling requirements for the prototype house with walls having an α of 0.25 and a U-value of approximately 0.10 Btu/(ft^2)(h)(°F) on the average are decreased by 3 percent from that of the α = 0.5 base case. The AHR are on the average increased by 2 percent. The ACR for the same house with walls having an α of 0.75 and a U-value of approximately 0.10 Btu/(ft^2)(h)(°F) on the average are increased by 3 percent from that of the α = 0.5 base case and the AHR are decreased by 2 percent. Figure 4 shows the effect of solar absorptance on AHR and ACR for the prototype house with 8-in block walls in the Washington, D C climate.

Variations in AHR and ACR that are attributable to differences in solar absorptance could be important if they resulted in a significant change in the expected energy savings due to the increased use of insulation. As would be expected, the data in tables 12 and 13 show that the reductions in AHR due to insulating the walls will be less for the darker colored walls (α = 0.75) and more for the lighter colored walls (α = 0.25). On the average, the reductions in AHR due to insulating an 8-in block wall with R-11.25 insulation are increased by 7 percent for the lighter wall and reduced by 7 percent on the darker wall, with smaller effects in the colder climates and larger effects in those climates with milder winters. When the lighter color wall is insulated as shown in table 12, ACR^+ increase in four of the locations (Albuquerque, Atlanta, Indianapolis, and Madison), although insignificantly. Reductions in ACR^+ in the remaining locations also tend to be insignificant, except in Phoenix. When the darker wall is insulated, as shown in table 13, ACR^+ decrease in all cases. ACR^T for the lighter wall tend to increase slightly more than for the medium-colored wall as insulation is added, while for the darker wall, ACR^T increase less. However, it is unlikely that these changes will have an effect on the optimal insulation level except in borderline cases. This will be discussed further in section 5.

While the effects of color will not likely affect the optimal level of insulation, careful consideration of wall color can improve the overall thermal performance of exterior walls in climates dominated by either space heating or space cooling requirements. However, if annual heating and cooling requirements are of the same order of magnitude, the seasonal effects of wall color tend to be offsetting.

4.1.3 Concrete Density Variations

As seen in table 1, the use of lightweight concrete (80 lb/ft^3) instead of medium-weight concrete (100 lb/ft^3) will reduce the weight of the 8-in block wall from 38.3 lb/ft^2 to 31.0 lb/ft^2 of wall area.[1] Likewise, the use of heavyweight concrete (120 lb/ft^3) will increase the weight of the 8-block wall to 45.5 lb/ft^2 of wall area. Since the weight of the wall is expected to affect its thermal performance, several simulations were run for the prototype

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[1] All wall weights are approximate, depending on the ratio of empty core to solid volume.

Table 13. Annual Heating and Cooling Requirements for Prototype House: 8-in Block Walls, $\alpha = 0.75$

Location	Overall Wall U-value Btu/(ft^2)(h)(°F)	R-value in Furring Space (ft^2)(h)(°F)/Btu	Annual Space Heating and Cooling[a] Requirements (million Btu)			
			AHR	ACR^+	ACR^-	ACR^T
Albuquerque	0.2417	0.96	20.83	9.86	4.57	14.42
	0.0693	11.25	10.08	8.77	5.88	14.65
Atlanta	0.2417	0.96	16.24	9.97	8.26	18.23
	0.0693	11.25	9.22	9.35	9.81	19.16
Indianapolis	0.2417	0.96	40.48	6.77	4.85	11.62
	0.0693	11.25	23.12	6.26	6.26	12.52
Jacksonville	0.2417	0.96	3.28	22.51	11.84	34.35
	0.0693	11.25	1.43	21.17	13.35	34.52
Madison	0.2417	0.96	47.68	3.44	2.63	6.07
	0.0693	11.25	26.15	3.28	4.18	7.46
Phoenix	0.2417	0.96	3.60	38.31	6.51	44.81
	0.0693	11.25	1.60	32.40	7.46	39.87
Tampa	0.2417	0.96	0.33	24.04	15.79	39.83
	0.0693	11.25	0.27	23.73	16.56	40.29
Washington, D.C.	0.2417	0.96	20.82	11.30	5.40	16.70
	0.1443	3.75	14.55	10.61	6.03	16.64
	0.0693	11.25	9.81	10.14	6.72	16.87

[a] $ACR^T = ACR^+ + ACR^-$.

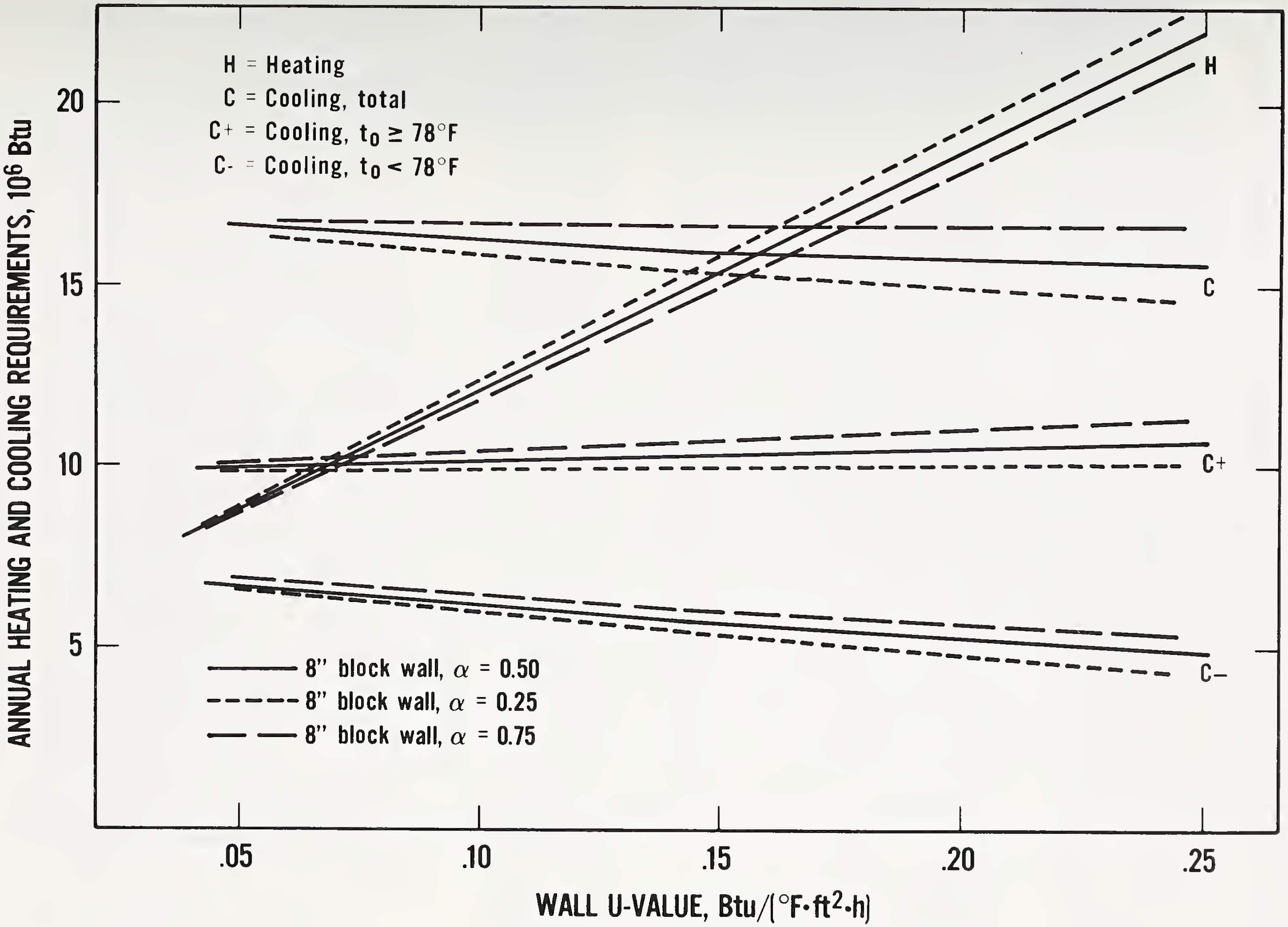

Figure 4. Effects of solar absorptance on AHR and ACR: 8-in block walls (Washington, D.C.).

house in the Washington, D.C., climate with each of these three walls at three different U-values. The results of these simulations are shown in table 14.

Because the U-value of the wall is increased as higher density concrete blocks are used, the effect of weight alone on thermal performance is masked. In order to consider the effects of weight alone, the AHR and ACR are interpolated to common U-values of 0.1 and 0.25 Btu/(ft^2)(h)(°F) in table 15. Here it can be seen that these moderate changes in wall weight have very small effects on space heating and cooling requirements and no significant effect on the change in AHR or ACR due to the use of additional insulation.

While the effect of mass alone on heat transfer through these three walls is insignificant, the effects of concrete density on overall wall U-values and the resulting effects on AHR are quite significant, especially for the uninsulated wall. The house with the heavier uninsulated wall (45.5 lb/ft^2) and higher wall U-value (0.42 Btu/(ft^2)(h)(°F)) has AHR that are 27 percent greater than the lighter uninsulated wall (31.0 lb/ft^2) with the lower U-value (0.31 Btu/(ft^2)(h)(°F)). The house with heavier walls insulated to R-11.25 has AHR that are only 3 percent greater than the house with lighter walls insulated to the same level. These differences are almost entirely attributable to the differences in wall U-value rather than wall weight. As a result, variations in weight alone for the 8-in block walls are not examined in other locations. However, the effects of changes in U-value on AHR and ACR can be calculated by interpolation for other density values in this same range using the data calculated for the 100 lb/ft^3 8-in block walls.

This analysis of relatively moderate weight differences for masonry walls implies that the use of stucco as an exterior surface material will not have any significant impact on the thermal performance of walls other than in terms of a change in U-value. For this reason, stucco exteriors have not been explicitly analyzed in this report.

4.1.4 8-in Block Walls (Insulated Cores)

Table 16 lists the AHR and ACR for the 8-in block wall (α = 0.5, concrete density = 100 lb/ft^3) with the cores empty (U = 0.2417 Btu/(ft^2)(h)(°F)) and filled with poured insulation having an R-value per inch of 2.7 (ft^2)(h)(°F)/Btu (U = 0.1116 Btu/(ft^2)(h)(°F)). (This is the approximate R-value per inch of perlite insulation.) AHR and ACR were calculated for all 11 locations listed in table 10. Figure 5 shows graphically the results of this analysis for the Washington, D.C., climate and contrasts these results with those of the 8-in block wall with uninsulated cores. Figures B.1 through B.11 in appendix B show the corresponding results for all 11 locations. Comparision of the two wall types shows that for the same wall U-value the wall with insulated cores has slightly lower AHR and ACR. This is due to the fact that the relative placement of insulation in the wall has been changed. Both AHR and ACR$^+$ are reduced with the pouring of insulation in the cores in all locations.

Table 14. Annual Heating and Cooling Requirements for Prototype House in Washington, D.C.: 8-in Block Walls, Variation in Concrete Density

Overall Wall U value (Btu/(ft^2)(h)(°F))	R-value in Furring Space ((ft^2)(h)(°F)/Btu)	Concrete Density (lb/ft^3)	Wall Weight (lb/ft^2)	Annual Space Heating and Cooling Requirements (million Btu)		
				AHR	ACR$^+$	ACR^T
0.3101[a]	0	80	31.0	26.28	11.35	15.75
0.3661[a]	0	100	38.3	29.94	11.49	15.73
0.4224[a]	0	120	45.5	33.51	11.63	15.77
0.1344	3.75	80	31.0	14.27	10.26	16.00
0.1443	3.75	100	38.3	14.92	10.26	15.94
0.1524	3.75	120	45.5	15.46	10.26	15.90
0.0669	11.25	80	31.0	9.81	9.98	16.52
0.0693	11.25	100	38.3	9.96	9.98	16.49
0.0711	11.25	120	45.5	10.08	9.97	16.47

[a] Unfinished interior, i.e., no wallboard or furring space.

Table 15. Calculation of AHR and ACR for Prototype House in Washington, D.C., Interpolated to Same U-Values: 8-in Block Walls, Three Concrete Densities

U-value (Btu/(ft^2)(h)(°F))	Concrete Density (lb/ft^3)	Wall Weight (lb/ft^2)	Annual Space Heating and Cooling Requirements (million Btu)		
			AHR	ACR$^+$	ACR^T
0.25	80	31.0	22.17	10.98	15.84
0.25	100	38.3	22.09	10.75	15.68
0.25	120	45.5	21.98	10.76	15.86
0.10	80	31.0	12.00	10.12	16.27
0.10	100	38.3	11.97	10.09	16.22
0.10	120	45.5	11.99	10.08	16.27

Table 16. Annual Heating and Cooling Requirements for Prototype House: 8-in Block Walls, Insulation in Cores[a]

			Annual Space Heating and Cooling[b] Requirements (million Btu)			
Location	Overall Wall U-value $Btu/(ft^2)(h)(°F)$	R-value in Core $(ft^2)(h)(°F)/Btu$	AHR	ACR^+	ACR^-	ACR^T
Albuquerque	0.2417	0.96	23.01	8.27	3.37	11.64
	0.0693	11.25	10.59	8.33	5.34	13.66
Atlanta	0.2417	0.96	17.40	8.77	6.64	15.41
	0.0693	11.25	9.50	9.02	9.17	18.19
Indianapolis	0.2417	0.96	42.22	5.87	3.87	9.73
	0.0693	11.25	23.57	6.01	5.81	11.82
Jacksonville	0.2417	0.96	3.73	20.80	10.28	31.08
	0.0693	11.25	1.51	20.71	12.72	33.43
Madison	0.2417	0.96	49.76	2.90	1.81	4.71
	0.0693	11.25	26.68	3.14	3.76	6.90
Phoenix	0.2417	0.96	4.31	34.56	4.72	39.28
	0.0693	11.25	1.75	31.32	6.73	38.06
Tampa	0.2417	0.96	0.89	23.46	13.17	36.62
	0.0693	11.25	0.28	23.29	16.01	39.30
Washington, D.C.	0.2417	0.96	22.24	10.10	4.53	14.63
	0.1443	3.75	15.31	9.90	5.34	15.24
	0.0693	11.25	10.13	9.81	6.32	16.12

[a] Perlite insulation in cores, R-value per inch = 2.7 $(ft^2)(h)(°F)/Btu$.

[b] $ACR^T = ACR^+ + ACR^-$.

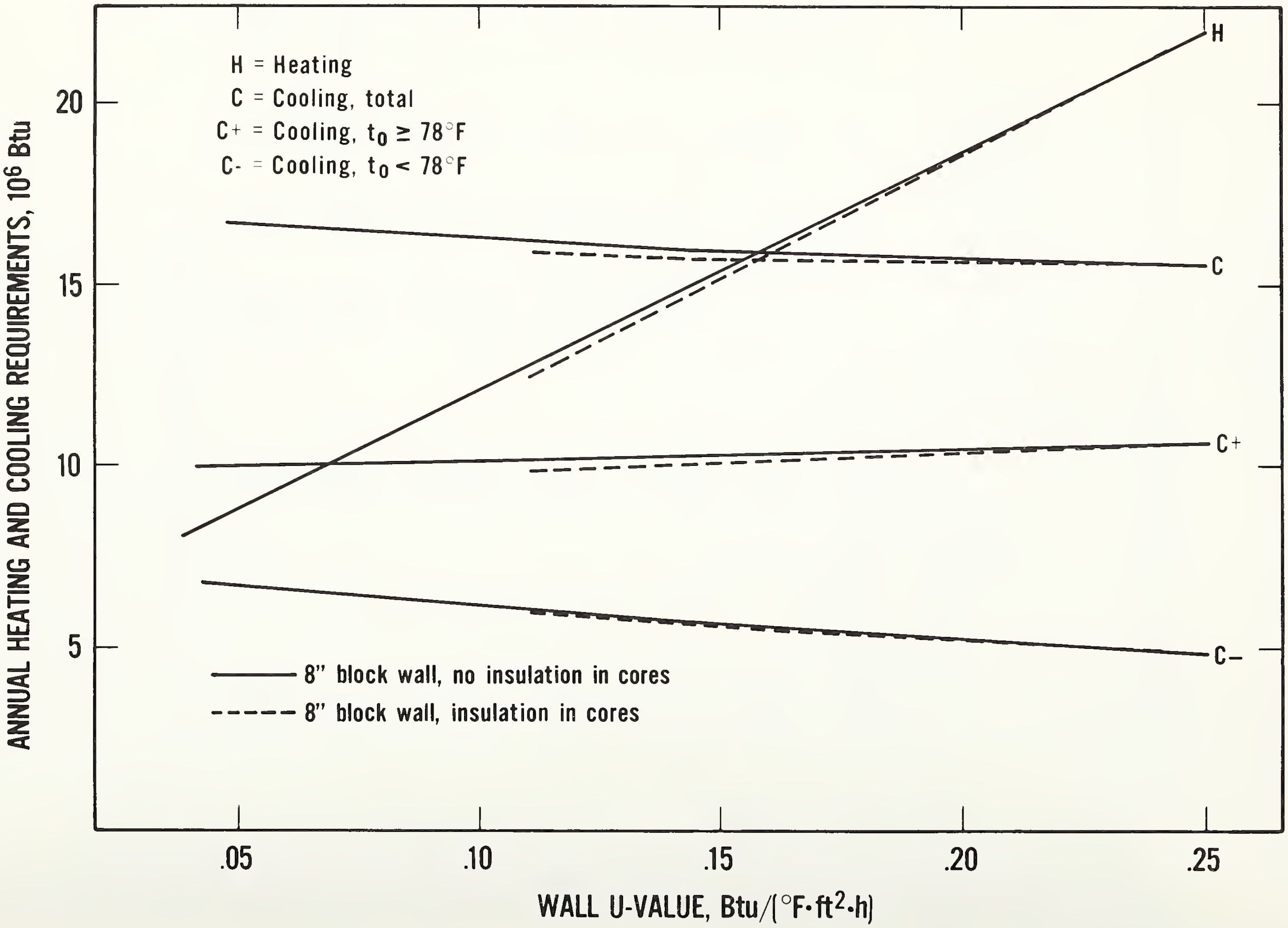

Figure 5. Relationship between AHR, ACR, and U-value: 8-in block walls, insulation in cores (Washington, D.C.).

4.2 INSULATION IN BRICK AND BLOCK WALLS

The construction detail of the brick and block wall modeled is provided in table 2. At 61.7 lb/ft^2 of wall area it has considerably more thermal mass than the 8-in block wall and thus somewhat improved thermal performance for any given overall U-value can be expected. In addition, the U-value of the uninsulated brick and block wall (0.20 $Btu/(ft^2)(h)(°F)$) is somewhat lower than that of the basic uninsulated 8-in block wall (0.24 $Btu/(ft^2)(h)(°F)$).

Two basic approaches to insulating the brick and block wall are considered here: insulation on the inside wall surface, covered with 0.5-in gypsum wallboard, and insulation in the cavity (i.e., between the brick and the block). It can be expected that the insulation in the cavity will perform better than insulation on the inside wall surface, since the insulation is moved toward the outside of the wall. Due to time and resource constraints, computer runs were made for only 8 of the 11 locations shown in table 10 (Albany, Jackson, and Salt Lake City were not included).

4.2.1 Insulation on Inside Surface

Table 17 shows the AHR and ACR of the prototype house with brick and block walls insulated on the inside wall surface for eight locations. This same data is shown graphically for Washington, D.C.,in figure 6 and for all eight locations in figures B.12 through B.19 in appendix B. The results of the thermal analysis of the basic 8-in block wall are included in these figures so that the thermal performance of the two wall types of different weights can be compared at equivalent U-values. In general, the thermal performance of the brick and block wall insulated on the inside surface is slightly better than that of the 8-in block wall when insulated to the same overall U-value. While it appears that the effect of wall weight on AHR and ACR diminishes as the wall U-value decreases, it should be noted that this is due largely to the decreased importance of the wall in establishing the overall AHR and ACR. If the thermal performance of the wall alone is considered, the effect of wall weight in terms of reducing heat loss through the wall over the heating season tends to remain relatively constant as the U-value is changed.[1]

Except in the case of Phoenix, the changes in ACR^+ due to increased insulation are insignificant. ACR^T for the brick and block wall house tend to increase slightly more than for the 8-in block wall as the wall U-value decreases. Again, ACR^T include cooling loads outside the normal air conditioning season.

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[1] It should be noted that the proportion of total heating or cooling requirements due to heat transfer through the walls of the house modeled in this report is not representative of a typical house since no floor losses are calculated.

Table 17. Annual Heating and Cooling Requirements for Prototype House: Brick and Block Walls, Insulation on Inside Surface

			Annual Space Heating and Cooling[a] Requirements (million Btu)			
Location	Overall Wall U-value Btu/(ft^2)(h)(°F)	R-value in Furring Space[b] (ft^2)(h)(°F)/Btu	AHR	ACR$^+$	ACR$^-$	ACR^T
Albuquerque	0.2007	0.96	18.95	8.23	4.35	12.58
	0.1286	3.75	14.08	8.25	4.91	13.16
	0.0654	11.25	10.00	8.34	5.69	14.03
Atlanta	0.2007	0.96	14.79	8.81	8.08	16.89
	0.1286	3.75	11.70	8.92	8.84	17.76
	0.0654	11.25	9.10	9.05	9.63	18.68
Indianapolis	0.2007	0.96	37.04	5.92	4.76	10.67
	0.1286	3.75	29.52	5.95	5.34	11.30
	0.0654	11.25	22.89	6.03	6.12	12.16
Jacksonville	0.2007	0.96	2.76	20.76	11.78	32.54
	0.1286	3.75	1.95	20.73	12.43	33.16
	0.0654	11.25	1.37	20.75	13.20	33.95
Madison	0.2007	0.96	43.34	2.93	2.43	5.36
	0.1286	3.75	34.04	3.03	3.09	6.11
	0.0654	11.25	25.84	3.15	4.02	7.17
Phoenix	0.2007	0.96	2.97	34.37	6.09	40.46
	0.1286	3.75	2.14	32.85	6.59	39.43
	0.0654	11.25	1.54	31.51	7.22	38.73
Tampa	0.2007	0.96	0.60	23.35	14.78	38.13
	0.1286	3.75	0.39	23.31	15.61	38.92
	0.0654	11.25	0.25	23.32	16.48	39.80
Washington, D.C.	0.2007	0.96	18.66	10.11	5.45	15.56
	0.1286	3.75	13.78	9.93	5.98	15.91
	0.0654	11.25	9.65	9.84	6.64	16.49

[a] $ACR^T = ACR^+ + ACR^-$.

[b] Air space (0.75 in) has an R-value of approximately 0.96 (ft^2)(h)(°F)/Btu. Insulation density in furring space is 2.2 lb/ft^3 with an R-value per inch of 5.0 (ft^2)(h)(°F)/Btu.

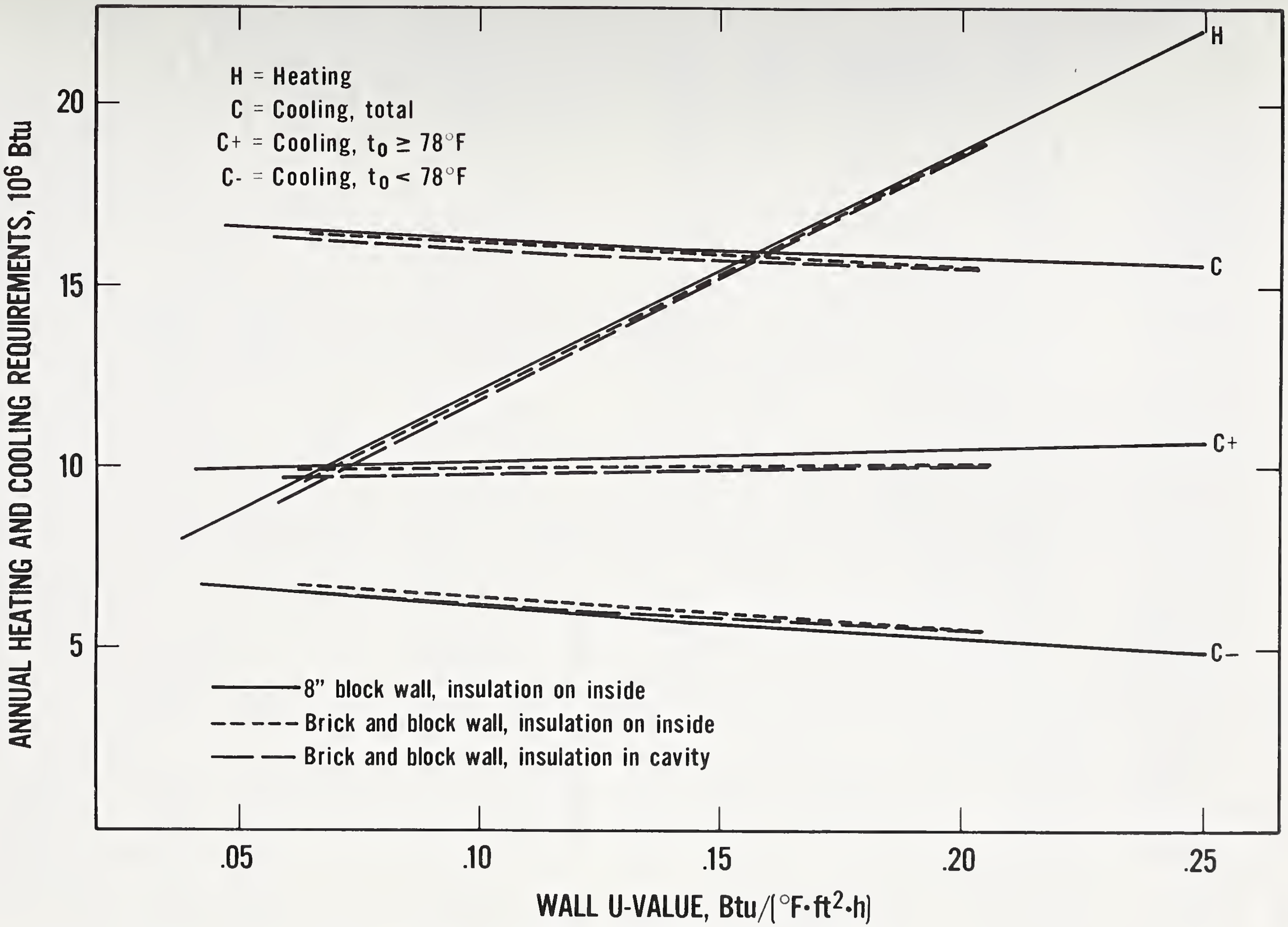

Figure 6. Relationship between AHR, ACR, and U-value: Brick and block walls (Washington, D.C.).

4.2.2 Insulation in Cavity

Table 18 shows the results of the NBSLD analysis of the prototype house with brick and block walls insulated in the cavity space in eight geographic locations. This data is plotted in figure 6 for Washington, D.C. Figures B.12 through B.19 in appendix B display this data for the other locations, in addition to the data for the brick and block walls insulated on the inside surface.

At a U-value of approximately 0.20 Btu/(ft^2)(h)(°F) the two walls are identical, since this is the uninsulated case. However, as insulation levels are increased, the cavity-insulated wall outperforms the wall insulated on the inside surface, in terms of reducing AHR, even when adjusted to the same U-value. (The U-value of the insulated cavity wall is slightly lower than that for the wall insulated on the inside surface as modeled here because the inside air space was eliminated in the NBSLD analysis of all walls insulated on the inside surface.) At an overall U-value of 0.065 Btu/(ft^2)(h)(°F), the house with the cavity-insulated walls has AHR that range from 1 percent less in the cold climates to 30 percent less in very mild winter climates than the house with the insulation on the inside wall surface. At the same U-value, the house with the cavity-insulated walls has ACR$^+$ and ACR^T that range from 2 percent less in the warmest climates to 7 percent less in the mildest summer climates than the house with insulation on the inside wall surface. Decreases in ACR$^+$ due to increased wall insulation tend to be insignificant except in Phoenix, while ACR^T tend to increase less than in the previous case where insulation was added to the inside surface.

4.3 THERMAL ANALYSIS OF WOOD-FRAME WALLS

Construction details of a 2 x 4-in, 24-in-on-center, wood-frame wall are provided in table 3. As can be seen, this is an extemely lightweight wall (approximately 6 lb/ft^2) relative to the two different masonry walls examined previously (38 and 62 lb/ft^2). This lightweight wall will have neglible heat storage characteristics relative to those heavier walls and thus it is expected that its thermal performance would be somewhat lower for equivalent U-values.

Table 19 shows the results of the thermal analysis for the uninsulated wall and 2 levels of insulation (R-11, R-18) in 11 locations. (Stud dimensions are increased to 2 x 6-in for the R-18 wall, 24 in on center.) This same data is shown graphically in figure 7 for Washington, D.C., and in figures B.1 through B.11 in appendix B for all 11 cities so that it can be easily contrasted with the 8-in block wall data. As observed previously, the weight of the wall does have some observable effect on its thermal performance, in that at any given U-value the AHR, ACR$^+$, and ACR^T for the wood-frame wall are higher than for the masonry wall. Note that the reduction in ACR$^+$ tends to be significantly greater for the wood-frame wall than for the masonry walls. When cooling loads are calculated only for the months of April through October, ACR^T tend to decrease as insulation levels increase in Jackson, Jacksonville, Phoenix, and Tampa. If the months of May through September are considered, Albuquerque and

Table 18. Annual Heating and Cooling Requirements for Prototype House: Brick and Block Walls, Insulation in Cavity

Location	Overall Wall U-value Btu/(ft^2)(h)(°F)	R-value in Cavity[b] (ft^2)(h)(°F)/Btu	Annual Space Heating and Cooling[a] Requirements (million Btu) AHR	ACR$^+$	ACR$^-$	ACR^T
Albuquerque	0.2007	0.96	18.95	8.23	4.35	12.58
	0.1145	3.75	12.86	8.18	4.89	13.07
	0.0615	11.25	9.23	8.11	5.39	13.50
Atlanta	0.2007	0.96	14.79	8.81	8.08	16.89
	0.1145	3.75	10.84	8.75	8.85	17.59
	0.0615	11.25	8.15	8.81	9.42	18.22
Indianapolis	0.2007	0.96	37.04	5.92	4.76	10.67
	0.1145	3.75	27.92	5.84	5.35	11.19
	0.0615	11.25	22.28	5.89	5.92	11.80
Jacksonville	0.2007	0.96	2.76	20.76	11.78	32.54
	0.1145	3.75	1.59	20.38	12.42	32.80
	0.0615	11.25	1.02	20.29	12.96	33.24
Madison	0.2007	0.96	43.34	2.93	2.43	5.36
	0.1145	3.75	32.05	2.95	3.03	5.98
	0.0615	11.25	25.06	3.03	3.70	6.72
Phoenix	0.2007	0.96	2.97	34.37	6.09	40.46
	0.1145	3.75	1.73	32.14	6.40	38.54
	0.0615	11.25	1.12	30.89	6.73	37.62
Tampa	0.2007	0.96	0.60	23.35	14.78	38.13
	0.1145	3.75	0.29	22.96	15.70	38.66
	0.0615	11.25	0.17	22.86	16.40	39.27
Washington, D.C.	0.2007	0.96	18.66	10.11	5.45	15.56
	0.1145	3.75	12.73	9.76	6.02	15.78
	0.0615	11.25	9.21	9.67	6.51	16.18

a $ACR^T = ACR^+ + ACR^-$.

b Air space (0.75 in) has an R-value of approximately 0.96 (ft^2)(h)(°F)/Btu. Insulation density in cavity is 2.2 lb/ft^3 with an R-value per inch of 5.0 (ft^2)(h)(°F)/Btu.

Table 19. Annual Heating and Cooling Requirements for Prototype House: Wood-Frame Walls

Location	Overall Wall U-value Btu/$(ft^2)(h)(°F)$	R-value in Stud Space[b] $(ft^2)(h)(°F)$/Btu	Annual Space Heating and Cooling[a] Requirements (million Btu) AHR	ACR^+	ACR^-	ACR^T
Albany	0.2130	0.94	48.27	3.62	3.63	7.25
	0.0781	11.00	31.35	3.33	4.64	7.97
	0.0543	18.00	28.24	3.27	4.94	8.22
Albuquerque	0.2130	0.94	20.52	10.10	4.42	14.52
	0.0781	11.00	11.11	9.02	5.45	14.48
	0.0543	18.00	9.43	8.79	5.82	14.61
Atlanta	0.2130	0.94	16.04	10.33	7.56	17.89
	0.0781	11.00	9.92	9.55	9.15	18.69
	0.0543	18.00	8.81	9.39	9.57	18.96
Indianapolis	0.2130	0.94	38.63	6.88	4.57	11.45
	0.0781	11.00	24.40	6.38	5.82	12.20
	0.0543	18.00	21.81	6.27	6.20	12.47
Jackson	0.2130	0.94	12.03	20.78	7.76	28.54
	0.0781	11.00	7.11	19.10	9.18	28.28
	0.0543	18.00	6.22	18.76	9.53	28.29
Jacksonville	0.2130	0.94	3.65	23.12	10.72	33.84
	0.0781	11.00	1.70	21.48	12.62	34.10
	0.0543	18.00	1.38	21.18	13.07	34.25
Madison	0.2130	0.94	45.44	3.67	2.71	6.38
	0.0781	11.00	27.72	3.38	3.88	7.27
	0.0543	18.00	24.51	3.32	4.25	7.57
Phoenix	0.2130	0.94	4.39	37.56	6.06	43.62
	0.0781	11.00	2.01	32.80	6.87	39.67
	0.0543	18.00	1.61	31.86	7.17	39.03
Salt Lake City	0.2130	0.94	37.28	9.24	3.02	12.26
	0.0781	11.00	22.59	8.19	3.79	11.98
	0.0543	18.00	19.91	7.99	4.02	12.01
Tampa	0.2130	0.94	0.86	25.61	13.42	39.03
	0.0781	11.00	0.33	24.04	15.79	39.83
Washington, D.C.	0.2130	0.94	19.82	11.32	4.94	16.27
	0.1515	3.00	15.64	10.88	5.37	16.25
	0.0781	11.00	10.65	10.31	6.26	16.57
	0.0710	13.00	10.17	10.25	6.36	16.61
	0.0543	18.00	9.04	10.10	6.64	16.73

[a] $ACR^T = ACR^+ + ACR^-$.

[b] Air space (3.5 in) has an R-value of approximately 0.94 $(ft^2)(h)(°F)$/Btu. Mineral wool insulation density in stud space is approximately 0.65 lb/ft^3.

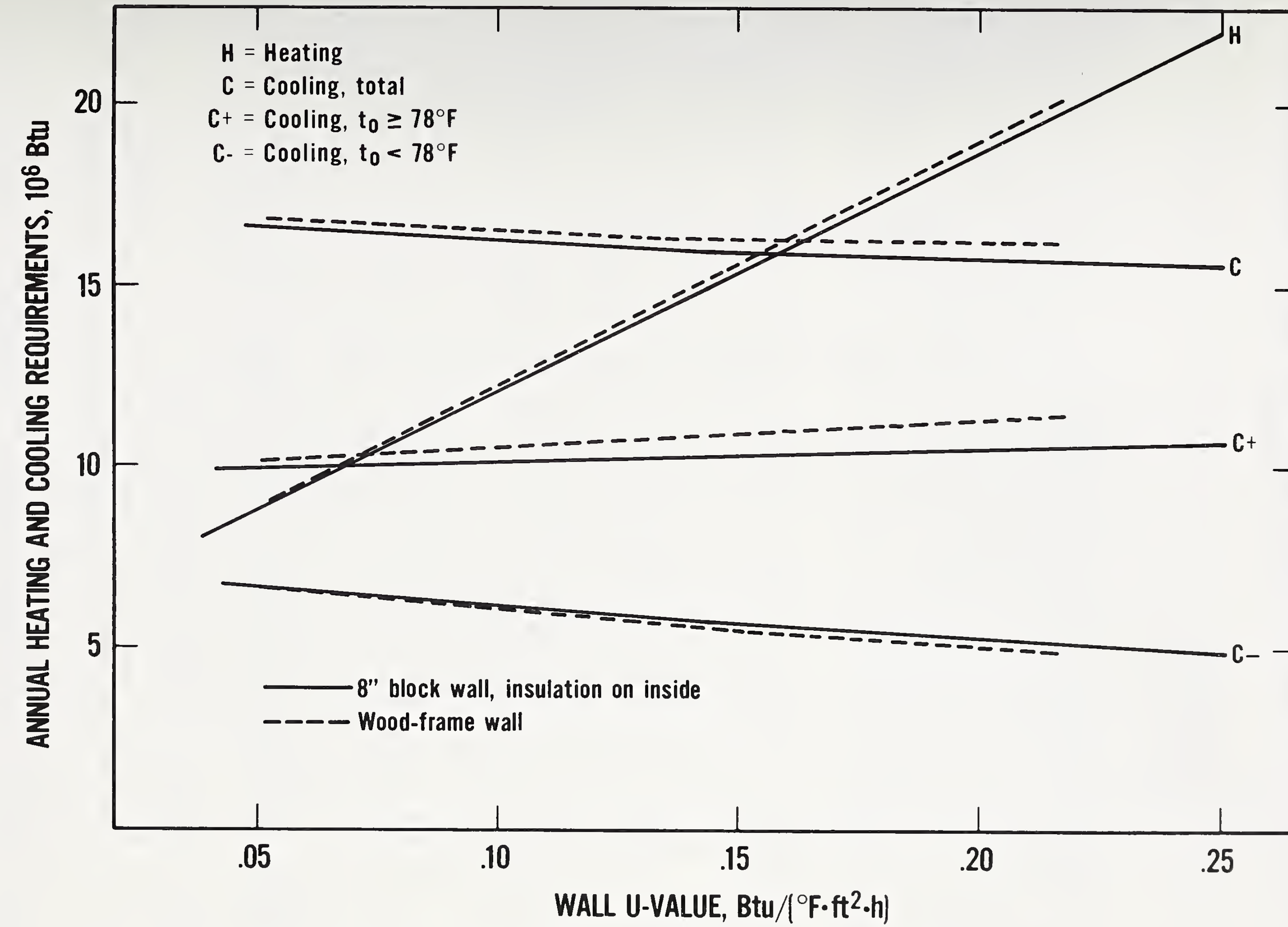

Figure 7. Relationship between AHR, ACR, and U-value: Wood-frame walls (Washington, D.C.).

Salt Lake City also show this decrease. In the remaining cities even during the months of May through September, ACR^T tend to increase slightly as walls are better insulated.

4.4 REDUCTIONS IN AHR AND ACR

4.4.1 Generalized Data Analysis

The AHR and ACR corresponding to a range of U-values for each wall type have been reported for a prototypical 1176 ft^2 single-story house in 11 locations (8 locations for brick and block walls). However, in an economic analysis of insulation usage, it is the change in AHR and ACR due to a change in insulation resistance that is the most relevant aspect of the thermal analysis. The reductions in AHR and ACR, converted to purchased energy savings and ultimately to present-value dollar savings over the life of the house, must be sufficient to justify the increased investment in insulation. In addition, the reductions in AHR (and ACR where relevant) will be more generally useful if they are expressed in terms of Btu per square foot of wall area and can be estimated for other climates as well.

For each geographic location examined, table 20 shows the reduction in AHR, per square foot of net wall area, due to a reduction in the wall U-value of 0.10 Btu/(ft^2)(h)(°F) for each of the basic walls and insulation variations considered.[1] For the 8-in block walls with poured insulation in cores, this represents a reduction in U-value from 0.21 to 0.11 Btu/(ft^2)(h)(°F). For the other columns shown, the reductions in AHR/ft^2 are due to a reduction in U-value from 0.15 to 0.05 Btu/(ft^2)(h)(°F), based on interpolated AHR values at those points, except as follows. For Jacksonville, Phoenix, and Tampa, the 0.10 Btu/(ft^2)(h)(°F) reduction in U-value represents the interval between the U-values of 0.20 and 0.10 Btu/(ft^2)(h)(°F). This somewhat higher interval was selected because it better represents the reduction in AHR in geographic regions with less than 500 HDD base 55°F and is the interval where the U-value for an optimally insulated masonry wall is most likely to occur in those regions. However, the reductions in AHR for changes in U-value outside these intervals are not significantly different because of the underlying linear relationship between AHR and U-value. A 0.10 Btu/(ft^2)(h)(°F) reduction in U-value is reported because it is easily used to scale the reduction in AHR/ft^2 for reductions in U-value other than 0.10 Btu/(ft^2)(h)(°F). Thus, to estimate the reduction in AHR per square foot for any given reduction in U-value for a given wall type, insulation variation, and geographic location, simply multiply the appropriate ΔAHR factor from table 20 by the reduction in U-value and divide by 0.1. For example, a 0.05 Btu/(ft^2)(h)(°F) reduction in the U-value of an 8-in block wall, insulated on the inside surface, in Albany, yields 6.43×10^3 Btu/ft^2 ((12.86)(0.05)/0.1) reduction in AHR.

Note that the differences between the ΔAHR/ft^2 per ΔU of 0.10 Btu/(ft^2)(h)(°F) for each wall type are insignificantly different in the coldest climates but

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[1] All walls have an exterior solar absorptance of 0.5.

Table 20. Change in AHR/ft^2 of Wall Area Normalized to $\Delta U = 0.1$ Btu/(ft^2)(h)(°F)

			ΔAHR (10^3 Btu/ft^2)				
			8-in Block Wall		Brick & Block Wall[a]		
Location	$HDD_{65°F}$	$HDD_{55°F}$	Insulation Inside[a]	Insulation In Core[b]	Insulation Inside	Insulation In Cavity	Wood-Frame Wall[a]
Albany	7118	4638	12.86	12.78	NA[c]	NA	13.04
Albuquerque	4397	2408	6.53	7.30	6.70	7.18	7.19
Atlanta	2959	1370	4.37	4.78	4.27	4.60	4.70
Indianapolis	5886	3719	10.84	10.81	10.76	10.91	10.94
Jackson	2352	1025	3.40	3.78	NA	NA	3.77
Jacksonville	1239	327	1.20	1.50	1.09	1.36	1.48
Madison	7311	4765	13.46	13.43	13.33	13.53	13.60
Phoenix	1571	404	1.34	1.73	1.12	1.44	1.81
(ΔACR^T)[d]			(1.77)	(2.82)	(1.34)	(2.15)	(2.93)
(ΔACR^+)[d]			(2.66)	(3.41)	(2.12)	(2.55)	(3.53)
Salt Lake City	6216	3928	11.04	11.17	NA	NA	11.31
Tampa	459	57	0.32	0.41	0.28	0.35	0.40
Washington, D.C.	4162	2185	6.79	7.09	6.77	6.91	6.98

[a] 0.10 Btu/(ft^2)(h)(°F) reduction in U-value from 0.15 to 0.05 Btu/(ft^2)(h)(°F) except for Jacksonville, Phoenix and Tampa, where it is from 0.20 to 0.10 Btu/(ft^2)(h)(°F).

[b] 0.10 Btu/(ft^2)(h)(°F) reduction in U-value from 0.21 to 0.11 Btu/(ft^2)(h)(°F) in all locations.

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

[d] 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 $t_o \geq 78°F$.

vary by as much as 60 percent in the mildest climates. However, in no case does this variation exceed 700 Btu/ft^2 of wall area per year.

In general, a reduction in wall U-value has a small and somewhat ambiguous effect on cooling requirements depending on the extent to which natural ventilation is used, except in the case of Phoenix. Assuming that limited natural ventilation is used throughout the year, the actual reduction in cooling requirements is likely to be negligible in most cases, again with the exception of Phoenix. As a result, the reductions in ACR^+ and ACR^T are reported only for that location in table 20.

4.4.2 Correlation with Climate Data

In order to develop a general relationship between the ΔAHR data shown in table 20 and the Test Reference Year climate data used in computing the ΔAHR, a number of linear regressions were computed using heating degree day (HDD) data from the TRY data records. Several degree day bases were tried in order to determine which base gave the best results. The highest coefficients of determination (R^2) were obtained for HDD base 55°F (HDD_{55}) in all cases. The resulting equations, adjusted to include the change in U-value, are given in table 21. These equations predict the reduction in AHR within 10 percent in all locations except Tampa. In Tampa, the predicted reduction tends to be 23 to 50 percent too high; however the absolute error is insignificant due to the very low AHR in that region.

It is interesting to note that the slopes of all five regression equations in table 21 are, for all practical purposes, identical, and that any significant variation is found only in the intercept term. This suggests that any advantage that one wall type or insulation method has over another (in terms of reducing annual heating requirements) is constant in absolute terms, regardless of geographic location. In the milder heating climates this absolute advantage may be relatively large, while in the colder climates this absolute advantage is dwarfed by the variable term in the regression equation.

A HDD_{55} map of the United States, based on long-term weather observations, is shown in figure 8. Using this map and the appropriate regression equation, the approximate ΔAHR/ft^2 of wall area can be found for any given ΔU, for each of the wall types and insulation methods examined.

Table 21. Regression Equations for Five Wall Insulation Variations

(1) <u>8-in Block Wall - Insulation Inside</u> ($R^2 = 0.997$):

$$\Delta AHR(10^3\ Btu/ft^2) = \Delta U(3.70 + 0.0274\ HDD_{55}) \qquad (4\text{-}1)$$

(2) <u>8-in Block Wall - Insulation in Cores</u> ($R^2 = 0.996$):

$$\Delta AHR(10^3\ Btu/ft^2) = \Delta U(7.78 + 0.0267\ HDD_{55}) \qquad (4\text{-}2)$$

(3) <u>Brick and Block Wall - Insulation Inside</u> ($R^2 = 0.997$):

$$\Delta AHR(10^3\ Btu/ft^2) = \Delta U(2.04 + 0.0280\ HDD_{55}) \qquad (4\text{-}3)$$

(4) <u>Brick and Block Wall - Cavity Insulation in Cavity</u> ($R^2 = 0.997$):

$$\Delta AHR(10^3\ Btu/ft^2) = \Delta U(4.57 + 0.0280\ HDD_{55}) \qquad (4\text{-}4)$$

(5) <u>Wood-Frame Wall</u> ($R^2 = 0.998$):

$$\Delta AHR(10^3\ Btu/ft^2) = \Delta U(7.13 + 0.0271\ HDD_{55}) \qquad (4\text{-}5)$$

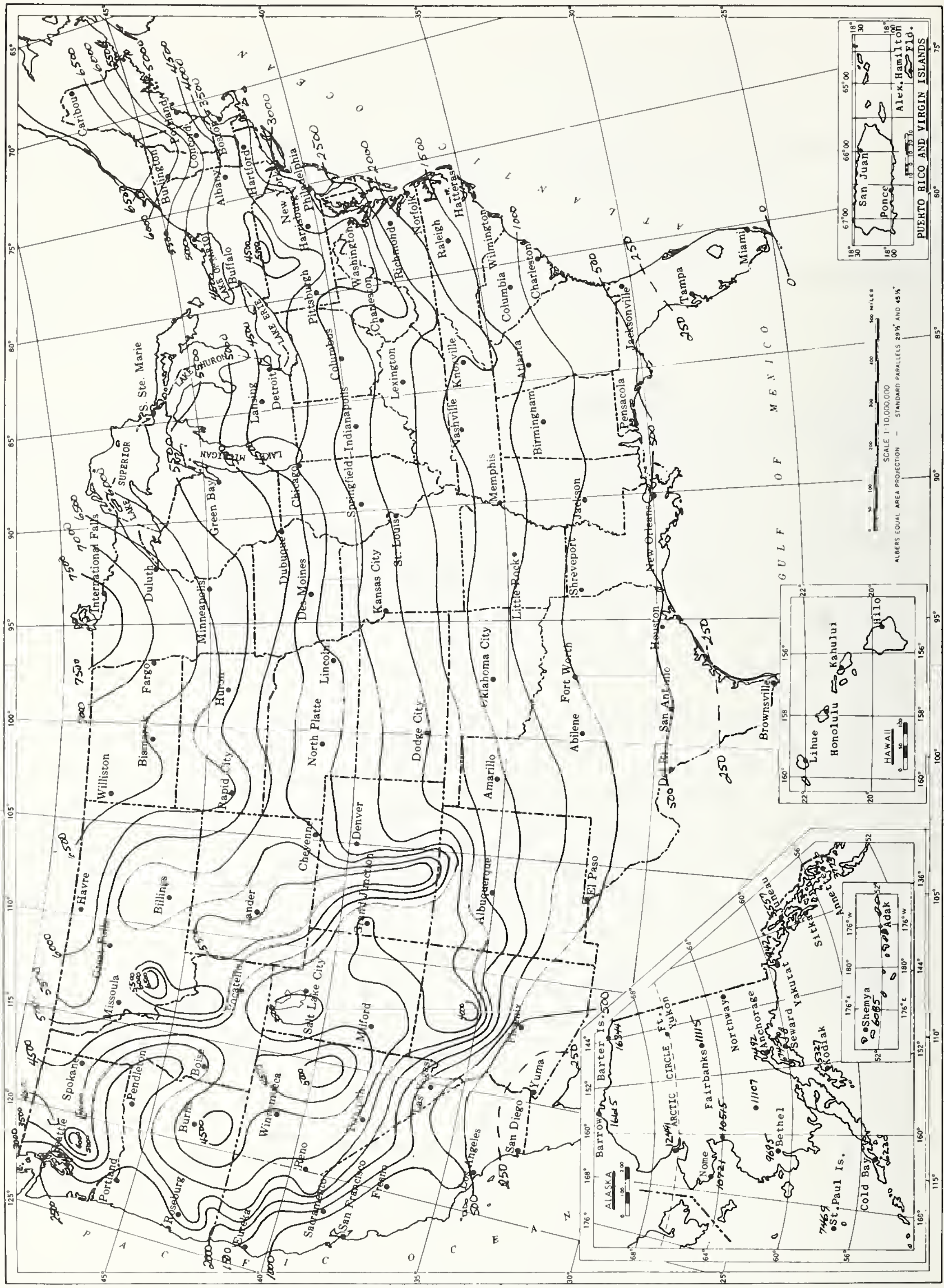

Figure 8. Heating degree days (base 55°F) map of the United States.

Facing page: *The economically optimal level of wall insulation is defined as that level which has the greatest present-value, life-cycle, net dollar savings.*

5. ECONOMIC ANALYSIS OF WALL INSULATION

In section 4 the reductions in annual heating and cooling requirements due to insulating the exterior walls of a single-story house were calculated and correlated with wall type, insulation method, and geographic location. In this section, the calculation of corresponding reductions in life-cycle energy costs will be discussed. Conditions for determining optimal insulation levels for each wall type will be outlined. Finally, guidelines for optimal insulation levels will be developed, based on a number of localized variables.

5.1 CALCULATING THE PRESENT DOLLAR VALUE OF ENERGY SAVINGS

In order to determine the extent to which wall insulation is cost effective on a life-cycle basis, changes in annual heating and cooling requirements due to the increased use of insulation must be evaluated on a present-value, life-cycle dollar basis. Incremental reductions in life-cycle heating and cooling costs can then be compared with incremental increases in wall construction costs in order to determine the economically optimal insulation level for a given wall design.[1]

Before the dollar value of changes in wall insulation levels can be determined, it is necessary to convert changes in AHR and ACR[2] (ΔAHR and ΔACR) to corresponding changes in annual metered heating and cooling energy requirements (ΔAMHR and ΔAMCR). Determination of ΔAMHR and ΔAMCR requires that the seasonal efficiencies of the heating (η_H) and cooling (η_C) system be known. The seasonal efficiency of each is defined here as the total energy output to the conditioned space divided by the total energy input to the equipment summed over the hours in which a heating or cooling load occurs.[3] Thus, changes in metered energy requirements are simply equivalent to the changes in space heating and cooling requirements divided by the seasonal efficiencies of the heating and cooling equipment, respectively:

$$\Delta AMHR = \Delta AHR/\eta_H, \text{ and} \tag{5-1}$$

$$\Delta AMCR = \Delta ACR/\eta_C. \tag{5-2}$$

Changes in annual heating and cooling costs (ΔAHC and ΔACC, respectively) are calculated as the change in annual metered requirements for heating and cooling energy multiplied by their respective prices (P_H and P_C) in equivalent units:

$$\Delta AHC = (\Delta AMHR)(P_H), \text{ and} \tag{5-3}$$

$$\Delta ACC = (\Delta AMCR)(P_C). \tag{5-4}$$

---

[1] Criteria for optimization is discussed in the following subsection.

[2] ΔACR here refers to the effective change in annual cooling requirements, i.e., the ΔACR that would be calculated if the actual operating procedures with regard to natural ventilation were known. The analysis in section 4 above showed that, except in Phoenix, ΔACR due to wall insulation is likely to be insignificant. However, a general methodology for evaluating dollar savings which can include cooling energy savings is shown here.

[3] By restricting seasonal efficiency calculations to actual heating or cooling hours, the energy used in a standing gas pilot light during non-load hours is not considered. In effect, equipment efficiencies should be evaluated as though they had an electronic ignition system when used to evaluate the energy savings due to shell modifications.

The present value of the sum of annual energy savings over the expected useful life of the insulation can be easily calculated once the appropriate uniform present worth factors are known. Since energy costs are expected to increase over time rather than remain constant, a modified uniform present worth factor (UPW*) must be calculated based on the expected useful life of the insulation (L), the projected annual rate of increase in energy prices (E), and the discount rate (D), which represents the time value of money, i.e., the rate of return on the best alternative investment opportunity available to the homeowner. If E is constant over the life of the insulation, the UPW* can be found as follows:[1]

$$UPW^* = \left(\frac{1+E}{D-E}\right)\left(1-\left(\frac{1+E}{1+D}\right)^L\right) \quad \text{if } D \neq E \text{, and} \qquad (5\text{-}5)$$

$$UPW^* = L \quad \text{if } D = E. \qquad (5\text{-}6)$$

If different energy types are used for heating and cooling, it is possible that different rates of energy price increase will be projected for each, and as a result, the UPW* may be different for heating energy and cooling energy.

Reductions in present-value, life-cycle heating costs and cooling costs (ΔLCHC, ΔLCCC, respectively) can then be calculated as:

$$\Delta LCHC = (\Delta AHC)(UPW^*_H) \text{, and} \qquad (5\text{-}7)$$

$$\Delta LCCC = (\Delta LCC)(UPW^*_C). \qquad (5\text{-}8)$$

The total reductions in present-value, life-cycle energy costs (ΔLCEC) can now be calculated as:

$$\Delta LCEC = \Delta LCHC + \Delta LCCC. \qquad (5\text{-}9)$$

In summary form,

$$\Delta LCEC = \left(\frac{\Delta AHR}{\eta_H}\right)(P_H)(UPW^*_H) + \left(\frac{\Delta ACR}{\eta_C}\right)(P_C)(UPW^*_C). \qquad (5\text{-}10)$$

---

[1] If E is not constant, the UPW* must be evaluated for each of the n time intervals, corresponding to the different values of E and summed together. This can be evaluated as follows:

$$UPW^* = \sum_{i=1}^{n} \left[\prod_{j=0}^{i-1} \left(\frac{1+E_j}{1+D}\right)^{T_j}\right] \left(\frac{1+E_i}{D-E_i}\right)\left(1-\left(\frac{1+E_i}{1+D}\right)^{T_i}\right)$$

where n = number of time intervals,
T_j = length of interval j ($T_0 = 0$), and
E_j = rate of price increase in interval j ($E_0 = 0$).

When the differences in equipment efficiencies, unit energy costs, and rates of energy price increase are considered, one can see why the simple summation of ΔAHR and ΔACR is meaningless from both an energy and economic standpoint.

5.2 CRITERIA FOR ECONOMIC OPTIMIZATION

The primary purpose of this report is to determine the economically optimal level of insulation for a given wall type in a variety of climates and for a variety of energy costs. The economically optimal insulation level is defined as that level which has the greatest cumulative net savings in any given installation; i.e. present-value, life-cycle savings less present-value, life-cycle costs. In order for any increase in the use of insulation to increase cumulative net savings, the incremental savings attributable to that change must be greater than or equal to its incremental cost. For this reason, accurate calculation of the change in energy requirements (and life-cycle energy costs) due to additional wall insulation is more important than finding the total energy requirements (and life-cycle energy costs) for the building.

These optimality criteria are shown graphically in figure 9. In the upper part of that figure (a), cumulative present-value life-cycle savings are shown as a function of the level of insulation used (in terms of thermal resistance) in the wall. Also shown is the cumulative installed cost of that insulation. Note that at any point between the origin and insulation level R', cumulative savings are greater than cumulative costs. However, cumulative net savings, also shown in the upper part of figure 9, are maximized at insulation level R. Thus R is the optimal insulation resistance level, in that any alternative level will result in lower net savings over the useful life of the insulation.

This same result can also be found by examining incremental savings and costs, as shown in the lower part of figure 9 (b). Here, incremental savings and incremental costs (the additional savings and costs attributable to each additional increment of thermal resistance) are shown as a function of insulation resistance. Incremental savings decrease as the overall resistance level is increased because of the reciprocal relationship between thermal resistance and thermal conductivity (i.e., $U = 1/R$).[1] Incremental costs for the first few units of resistance (e.g., up to R-11 for mineral wool insulation in wood-frame walls) tend to decrease because installation costs are somewhat fixed and are applied to the first unit. However, beyond some point, incremental costs per resistance unit begin to increase as wall modifications are needed to accomodate more insulation, or as more thermally efficient, but more expensive, insulation materials (e.g., rigid foam) are substituted for less efficient materials. The intersection of the incremental savings and cost curves

[1] Here R refers to the overall thermal resistance of the wall, which includes not only the insulation but the other materials and air resistance values. Note that this reciprocal relationship means that as R increases at a constant rate, U decreases at a decreasing rate.

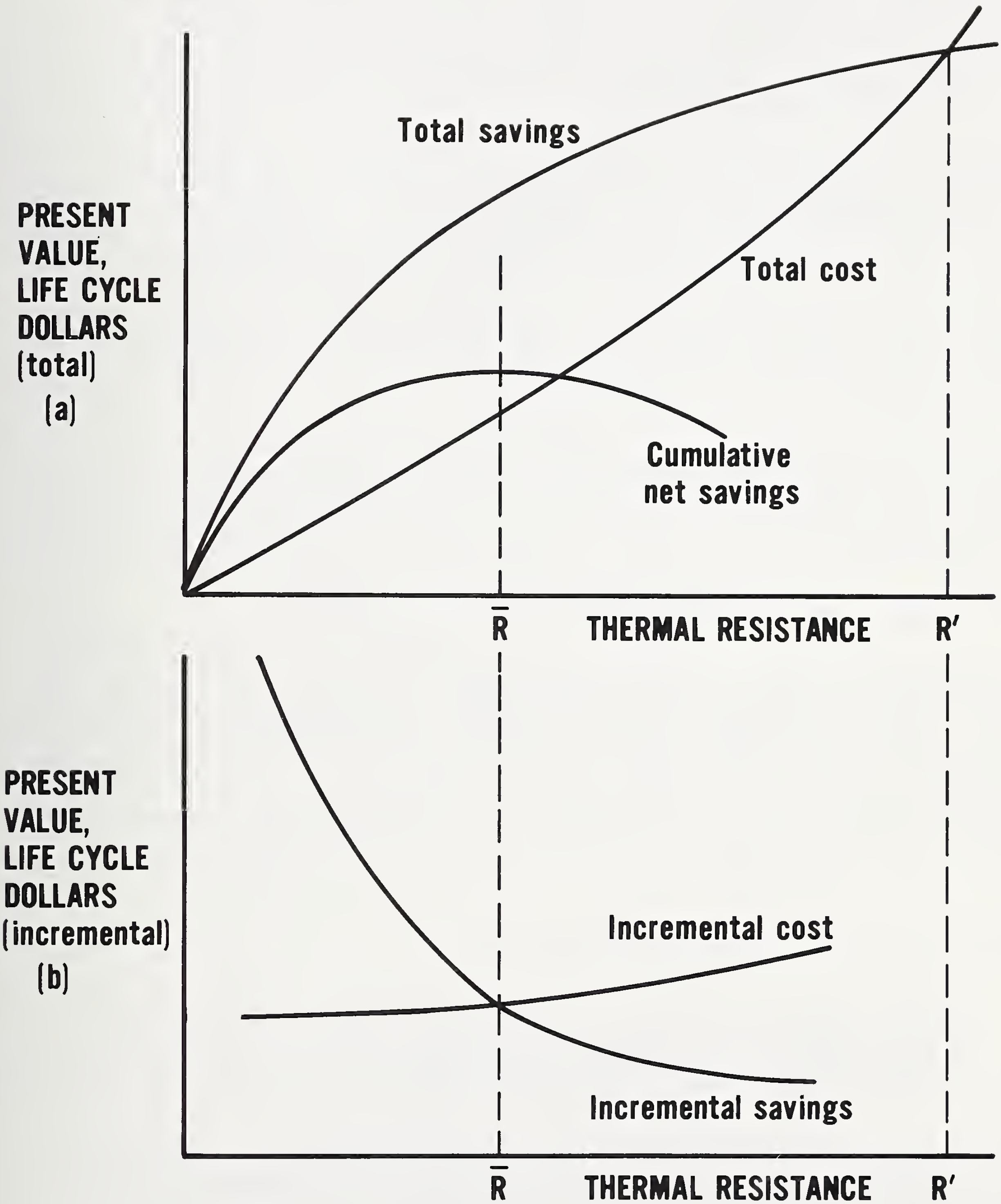

Figure 9. Economic optimization criteria for insulation.

occurs at the optimal resistance level, $\bar{R}$. Any increase in R would incur additional costs greater than additional savings, thereby decreasing cumulative net savings. Any decrease in R would give up resistance units which contribute greater savings than costs, also decreasing cumulative net savings. Thus, the level of thermal resistance at which incremental savings just equals incremental costs maximizes cumulative net savings and is therefore the economically optimal insulation level.[1]

However, because insulation materials are not generally available in a continuous range of resistance values, it is not likely that the point where incremental savings just equals incremental costs is practical. In this case, an alternative criterion requires that insulation resistance be increased as long as the additional savings attributable to each available increment are at least as great as the cost of that increment. When no further increase in the overall insulation resistance can generate incremental savings greater than or equal to incremental costs, the optimal insulation resistance level has been reached. No alternative resistance level will have higher cumulative net savings.

This incremental approach to economic optimization is quite useful in the analysis of thermal insulation because changes in savings and costs due to increases in thermal resistance are usually more accurately estimated than total savings and costs. For this reason, the incremental approach is used in this report.

5.3 CALCULATION OF OPTIMAL INSULATION LEVELS: EXAMPLES

In this subsection, the methodology for determining the optimal insulation resistance for a given wall type and climate location is demonstrated. The first and second examples are based directly on the reductions in annual heating requirements (ΔAHR) reported in table 20. That is, ΔAHR are calculated by adjusting those given for $\Delta U = 0.1$ Btu/(ft^2)(h)(°F) to correspond to the actual ΔU achieved. The third example is based on the equations in table 21 which relate the reduction in annual heating requirements to heating degree days (base 55°F, HDD_{55}).

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[1] This criterion is sometimes expressed as

$$MS = MC$$

where MS = marginal (i.e. incremental) savings,
MC = marginal (i.e. incremental) costs.

Second order conditions for the criterion require that MS - MC be decreasing in the region of optimal insulation resistance. In addition, cumulative savings must be greater than cumulative costs at this point or the optimal insulation resistance is 0 (i.e., no insulation). For more information on this subject, see S. R. Petersen, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis.

Example #1: 8-in Block Wall in Albuquerque

A house is to be built in Albuquerque with 8-in block walls having an area of 1000 square feet net of windows. Unless a greater resistance value can be justified on a life-cycle cost basis, foil-backed gypsum board (approximately R-3) will be the only means of insulation used. However, if more insulation is cost justified, 2 x 3-in framing will be used along with mineral wool insulation. The alternative insulation resistance levels, U-values, and costs (from table 4), as well as corresponding reductions in AHR (based on table 20) are shown in table 22. A natural gas furnace with a seasonal efficiency (η_H) of 70 percent is assumed for heating. Natural gas prices are expected to be \$0.30 per therm (\$3.00 per million Btu) and are expected to increase in real terms (i.e., adjusted to remove the effects of inflation) at 5 percent per year.[1] Cooling savings are not expected to be significant.

Since the useful life of the insulation is expected to be at least as long as the typical mortgage life, a 30-year life will be assumed in the analysis. A real discount rate of 4 percent is used in the example to represent the time value of money to a homeowner. This represents a minimum acceptable after-tax rate of return for a long-term investment, adjusted to remove the effects of inflation. (In fact this is quite high for most homeowners who are able to make long-term investments. However for homeowners who keep outstanding nominal 18 percent credit card balances, a 4 percent real discount rate may be more realistic given recent inflation rates.[2]) Thus the modified uniform present worth factor (UPW*) is computed, using equation 5-5 as:

$$\left(\frac{1.05}{-0.01}\right)\left(1 - \left(\frac{1.05}{1.04}\right)^{30}\right) = 34.92.$$

Using equation 5-10, the incremental reduction in life-cycle energy costs (ΔLCEC) for each additional level of resistance shown in table 22 can be computed. For example,

ΔLCEC for R-3 is computed as:

$$\Delta\text{LCEC} = \left(\frac{5.22 \text{ million Btu}}{0.70}\right)(\$3.00/\text{million Btu})(34.92) = \$781$$

---

[1] These price data are for example purposes only. Current DoE price projections by region can be found in Sitzer, Moden, and Don Vito, Historical and Forecasted Energy Prices by DoE Region and Fuel Type for Three Microeconomic Scenarios, DoE/EIA-0184/15 (Washington, D.C.: U.S. Department of Energy, July 1979)

[2] For example, for a homeowner in the 25 percent tax bracket (combined Federal and State), an 18 percent interest rate would be reduced to an effective rate of 13.5 percent ((1-0.25)(0.18)). At an average inflation rate of 10 percent this would equal a real interest rate of approximately 3.5 percent.

Table 22. Example #1: Albuquerque - 8-in Block Walls (1000 ft^2) Insulated on Inside Surface

Description	U-value[a] (Btu/(ft^2)(h)(°F))	ΔU	ΔAHR[b] (million Btu)	Cost[a] (1000 ft^2)
Base Wall	0.242	--	--	--
R-3 (foil-backed wallboard)	0.162	0.080	5.22	$ 100
R-11 (mineral wool)	0.074	0.088	5.75	750
R-13 (mineral wool)	0.066	0.008	0.52	800
R-19 (mineral wool)	0.046	0.020	1.31	1000

[a] Based on table 4.

[b] Calculated from table 20 (ΔAHR = (6530 Btu/ft^2)(1000 ft^2)(ΔU)/0.1).

Table 23. Example #1. Incremental Life-Cycle Savings and Costs

Description	ΔLCEC[a]	ΔCost	Cumulative Net Savings
R-3	$781	$100	$681
R-11	861	650	892
R-13	78	50	920
R-19	196	200	916

[a] Based on natural gas price of $3.00 per million Btu, a UPW* of 34.92, and a heating efficiency of 70 percent.

The ΔLCEC for each incremental level of resistance shown in table 22 has been calculated and displayed in table 23, along with the corresponding incremental cost and cumulative net savings of those resistance levels.

Where incremental savings are greater than incremental costs, cumulative net savings increase. When incremental savings are less than incremental costs, cumulative net savings decrease. The R-13 insulation level has the greatest cumulative net savings, $920, and is therefore the economically optimal level of insulation resistance for the 8-in block walls in this example for Albuquerque.

Example #2: Brick and Block Wall in Phoenix

In this example, a house with 1000 square feet of wall area is to be built with brick and block and insulated in the cavity. Reductions in both annual heating requirements and annual cooling requirements are expected. A gas furnace with a seasonal efficiency of 70 percent will be used for heating. A central air conditioner with a seasonal efficiency of 2.5 will be used for cooling. In general, the air conditioner will be used only when the outdoor temperature exceeds 78°F. Natural gas is expected to cost $0.35 per therm ($3.50 per million Btu) and to increase at an annual real rate of 5 percent. Electricity is expected to cost $0.05 per kWh ($14.65 per million Btu) and to increase at a real rate of 2 percent per year. A 30-year useful life and 4 percent real discount rate is assumed. As computed in example #1, the UPW* factor for gas is 34.92. The UPW* factor for electricity is calculated as:

$$UPW^* = \left(\frac{1.02}{0.02}\right)\left(1 - \left(\frac{1.02}{1.04}\right)^{30}\right) = 22.52$$

Table 24 shows the alternative insulation resistance levels considered, the wall U-values, and the corresponding insulation costs based on table 5. In addition, table 24 shows the corresponding ΔAHR and ΔACR based on table 20. The ΔLCEC for the R-4 insulation is calculated, using equation 5-10, as:

$$\Delta LCEC = \left(\frac{1.30 \text{ million Btu}}{0.70}\right)(\$3.50/\text{million Btu})(34.92)$$

$$+ \left(\frac{2.30 \text{ million Btu}}{2.5}\right)(\$14.65/\text{million Btu})(22.52) = \$531.$$

Table 25 shows the ΔLCEC for each resistance level examined in table 24, along with the incremental cost and cumulative net savings for each level. In this example, the R-4 insulation has the highest cumulative net savings ($21) and thus is optimal. The cumulative net savings for resistance levels higher than R-4 are negative in this example.

Table 24. Example #2: Phoenix - Brick and Block Walls (1000 ft^2) Insulated in Cavity

Description	U-value[a] (Btu/(ft^2)(h)(°F)	ΔU	ΔAHR[b] (million Btu)	ΔACR[b] (million Btu)	Cost[a] (1000 ft^2)
Base Wall	0.201	--	--	--	--
R-4	0.111	0.090	1.30	2.30	$ 510
R-6	0.091	0.020	0.29	0.51	$ 660
R-9	0.071	0.020	0.29	0.51	$ 900
R-12	0.059	0.012	0.17	0.31	$1130

[a] Based on table 5.

[b] Calculated from table 20 (ΔAHR = (1440 Btu/ft^2)(1000 ft^2)(ΔU)/0.1;
ΔACR = (2550 Btu/ft^2)(1000 ft^2)(ΔU)/0.1).

Table 25. Example #2: Incremental Life-Cycle Savings and Costs

Description	ΔLCEC[a]	ΔCost	Cumulative Net Savings
R-4	$531	$510	$ 21
R-6	118	150	-11
R-9	118	240	-133
R-12	71	230	-292

[a] Based on natural gas price of $3.50 per million Btu, a UPW* of 34.92, and efficiency of 70 percent for heating; electricity price of $14.65 per million Btu, a UPW* of 22.52, and efficiency of 2.5 for cooling.

Example #3: Wood-Frame Wall in 6000 HDD_{55} Climate

A house is to be built in Rapid City, S.D. (6000 HDD_{55}) with wood-frame walls to be insulated with mineral wool insulation. The house has 1000 square feet of wall area net of windows. Table 26 shows the alternative levels of insulation resistance to be considered, including the corresponding reductions in AHR for wood-frame walls in a 6000 HDD_{55} climate, based on equation 4-5 in table 21. An electric resistance furnace with a seasonal efficiency (η_H) of 100 percent will be used for heating. Electricity for heating is assumed to have an incremental cost of $0.042 per kWh ($12.31 per million Btu), with an annual real rate of increase projected to be approximately 2 percent. Cooling savings are expected to be insignificant. Again a 4 percent real discount rate and a 30-year useful life is assumed in the example. Thus the UPW* is the same as in example #2, 22.52.

The reduction in life-cycle energy costs is calculated for R-3 using equation 5-10 and the ΔAHR data in table 26:

$$\Delta LCEC = \left(\frac{10.35 \text{ million Btu}}{1.00}\right)(\$12.31/\text{million Btu})(22.52) = \$2869 .$$

The ΔLCEC for each incremental level of resistance shown in table 26 has been calculated and displayed in table 27, along with the corresponding incremental cost and cumulative net savings for each. In this example, the R-18 mineral wool plus R-5 rigid foam sheathing is the economically optimal insulation level of those alternatives considered. Since the incremental savings are considerably higher than incremental costs at this point, more insulated sheathing may still be cost effective beyond the R-5 assumed.

If the wood-frame wall is to be covered with brick veneer instead of lightweight siding, the reduction in AHR and corresponding ΔLCEC should be based on equation 4-1, since these walls perform much the same as 8-in block walls insulated on the inside. This will have little effect on the optimal level of insulation, however, except in the very mildest climates. The insulation cost data will be the same for all wood-frame walls regardless of siding used.

Table 26. Example #3: Wood-Frame Walls (1000 ft^2) in 6000 HDD_{55} Climate

Description	U-value[a] (Btu/(ft^2)(h)(°F))	ΔU	ΔAHR[b] (million Btu)	Cost[a] (1000 ft^2)
Base Wall	0.213	--	--	--
R-3 (foil-backed wallboard)	0.152	0.061	10.35	$100
R-11 (mineral wool)	0.078	0.074	12.56	300
R-13 (mineral wool)	0.071	0.007	1.19	350
R-18 (mineral wool)	0.055	0.016	2.72	700
R-18 mineral wool and R-5 rigid foam sheathing	0.045	0.009	1.70	900

[a] Based on table 6.

[b] Calculated using equation 4-5 for wood-frame walls in table 21:
$\Delta AHR\ (10^3\ Btu/ft^2) = \Delta U(7.13 + (0.0271)(6000))$.

Table 27. Example #3: Incremental Life-Cycle Savings and Costs

Description	ΔLCEC[a]	ΔCost	Cumulative Net Savings
R-3	$2869	$100	$2769
R-11	3482	200	6051
R-13	330	50	6331
R-18	754	350	6735
R-23	471	200	7006

[a] Based on electricity at $12.31 per million Btu, a UPW* of 22.52, and a heating efficiency of 100 percent.

Facing page: *Framing the inside of masonry walls with 2 X 3-in studs and insulating with mineral wool was found to be a more cost-effective method than using rigid foam.*

6. INDEX NUMBER SYSTEM TO DETERMINE OPTIMAL INSULATION LEVELS

In order to provide a flexible methodology for determining optimal insulation levels for each wall type examined, based on the insulation specifications and costs listed in section 2, an index number system is developed here. This index system allows the user to vary energy prices, equipment efficiencies, lifetimes, discount rates, projections of annual energy price increases, heating degree days, and insulation costs in order to determine the optimal insulation level for a given wall type and a given insulation type. This index number system is based on reductions in space heating requirements only and is therefore appropriate only where changes in air conditioning requirements due to an increased level of wall insulation are assumed to be insignificant.

As noted in section 4, this assumption is reasonable if natural ventilation is frequently used when the outdoor temperature is lower than the thermostat setpoint (78°F in this report). In Phoenix and other regions where reductions in cooling requirements are known to be significant, the calculation procedure shown in the previous section should be used instead.

The index number system is based on the economic criteria for optimality, requiring that incremental life-cycle savings from additional insulation be at least as large as incremental costs (reference equation 5-10 with $\Delta ACR = 0$). That is:

$$\left(\frac{\Delta AHR_i}{\eta_H}\right)(P_H)(UPW_H^*) \geqslant \Delta K_i \ , \tag{6-1}$$

where ΔAHR_i = the incremental reduction in annual heating requirements per unit of net wall area due to the i^{th} level of insulation relative to the $(i-1)^{th}$ level,

P_H = price of purchased energy in same units as ΔAHR,

η_H = seasonal efficiency of heating equipment,

UPW_H^* = modified uniform present worth factor, and

ΔK_i = the incremental cost of the i^{th} level of insulation relative to the $(i-1)^{th}$ level per unit of net wall area.

Equation 6-1 can be transposed to:

$$\frac{(P_H)(UPW_H^*)}{\eta_H} \geqslant \frac{\Delta K_i}{\Delta AHR_i}, \tag{6-2}$$

or

$$I \geqslant \frac{\Delta K_i}{\Delta AHR_i} \ , \tag{6-3}$$

where

$$I = \frac{(P_H)(UPW_H^*)}{\eta_H} \ . \tag{6-4}$$

If I, the index number, is greater than or equal to $\Delta K_i/\Delta AHR_i$, the "breakpoint" ratio for the ith level of insulation, that level of insulation is cost justified.

In general, this breakpoint ratio should increase for each additional level of insulation considered. (If the ratio for a succeeding increment of insulation resistance is lower than that for the preceding increment, the two increments should be combined and a new ratio computed.) Then the insulation level with the highest breakpoint ratio which does not exceed this index number (I) is the optimal insulation level.

The index number, I, can be calculated as the product of UPW_H^* and (P_H/η_H). Tables 28 and 29 can be used to find the appropriate UPW^* and price per million Btu output from the furnance, P_H/η_H, respectively. Table 28 gives the UPW^* for several discount rates at the intersection of the "expected useful lifetime" column and the "rate of energy price increase" row. Table 29 gives the price per million Btu output for selected energy types and seasonal furnace efficiencies. Part A gives the price per million Btu, as metered at the building boundary, for a range of unit prices for natural gas, fuel oil, and electricity. Part B gives the price per million Btu output at the intersection of the "price per million Btu (metered)" column and "furnace efficiency" row. The following example shows how the index number can be calculated using tables 28 and 29.

Example #4: Find the index number for wall insulation based on oil heat at $0.84 per gallon, expected to increase at an annual rate of 4 percent (real) over the building life of 30 years. A real discount rate of 4 percent and a seasonal efficiency of 70 percent are assumed.

Solution: Using table 28, a UPW^* of 30.0 is found. Using table 29, a cost of $8.57 per million Btu output is found. By simple multiplication of the UPW^* and price per million Btu output, the index number is found to be approximately 257.

Breakpoint ratios for the insulation levels examined in this section have been calculated for the 8-in block wall insulated on the inside surface in table 30, the brick and block wall with insulation on the inside wall surface in table 31, the brick and block wall with insulation in the cavity in table 32, and the wood-frame wall in table 33. (Breakpoint ratios are not calculated for insulation poured into the cores of 8-in block walls since this is more expensive than the other alternatives examined.) These ratios are based on the insulation resistances and costs shown in tables 4 to 6 and the ΔAHR are based on the equations in table 21. Using these tables and the appropriate index number, the optimal insulation level can be quickly determined for each wall type and insulation type, as shown in the following example.

Example #5: Find the optimal level of rigid foam insulation in an 8-in block wall for the 3000 HDD_{55} region, given an index number of 257.

Solution: Using the 3000 HDD_{55} row in table 30, the highest index number for rigid foam insulation in the 8-in block wall not exceeding 257 is 243, corresponding to R-15 (approximately 2-in rigid foam plus 0.75-in reflective air space). This wall has an overall (opaque area) U-value of 0.055 Btu/(ft^2)(h)(°F).

Note in tables 30 and 31 that two columns are shown for R-13 mineral wool insulation. The first column represents R-13 in an incremental fashion to R-11 (i.e., an increase of 2 resistance units). The second column represents R-13

Table 28. Modified Uniform Present Worth Factors (UPW*)

Discount Rate	Rate of Fuel Price Increase	Useful Lifetime (years)				
		20	25	30	35	40
0%	0%	20.0	25.0	30.0	35.0	40.0
	2%	24.8	32.7	41.4	51.0	61.6
	4%	31.0	43.3	58.3	76.6	98.8
	6%	39.0	58.2	83.8	118.1	164.0
	8%	49.4	79.0	122.3	186.1	279.8
	10%	63.0	108.2	180.9	298.1	486.9
	12%	80.7	149.3	270.3	483.5	859.1
		20	25	30	35	40
2%	0%	16.4	19.5	22.4	25.0	27.4
	2%	20.0	25.0	30.0	35.0	40.0
	4%	24.7	32.5	41.1	50.6	61.1
	6%	30.7	42.8	57.5	75.3	96.9
	8%	38.5	57.1	82.0	115.1	159.1
	10%	48.5	77.1	118.7	179.5	268.1
	12%	61.5	104.9	174.0	284.5	460.8
		20	25	30	35	40
4%	0%	13.6	15.6	17.3	18.7	19.8
	2%	16.4	19.6	22.5	25.2	27.5
	4%	20.0	25.0	30.0	35.0	40.0
	6%	24.6	32.3	40.9	50.2	60.5
	8%	30.4	42.4	56.8	74.2	95.2
	10%	38.0	56.2	80.3	112.2	154.5
	12%	47.6	75.3	115.3	173.3	257.3
		20	25	30	35	40
6%	0%	11.5	12.8	13.8	14.5	15.0
	2%	13.7	15.8	17.5	18.9	20.0
	4%	16.5	19.7	22.6	25.3	27.7
	6%	20.0	25.0	30.0	35.0	40.0
	8%	24.5	32.2	40.6	49.9	60.1
	10%	30.2	41.9	56.0	73.0	93.5
	12%	37.5	55.3	78.7	109.6	150.2
		20	25	30	35	40
10%	0%	8.5	9.1	9.4	9.6	9.8
	2%	9.9	10.8	11.4	11.8	12.1
	4%	11.7	13.1	14.1	14.9	15.5
	6%	13.9	16.0	17.8	19.3	20.5
	8%	16.6	19.9	22.9	25.6	28.1
	10%	20.0	25.0	30.0	35.0	40.0
	12%	24.3	31.9	40.1	49.2	59.1

Table 29. Unit Energy Prices (Metered) and Corresponding Price per Million Btu Output from Furnace

A. Price per Million Btu Metered (P_H/η_H) for Selected Fuel Types

Fuel Type	Price Unit	Unit Energy Price									
Gas	$/therm	0.20	0.30	0.40	0.50	0.60	0.80	1.00	1.20	1.50	1.80
Oil	$/gallon	0.28	0.42	0.56	0.70	0.84	1.12	1.40	1.68	2.10	2.52
Elec.	¢/kWh	0.70	1.00	1.40	1.70	2.10	2.70	3.40	4.10	5.10	6.10
$/Million Btu (metered)		2.00	3.00	4.00	5.00	6.00	8.00	10.00	12.00	15.00	18.00

B. Price per Million Btu Output for Selected Furnace Efficiencies

	Price per Million Btu Metered (P_H/η_H)									
Furnace Efficiency[a]	2.00	3.00	4.00	5.00	6.00	8.00	10.00	12.00	15.00	18.00
0.6	3.33	5.00	6.67	8.33	10.00	13.33	16.67	20.00	25.00	30.00
0.7	2.86	4.29	5.71	7.14	8.57	11.43	14.29	17.14	21.43	25.71
0.8	2.56	3.75	5.00	6.25	7.50	10.00	12.56	15.00	18.75	22.50
0.9	2.22	3.33	4.44	5.56	6.67	8.89	11.11	13.33	16.67	20.00
1.0	2.00	3.00	4.00	5.00	6.00	8.00	10.00	12.00	15.00	18.00
1.4	1.43	2.14	2.86	3.57	4.49	5.71	7.14	8.57	10.71	12.86
1.6	1.25	1.88	2.50	3.13	3.75	5.00	6.25	7.50	9.38	11.25
1.8	1.11	1.67	2.22	2.78	3.33	4.44	5.56	6.67	8.33	10.00
2.0	1.00	1.50	2.00	2.50	3.00	4.00	5.00	6.00	7.50	9.00
2.2	0.91	1.36	1.82	2.27	2.73	3.64	4.55	5.45	6.82	8.18

[a] Efficiencies greater than 1.0 are for heat pumps.

Table 30. Breakpoint Ratios for 8-in Block Walls (Insulation on Inside Surface)

Heating Degree Days (Base 55°F)		Breakpoint Ratios									
		Foil-backed Wallboard	Mineral Wool (replaces foil-backed wallboard)				Rigid Foam & Foil-backed Wallboard (R-3)				
	R-value	3	11	13	13[a]	19	7	9	12	15	18
	U-value	0.162	0.074	0.066	0.066	0.046	0.098	0.082	0.066	0.055	0.047
	cost/ft^2	\$0.10	\$0.75	\$0.80	\$0.80	\$1.00	\$0.61	\$0.76	\$1.00	\$1.23	\$1.46
	ΔU	0.080	0.088	0.008	0.096	0.020	0.064	0.016	0.016	0.011	0.008
	Δcost/ft^2	\$0.10	\$0.65	\$0.05	\$0.70	\$0.20	\$0.51	\$0.15	\$0.24	\$0.23	\$0.23
500		72	425	359	419	575	458	539	862	1202	1652
1000		40	238	201	234	322	256	301	482	672	924
1500		28	165	140	163	223	178	209	335	467	642
2000		21	126	107	125	171	136	160	256	357	491
2500		17	102	87	101	139	110	130	208	290	398
3000		15	86	73	85	116	93	109	175	243	335
4000		11	65	55	64	88	70	83	132	185	254
5000		9	52	44	52	71	57	67	107	149	204
6000		7	44	37	43	59	47	56	89	124	171
7000		6	38	32	37	51	41	48	77	107	147

[a] This column represents R-13 evaluated directly after R-3 since R-13 is more cost effective (i.e., has lower breakpoint ratios) than R-11.

Table 31. Breakpoint Ratios for Brick and Block Walls (Insulation on Inside Surface)

Heating Degree Days (Base 55°F)		Breakpoint Ratios: Foil-backed Wallboard	Mineral Wool (replaces foil-backed wallboard)				Rigid Foam & Foil-backed Wallboard (R-3)				
	R-value	3	11	13	13[a]	19	7	9	12	15	18
	U-value	0.142	0.070	0.062	0.062	0.045	0.091	0.077	0.062	0.053	0.045
	cost/ft^2	$0.10	$0.75	$0.80	$0.80	$1.00	$0.61	$0.76	$1.00	$1.23	$1.46
	ΔU	0.059	0.072	0.008	0.080	0.017	0.051	0.014	0.015	0.009	0.008
	Δcost/ft^2	$0.10	$0.65	$0.05	$0.70	$0.20	$0.51	$0.15	$0.24	$0.23	$0.23
500		106	563	390	546	733	623	668	998	1593	1792
1000		56	301	208	291	392	333	357	533	851	957
1500		38	205	142	199	267	227	243	363	580	653
2000		29	156	108	151	203	172	185	276	440	495
2500		24	125	87	121	163	139	149	222	355	399
3000		20	105	73	102	137	116	125	186	297	334
4000		15	79	55	77	103	88	94	140	224	252
5000		12	64	44	62	83	70	75	113	180	202
6000		10	53	37	51	69	59	63	94	150	169
7000		9	46	32	44	59	50	54	81	129	145

[a] This column represents R-13 evaluated directly after R-3 since R-13 is more cost effective (i.e., has lower breakpoint ratios) than R-11.

Table 32. Breakpoint Ratios for Brick and Block Walls (Insulation in Cavity)

Heating Degree Days (Base 55°F)		Breakpoint Ratios: Rigid Foam					
	R-value	4	6	9	12	15	18
	U-value	0.111	0.091	0.071	0.059	0.050	0.043
	cost/ft^2	\$0.51	\$0.66	\$0.90	\$1.13	\$1.36	\$1.57
	ΔU	0.090	0.020	0.020	0.012	0.009	0.007
	Δcost/ft^2	\$0.51	\$0.15	\$0.24	\$0.23	\$0.23	\$0.21
500		305	404	646	1032	1376	1616
1000		174	230	368	588	785	921
1500		122	161	258	412	549	644
2000		94	124	198	316	422	495
2500		76	101	161	257	343	402
3000		64	85	135	216	289	339
4000		49	64	103	164	219	257
5000		39	52	83	133	177	208
6000		33	43	70	111	148	174
7000		28	37	60	96	127	150

Table 33. Breakpoint Ratios for Wood-Frame Walls

Heating Degree Days (Base 55°F)		Breakpoint Ratios: Foil-backed Wallboard	Breakpoint Ratios: Mineral Wool (replaces foil-backed wallboard)			
	R-value	3	11	13	18	23[a]
	U-value	0.152	0.078	0.071	0.055	0.045
	cost/ft^2	\$0.10	\$0.30	\$0.35	\$0.55	\$0.90
	ΔU	0.061	0.074	0.007	0.016	0.010
	Δcost/ft^2	\$0.10	\$0.20	\$0.05	\$0.20	\$0.35
500		79	131	345	604	1692
1000		48	79	209	365	1022
1500		34	57	149	262	733
2000		27	44	116	204	571
2500		22	36	95	167	467
3000		19	31	81	141	396
4000		14	23	62	108	303
5000		11	19	50	88	245
6000		10	16	42	74	206
7000		8	14	36	64	178

[a] R-5 rigid foam sheathing replaces R-1.32 fiberboard sheathing.

incremental to R-3. In these two tables, the breakpoint ratios for R-13 incremental to R-11 are lower than for the R-11 level. This indicates that if R-11 is cost effective (including the cost of the 2 x 3-in framing), then R-13 will be even more cost effective. As stated above, when a succeeding increment of insulation resistance has a breakpoint ratio lower than that for the preceding increment, the two increments should be combined and a new ratio computed. The second column for R-13 insulation represents this combination of two increments (R-3 to R-11 and R-11 to R-13).

Example #6: Find the optimal level of thermal resistance for a brick and block wall being insulated on the inside with mineral wool insulation in the 3000 HDD_{55} region, given an index number of 102.

Solution: Using table 31, R-11 insulation is not quite cost effective since its breakpoint ratio is 105. However, the R-13 insulation, being slightly more cost effective, is cost effective at the breakpoint ratio of 102. Since no higher level is cost effective, R-13 is the optimal insulation level in this case.

While this index number methodology provides a good basis for determining optimal insulation levels, it should be recognized that the estimated ΔAHR and ΔK (and, thus, the breakpoint ratio, $\Delta K/\Delta AHR$) are subject to considerable variation. Variations in ΔAHR may result from differences in the operational profile (e.g., no night thermostat setback), differences in local climatic factors, differences in exterior absorptance, and differences in the overall design of the house. Factors which affect ΔK include regional variations in material and labor costs, the use of union or non-union labor, general inflation over time, the use or non-use of subcontractors, and overhead and profit rates. As a result, for insulation levels with breakpoint ratios that are quite close to the appropriate index number, some subjective considerations should be made as to whether the lower or higher level of insulation at that point is the more appropriate point to stop insulating. For example, for exterior wall surfaces that are very light in color (and thus do not absorb as much solar radiation) the higher level of insulation may be cost effective, while for dark surfaces the lower insulation level may be the maximum cost-effective level. Similarly, if no night thermostat setback is used and the house is heated throughout the winter, the ΔAHR will be greater and therefore the higher insulation level will likely be cost effective.

Facing page: *Additional research is needed to develop more cost-effective methods of insulating masonry walls.*

7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.1 SUMMARY

The purpose of this report is to determine economically optimal insulation methods and resistance levels for both masonry and wood-frame walls in single-family housing. The economically optimal method and level of insulation has the greatest present-value net savings (total savings less total costs) over its expected life of all alternatives considered. Since net savings are determined in part by climate and projected energy costs, optimal insulation methods and levels can be expected to vary with both geographic location and the energy types used for space heating and cooling. In addition, since the costs of insulating different wall types (e.g., masonry and wood-frame) may vary significantly, and the effect of insulation in the different wall types may vary as well, optimal insulation methods and resistance levels may vary by wall type in many cases.

This report examines each of these key variables in order to determine optimal insulation levels for exterior walls. Reductions in annual heating requirements (AHR) and annual cooling requirements (ACR) due to several levels of thermal resistance are calculated for 3 basic wall types in 11 locations for 8-in block and wood-frame walls, and in 8 locations for brick and block walls. Generalized relationships between reductions in U-value and reductions in AHR are developed and correlated with heating degree days (base 55°F). Representative costs for the most common insulating methods are estimated over a range of commonly available thermal resistances. A methodology is outlined for determining the present value of the energy savings from the increased use of insulation based on current energy prices, projected energy price escalation rates, a discount rate, and useful insulation life. An index number system is devised to aid the reader in determining optimal insulation levels for each wall type with a minimum of computation required.

7.2 CONCLUSIONS

A number of important conclusions have been reached in this study. It is anticipated that some of these may have a significant impact on insulation practices for new home construction if they are confirmed and accepted by the home-building industry.

- Since the insulation of masonry walls is considerably more expensive than the insulation in wood-frame walls, the economically optimal level is considerably lower for the former than the latter. In much of the Southern and Southwestern United States, no more than R-3 (reflective air space) insulation is cost effective for masonry walls in gas-heated houses, while R-11 or R-13 mineral wool insulation is cost effective in similar houses with wood-frame walls in the same locations.

- Framing the inside of masonry walls with 2 x 3-in studs and insulating with mineral wool is significantly less costly than the use of rigid foam insulation, even after adjustment for lost interior space. When mineral wool is used, the optimal insulation levels are generally similar to those for wood-frame housing, except in the mildest heating climates. In general, if mineral wool insulation is used, R-11 or R-13 is more cost effective than lower levels (e.g., R-5 or R-7) because the extra cost is quite low relative to the extra benefits.

- Reductions in annual heating requirements due to insulating exterior walls are similar for both wood-frame and masonry walls insulated on the inside surface in regions with greater than 3000 heating degree days (base 65°F). The reductions tend to be quite significant if the other shell components (i.e., attic, windows, floors) are insulated in a cost-effective manner. In regions with less than 3000 heating degree days, the reductions tend to be relatively less for the insulation in masonry walls than in wood-frame walls (given equivalent reductions in U-values). However, these differences are generally small in absolute terms.

- Changes in annual cooling requirements due to increasing insulation levels are not likely to be significant except in regions with extremely hot summers like those in southern Arizona. In fact, cooling requirements may increase if a house is kept tightly closed up, especially in the spring and fall. Small reductions in annual cooling requirements may occur if air conditioning is only used when the outdoor temperature is warmer than the thermostat setpoint. Except in regions with very mild heating climates, however, such savings do not have a significant effect in selecting the optimal insulation level.

- In climates typified by mild winters or summers, increased mass can significantly improve the thermal performance of exterior walls, in terms of reducing annual heating or cooling requirements. However, in these regions heating or cooling requirements tend to be relatively small to begin with. As more severe climates are encountered, the advantages of mass over lighter construction techniques are sharply reduced.

- Insulation in the cavity of a brick and block wall generally performs significantly better than the same insulation placed on the inside surface of the wall. If the installed cost per resistance unit of cavity insulation is the same as for insulation on the inside surface, cavity insulation is generally more cost effective.

- Insulation in the cores of 8-in concrete blocks is generally less cost effective than an equivalent level (in terms of overall U-value) of insulation installed on the inside wall surface, even though the former is slightly more effective than the latter in reducing heat loss.

- The color of the exterior surfaces of walls may have more effect on AHR and ACR than mass in those walls. However, unless the location of the house is clearly dominated by either heating or cooling loads, the advantages of color in one season will be offset by the disadvantages of the same color in the opposite season.

7.3 RECOMMENDATIONS FOR FURTHER RESEARCH

The results of this report, in terms of identifying maximum cost-effective levels of insulation in exterior walls for single-family housing, are based largely on simulations of the thermal performance of walls in a single prototypical house. The primary advantage of simulation data is in being able to hold all relevant factors constant except the one to be examined in a sensitivity analysis. However, it is important that the simulation algorithms be adequately verified by actual measured data. While small scale validation measurements have been successfully made for the NBSLD computer program, additional measurement data are needed to demonstrate the sensitivity of the algorithms to changes in thermal mass and insulation levels.

Research into more cost-effective methods of insulating masonry walls is needed. Because of the high cost of insulating with rigid foam insulation, the maximum economic level of rigid foam insulation is generally considerably lower than that for mineral wool insulation. However, the mineral wool insulation is approximately twice as thick as the rigid foam, and may therefore be less attractive to the builder and buyer. Placement of insulation near the outside of the wall can significantly improve the thermal performance of the wall but this is generally a more costly approach than insulating on the inside, since a protective coating must be applied. Insulation systems which can significantly reduce this cost are needed.

Expansion of this research to include data for multifamily housing and commercial buildings will be of considerable benefit to the building community. At present, masonry wall construction is more prevalent in these buildings than in single-family housing in most parts of the United States. As a result, the potential savings from improved insulation guidelines are likely to be considerably greater as well.

REFERENCES

Arens, Edward A. and Carroll, William L., Geographical Variation in the Heating and Cooling Requirements of a Typical Single-Family House, and Correlation of these Requirements to Degree Days, BSS 116, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., November 1978.

ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, 1972.

"BIA Technical Notes on Brick Construction - 21," Brick Institute of America, McLean, Va.

Hastings, S. R., Three Proposed Typical House Designs for Energy Conservation Research, NBSIR 77-1309, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., 1977.

Kusuda, T., NBSLD, The Computer Program for Heating and Cooling Loads in Buildings, BSS 69, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., 1976.

Means Building Construction Cost Data, 1980, Robert Snow Means Company, Inc., Duxbury, Mass., 1979.

NAHB Research Foundation, Inc., "Annual Builder Practices Survey," Rockville, Md.

Peavy, B., Burch, D., Powell, F., and Hunt, C. M., Comparision of Measured and Computer-Predicted Thermal Performance of a Four Bedroom Wood-Frame Townhouse, BSS 57, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., 1973.

Peavy, B., Powell, F., and Burch, D., Dynamic Thermal Performance of an Experimental Masonry Building, BSS 45, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., 1972.

Petersen, Stephen R., Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, BSS 64, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., December 1974.

Petersen, Stephen R. and Barnett, James P., Expanded NBSLD Output for Analysis of Thermal Performance of Building Envelope Components, NBSIR 80-2076, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., July 1980.

Reagan, J. A. and Acklam, D. M., "Solar Reflectivity of Common Roofing Materials and Its Influence on the Roof Heat Gain of Typical Southwestern Residences," Summer Attic and Whole-House Ventilation, NBS Special Publication 548, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., July 1979 (proceedings of a workshop sponsored by the Department of Energy and the Attic Ventilation Industry).

Roberts, Nall, Rogers, and Greenburg, "Comparison of Computer-Predicted Thermal Loads with Measured Data from Three Occupied Townhouses," ASHRAE Transactions, Vol. 83, Part I, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, 1978.

Sitzer, Moden, and Don Vito, Historical and Forecasted Energy Prices by DoE Region and Fuel Type for Three Microeconomic Scenarios, DoE/EIA-0184/15, U.S. Department of Energy, Washington, D.C., July 1979.

Snell, J. E., Achenbach, P. R., and Petersen, S. R., "Energy Conservation in New Housing Design," Science, Vol. 192, June 25, 1976.

Stamper, E., "Weather Data," ASHRAE Journal, February 1977.

Tietsma, G. J. and Peavy, B. A., The Thermal Performance of a Two-Bedroom Mobile Home, BSS 102, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., 1978.

U.S. Department of Agriculture, Farmers Home Administration, "Thermal Performance Standards," Washington, D.C., 1979.

U.S. Department of Energy, Office of Conservation and Solar Energy, Economic Analysis, Energy Performance Standards for New Buildings, Doc. 9568.00, Washington, D.C., November 1979.

U.S. Department of Housing and Urban Development, "Minimum Property Standards for One- and Two-Family Dwellings," Washington, D.C., 1979.

APPENDIX A

GLOSSARY OF SELECTED TECHNICAL TERMS

annual cooling requirements - the total yearly output from the cooling system into the conditioned space of a building needed to maintain the indoor temperature specified.

annual heating requirements - the total yearly output from the heating system into the conditioned space of a building needed to maintain the indoor temperature specified.

core cross section - the cross section of a concrete masonry unit that contains a hollow cell or a cell filled with an insulating material.

discount rate - the rate of interest reflecting the time value of money that is used to convert benefits and costs occurring at different times to a common time.

life-cycle cost - the total owning and operating costs of a building or building subsystem over its useful life, usually discounted to present value.

metered energy requirements - purchased energy as measured at the building boundary, i.e., before heating or cooling equipment conversion efficiency is considered.

mineral wool insulation - inorganic fibrous insulating materials, available in batt, blanket, rigid, and loose-fill form.

net savings - the savings attributable to a given alternative less the costs of that alternative.

optimal insulation level - the level of insulation (best expressed in terms of thermal resistance) which minimizes the life-cycle heating and cooling costs, including the cost of insulation, attributable to a given building envelope component.

R - thermal resistance $((ft^2)(h)(°F)/Btu)$; the reciprocal of the heat transfer coefficient of a building envelope component or a particular material within the component.

response factor method - a method for calculating the thermal transmission through a building envelope component which considers the ability of the component to store heat and the amount of heat which has been stored in the component in previous hours.

rigid foam insulation - organic cellular insulating materials in rectangular dimensions, preformed to standard lengths, widths, and thicknesses.

solar absorptance - the ratio of the radiant flux from the Sun absorbed by a body to that incident to it.

specific heat - the ratio of the quantity of heat required to raise the temperature of a body 1 °F to that required to raise the temperature of an equal mass of water 1 °F.

thermal mass - the weight of a given volume of material multiplied by its specific heat.

thermal performance - for a building component, the ability to reduce heat transmission which contributes to a heating or cooling load.

U - overall coefficient of heat transmission or thermal transmittance (air to air) through a building envelope component, usually expressed in Btu/(ft^2)(h)(°F) where °F is fahrenheit degree temperature difference between air on the inside and air on the outside of a building envelope component.

web cross section - the cross section of a concrete masonry unit that is solid concrete.

APPENDIX B

GRAPHICAL REPRESENTATIONS OF ANNUAL HEATING AND COOLING REQUIREMENTS FOR SELECTED CITIES

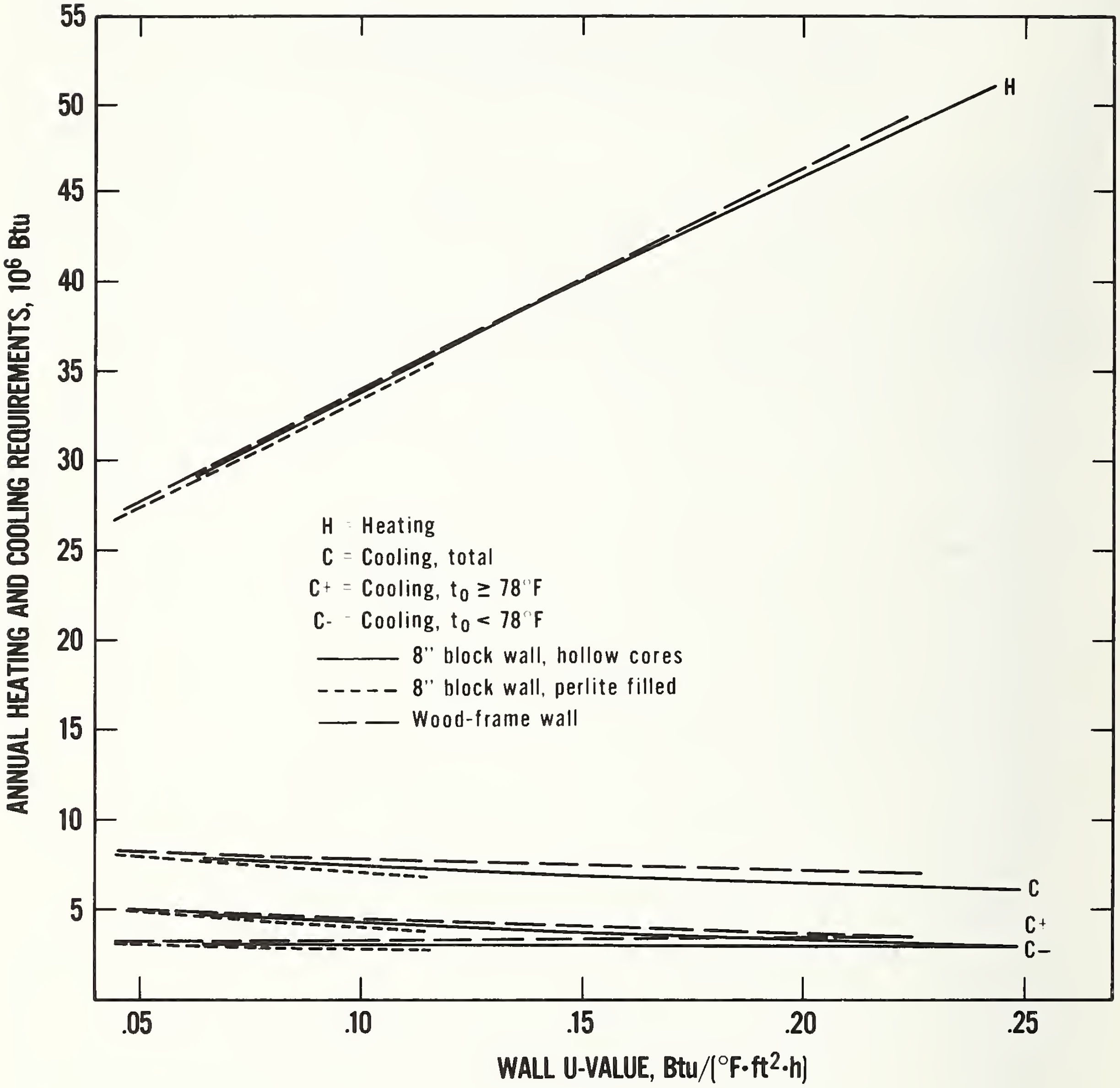

Figure B.1 Albany, New York: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

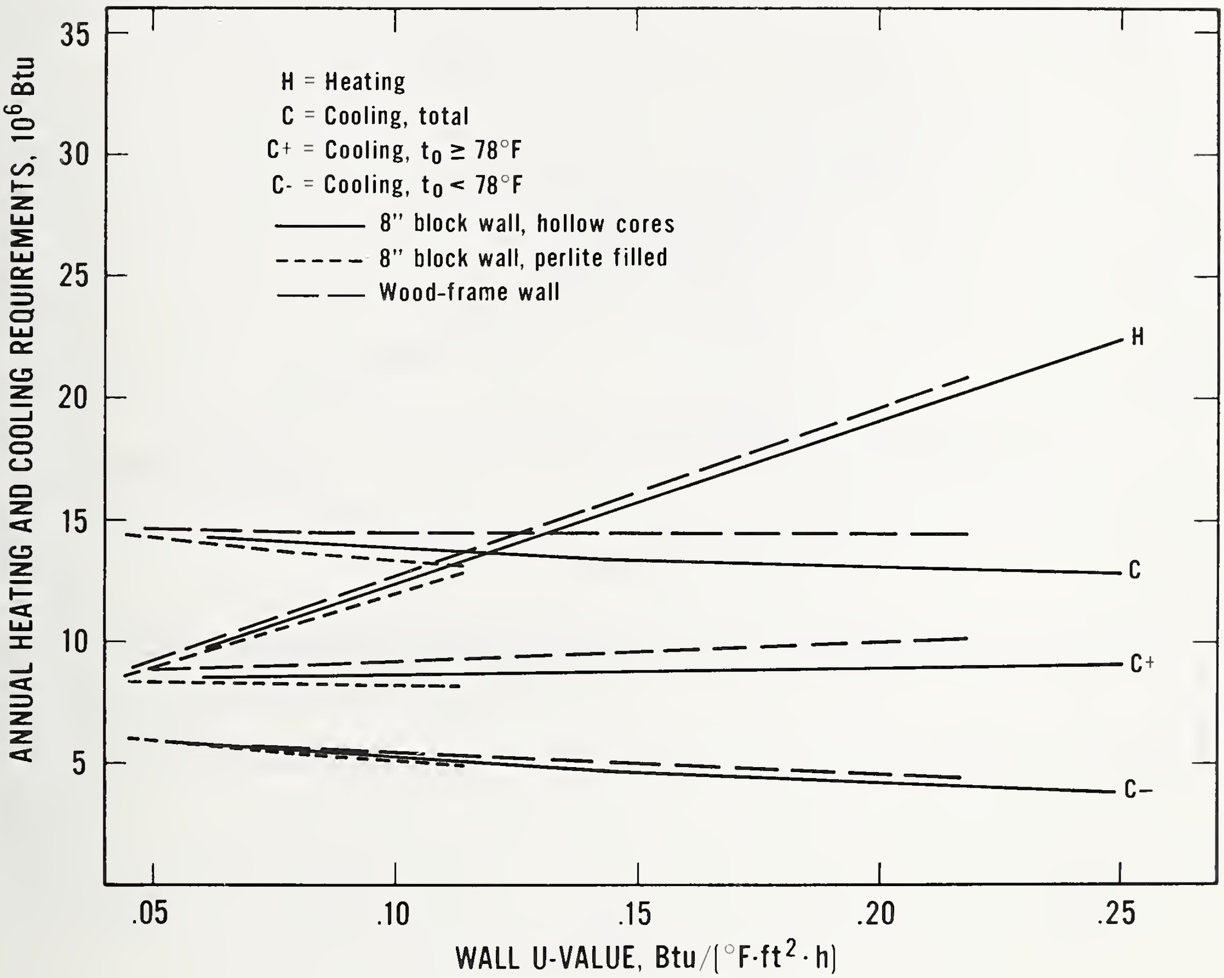

Figure B.2 Albuquerque, New Mexico: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

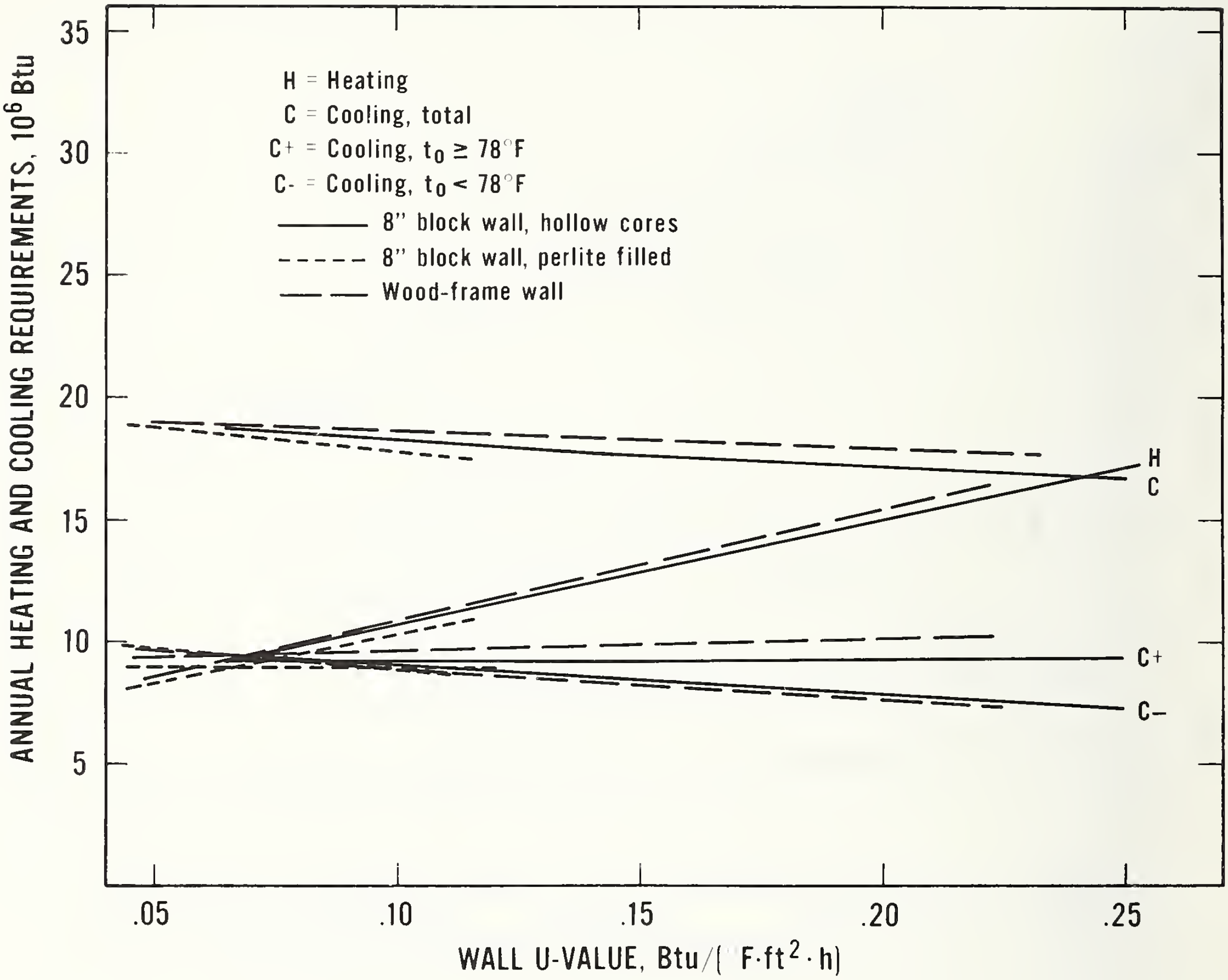

Figure B.3 Atlanta, Georgia: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

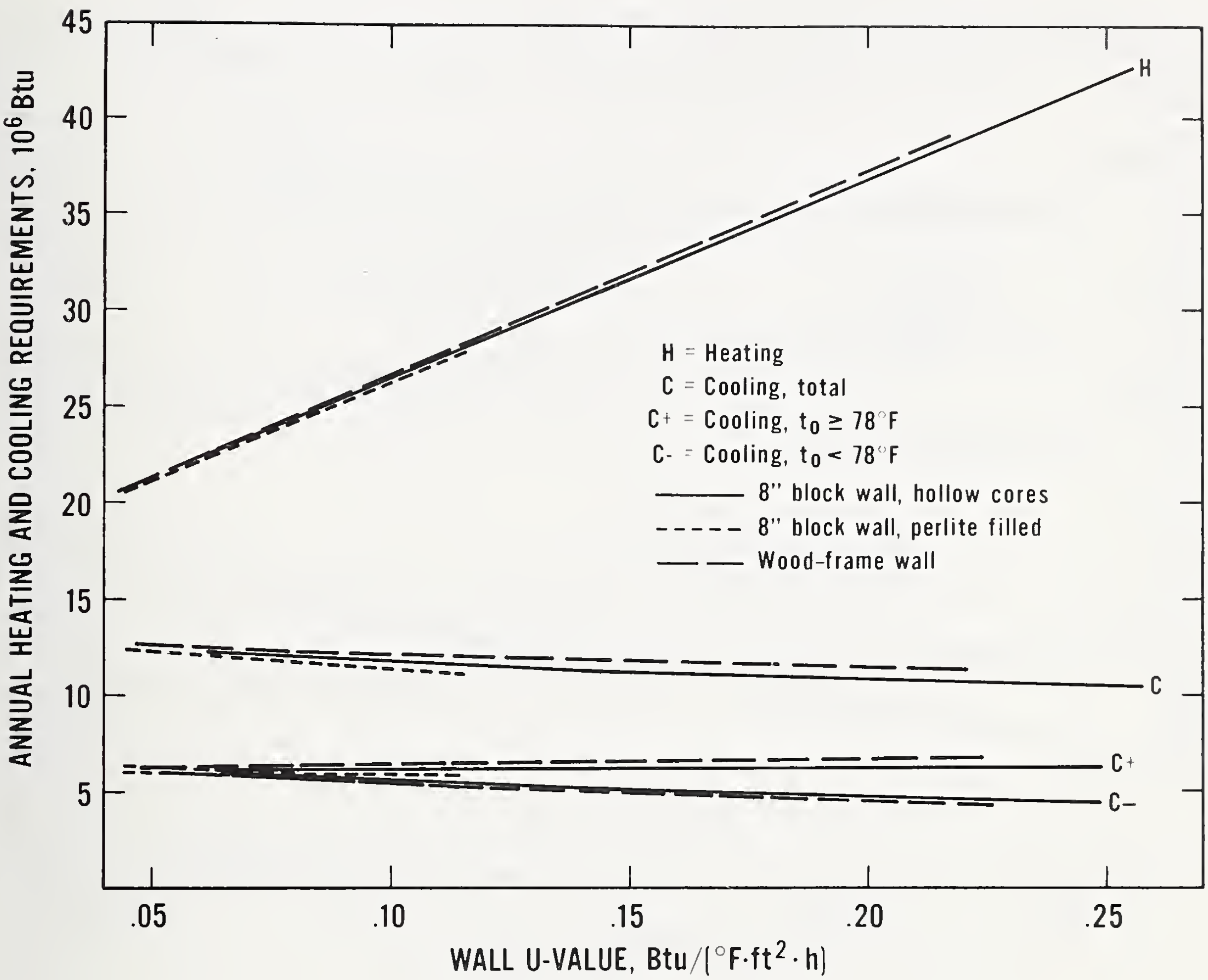

Figure B.4 Indianapolis, Indiana: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

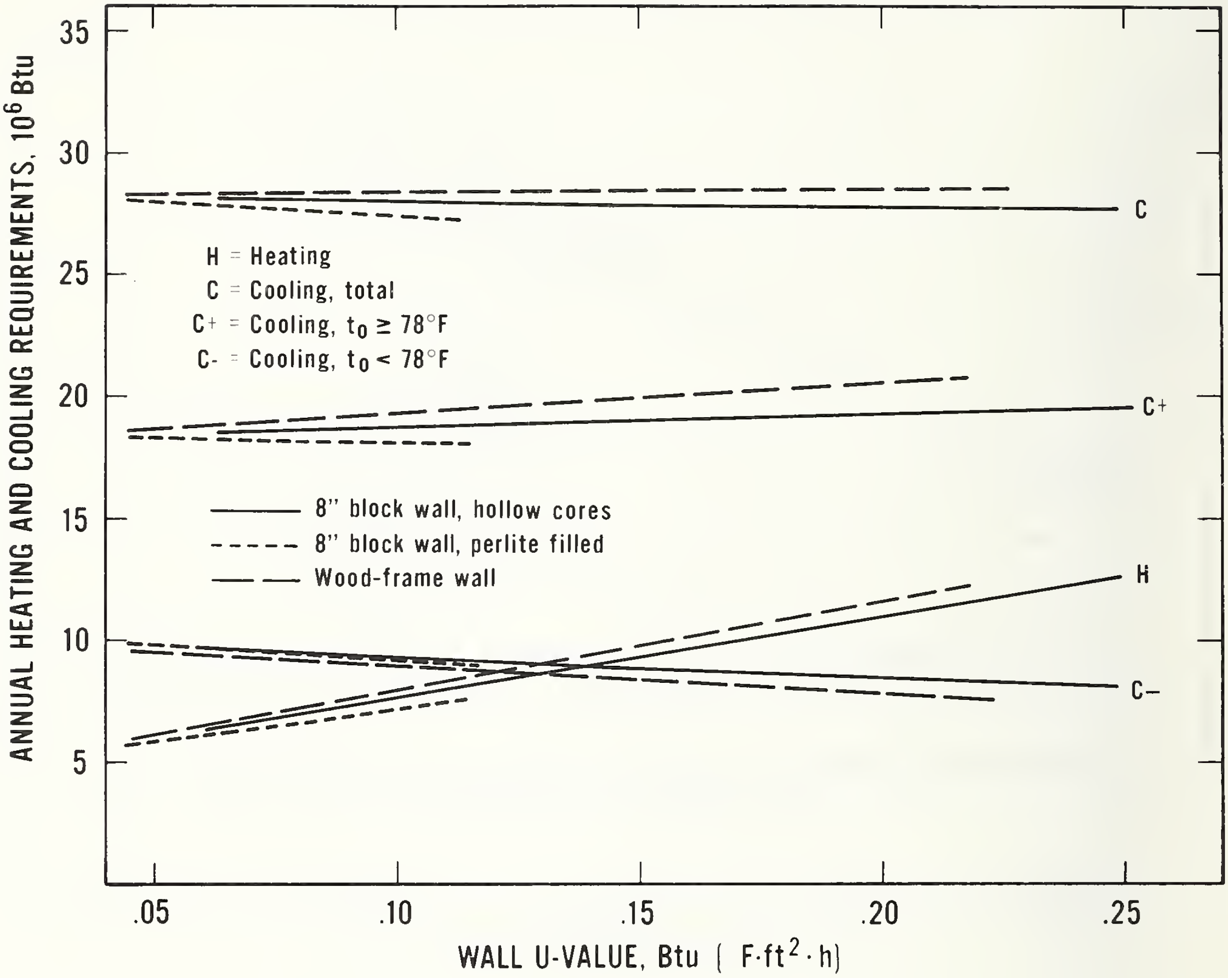

Figure B.5 Jackson, Mississippi: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

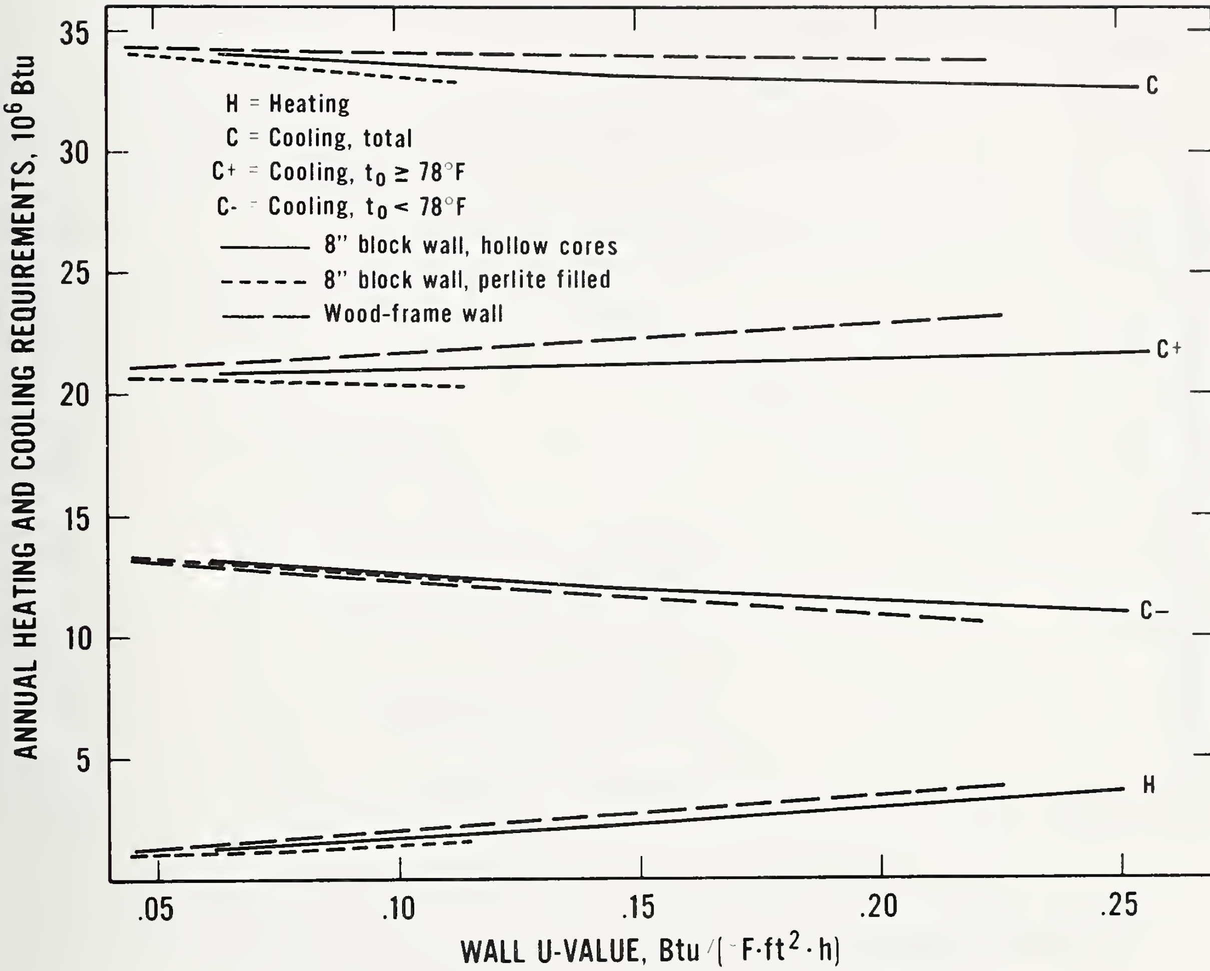

Figure B.6 Jacksonville, Florida: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

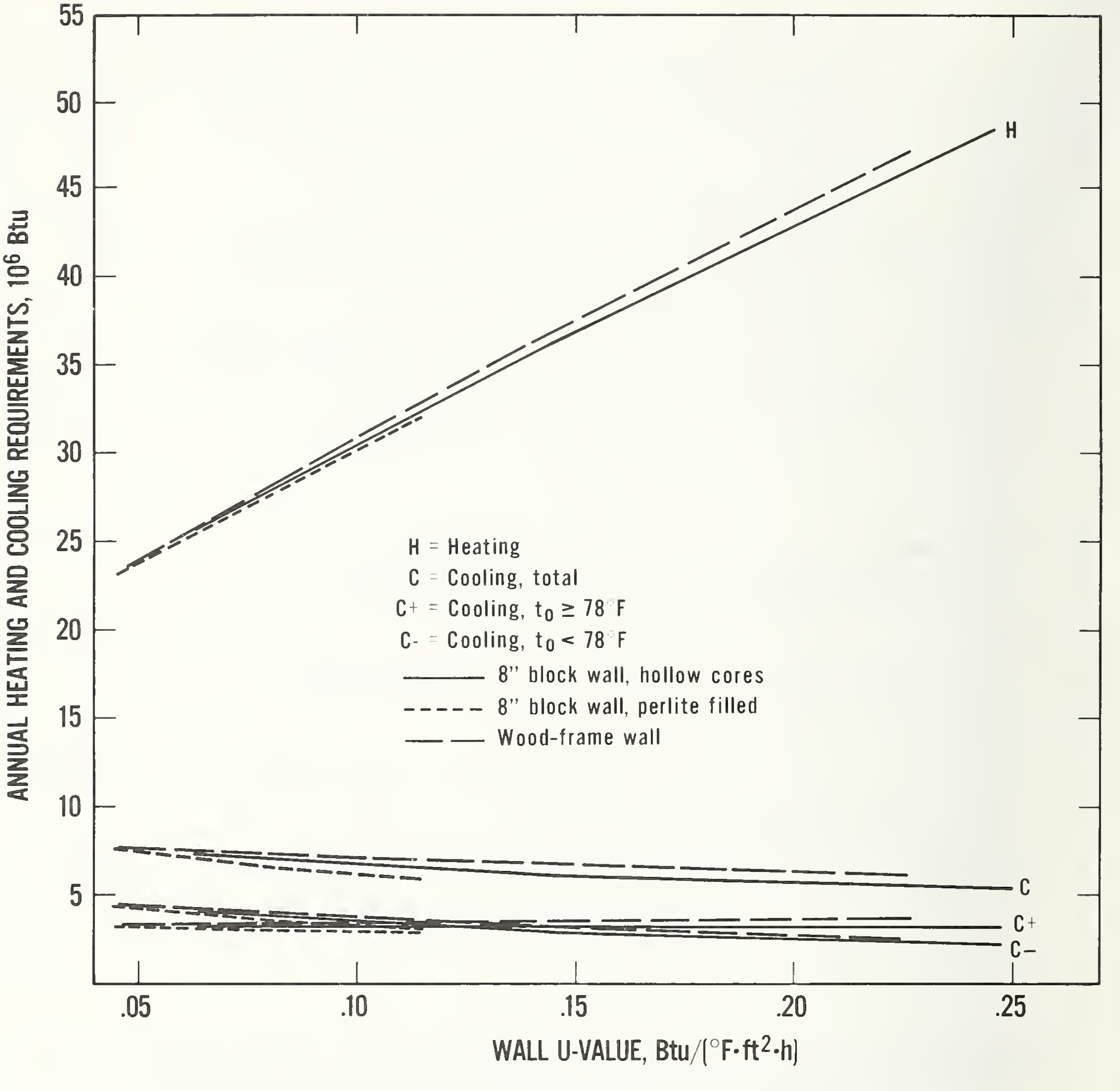

Figure B.7 Madison, Wisconsin: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

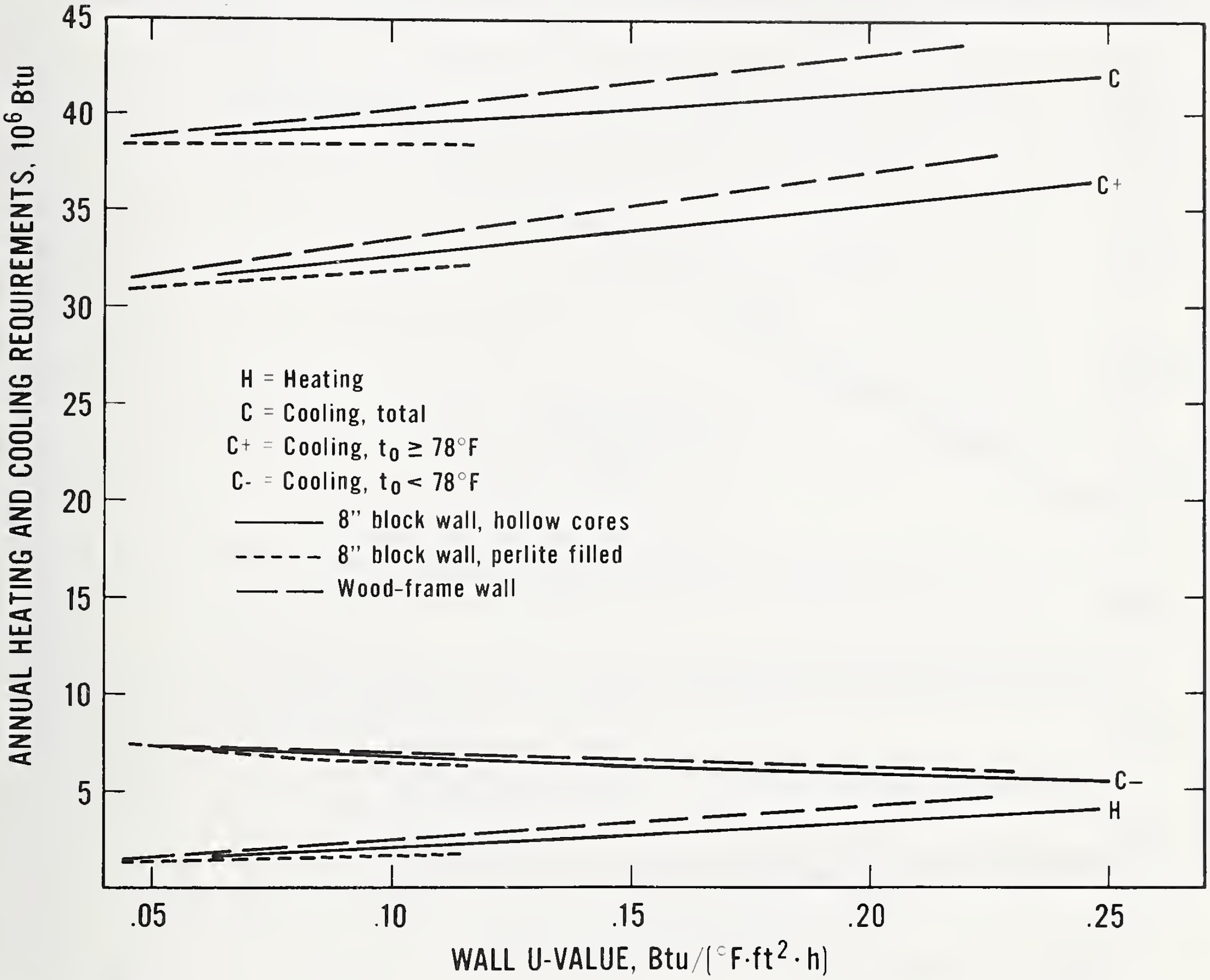

Figure B.8 Phoenix, Arizona: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

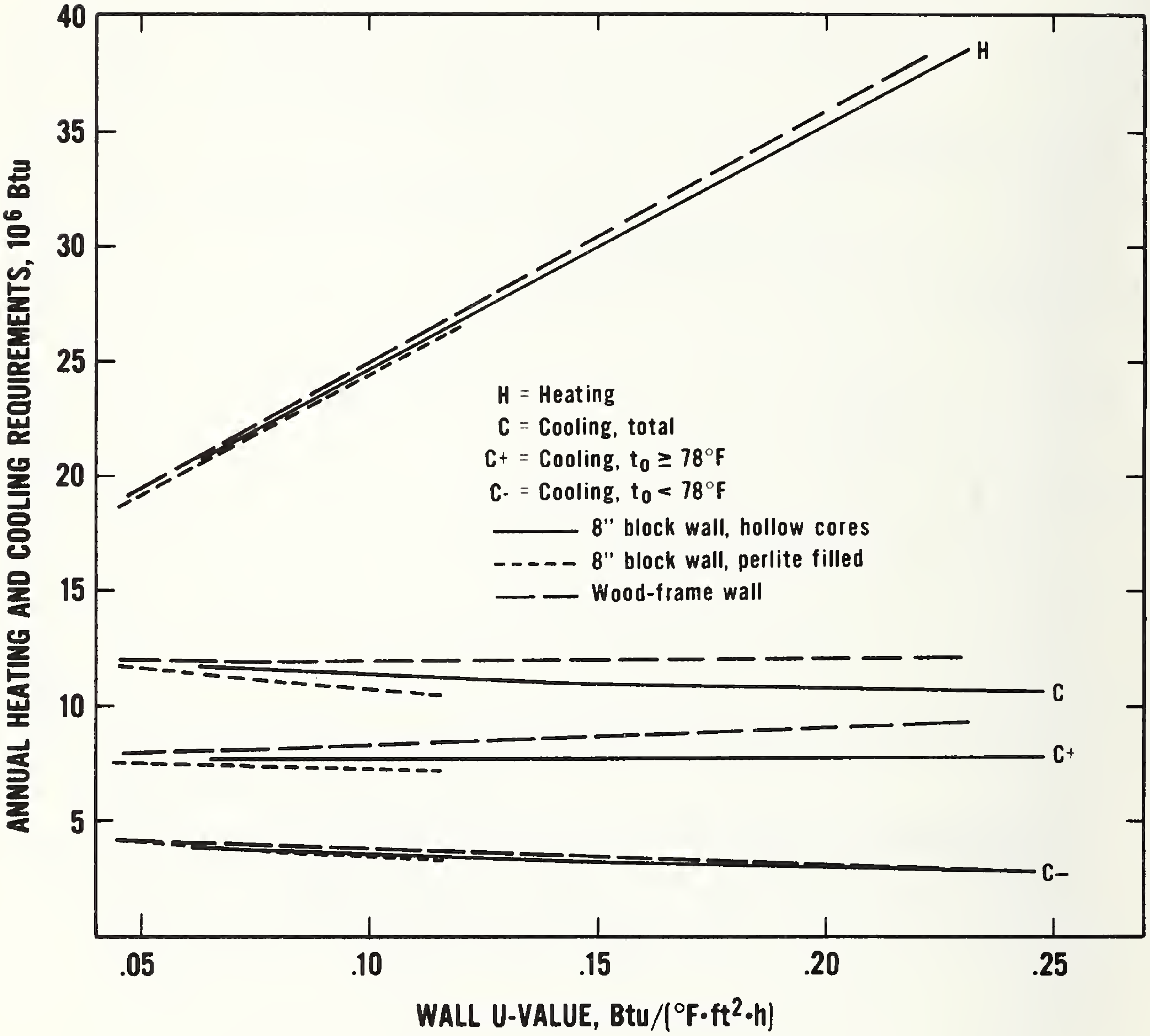

Figure B.9 Salt Lake City, Utah: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

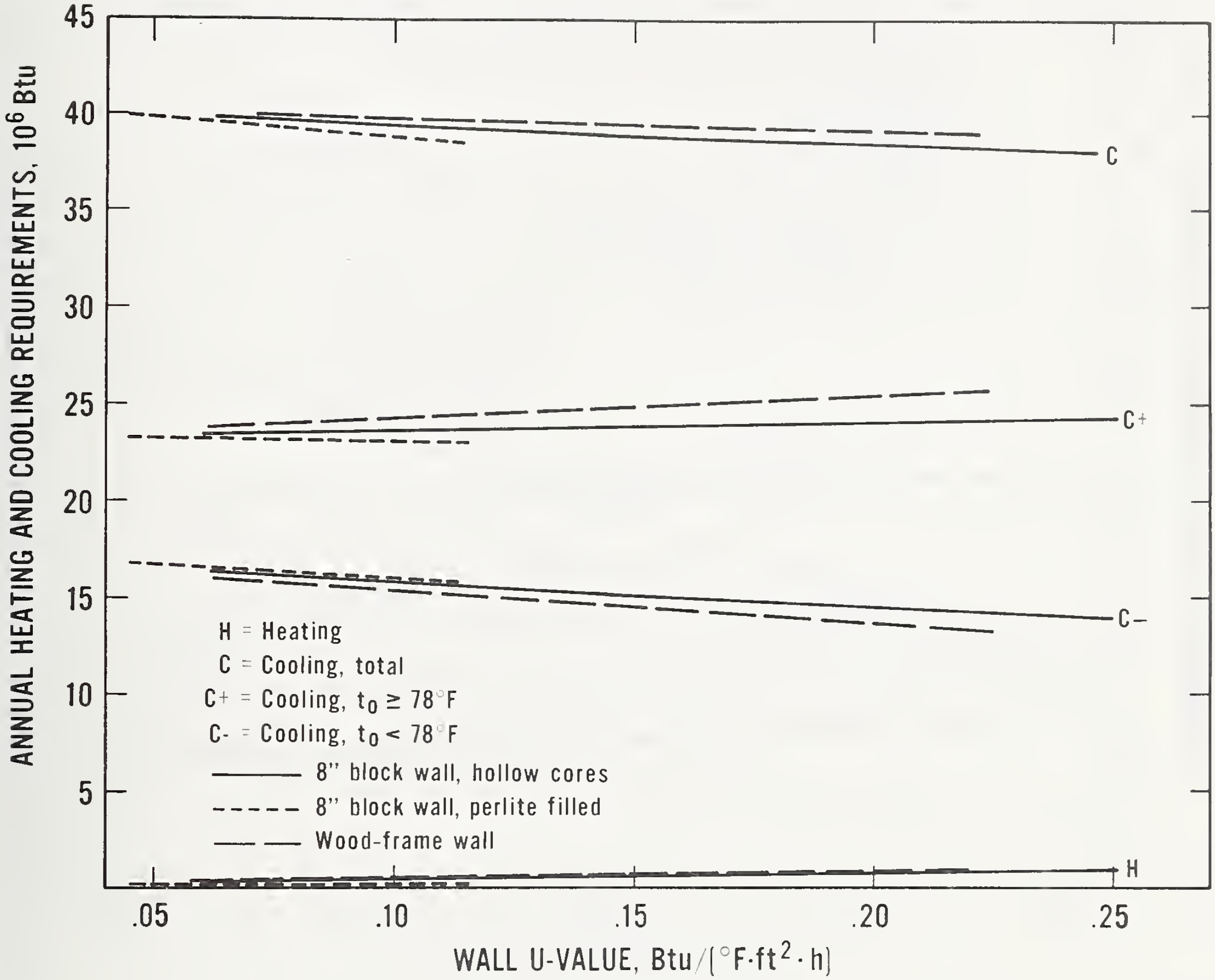

Figure B.10 Tampa, Florida: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

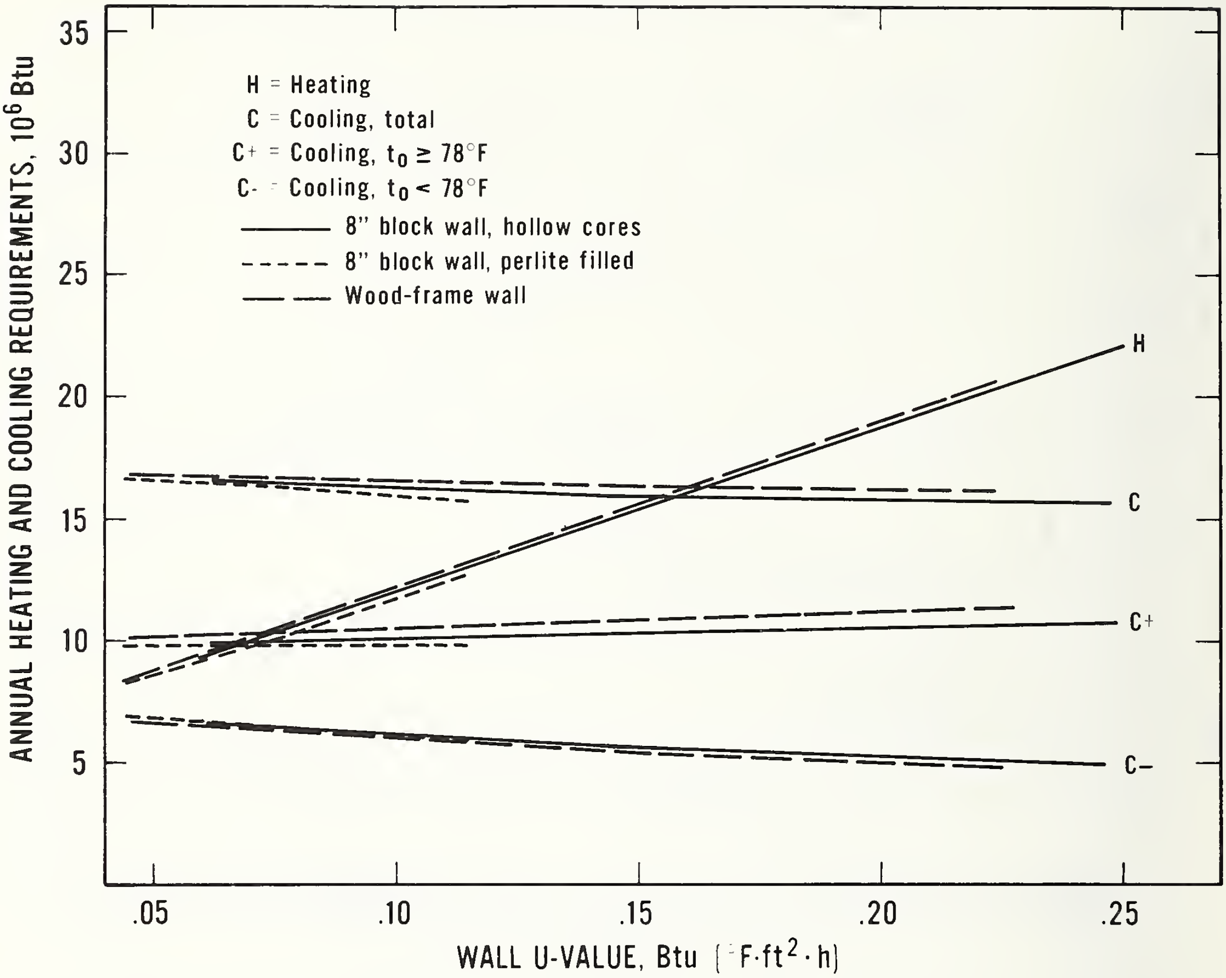

Figure B.11 Washington, D.C.: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Wood-Frame Walls)

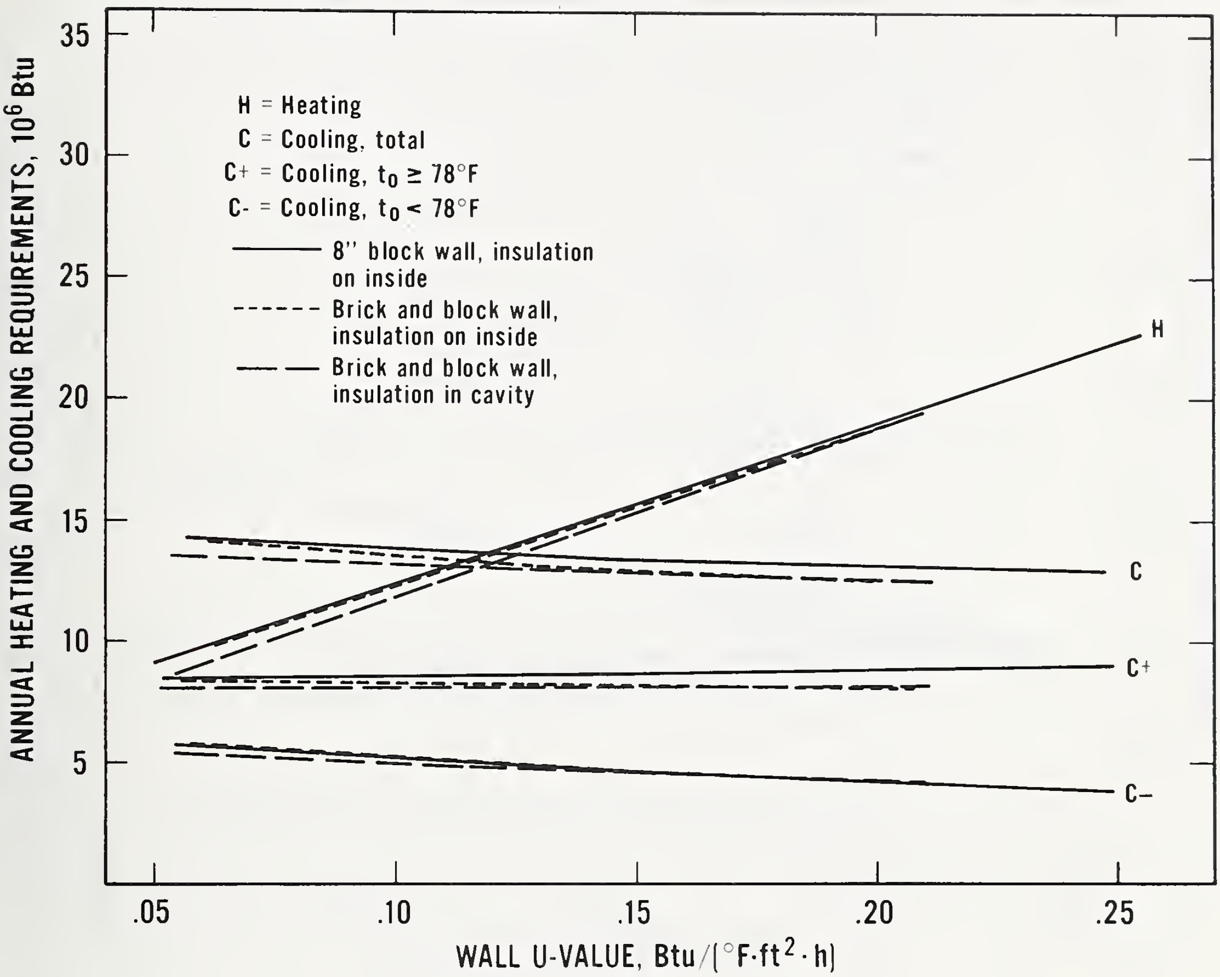

Figure B.12 Albuquerque, New Mexico: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Brick and Block Walls)

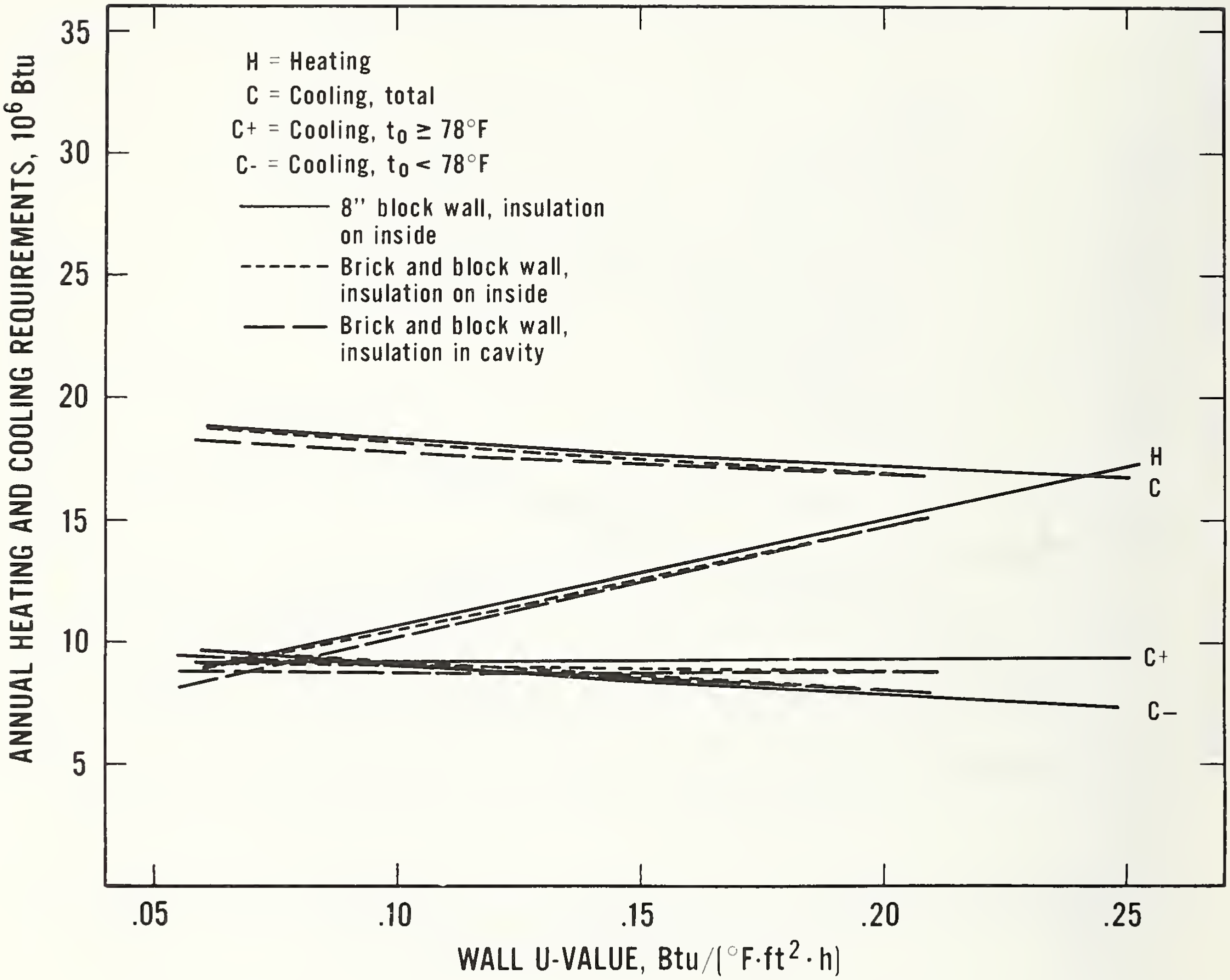

Figure B.13 Atlanta, Georgia: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Brick and Block Walls)

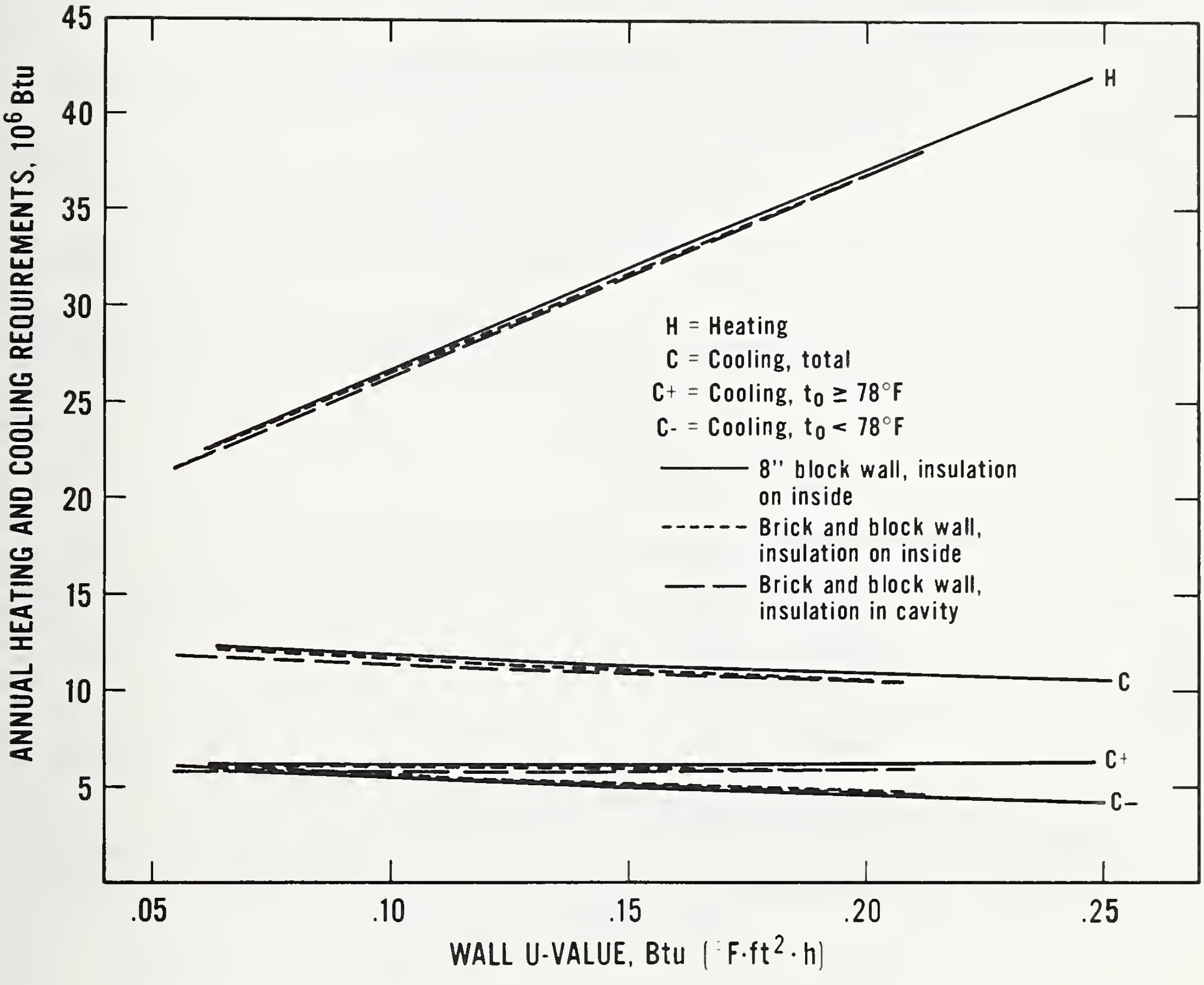

Figure B.14 Indianapolis, Indiana: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Brick and Block Walls)

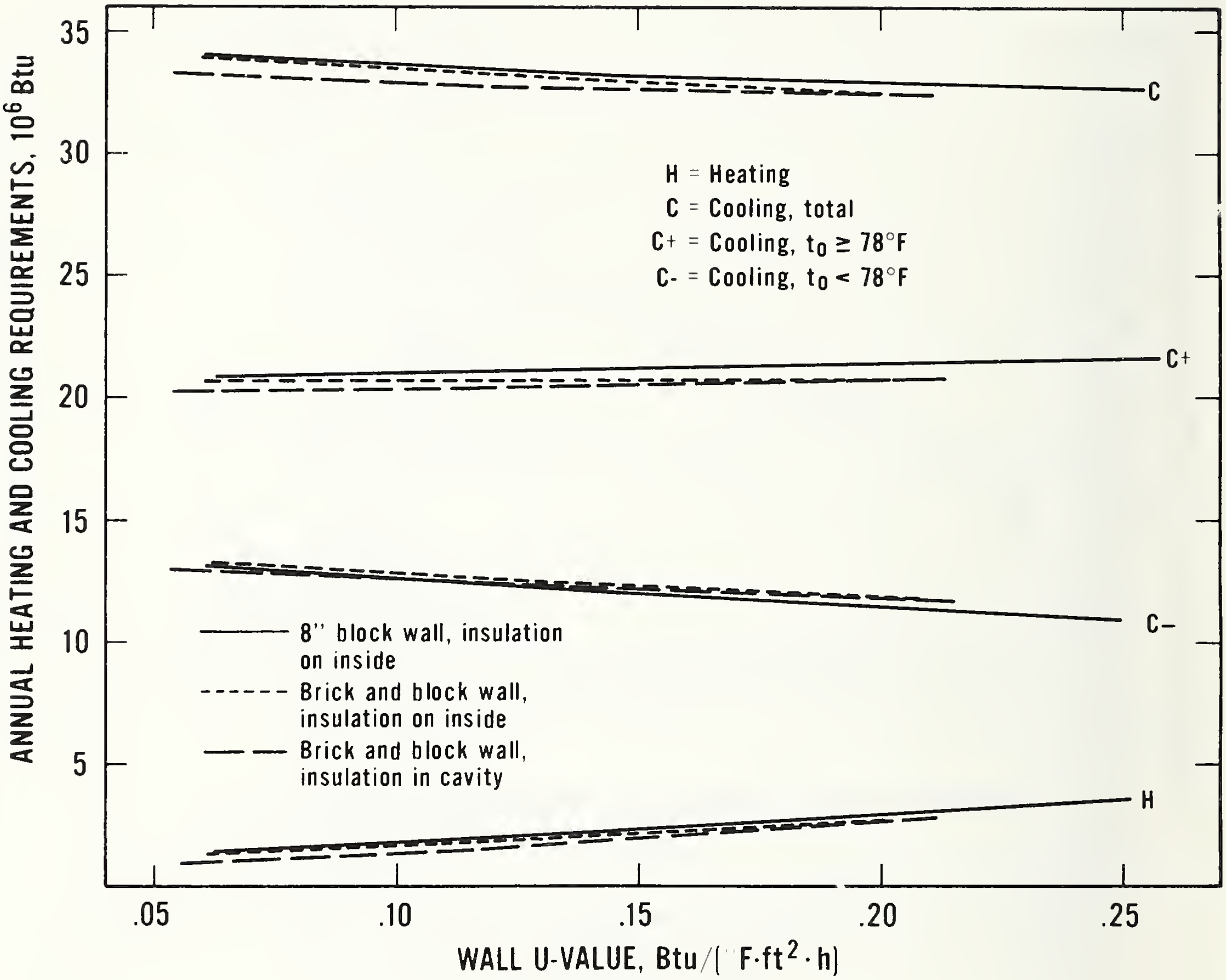

Figure B.15 Jacksonville, Florida: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Brick and Block Walls)

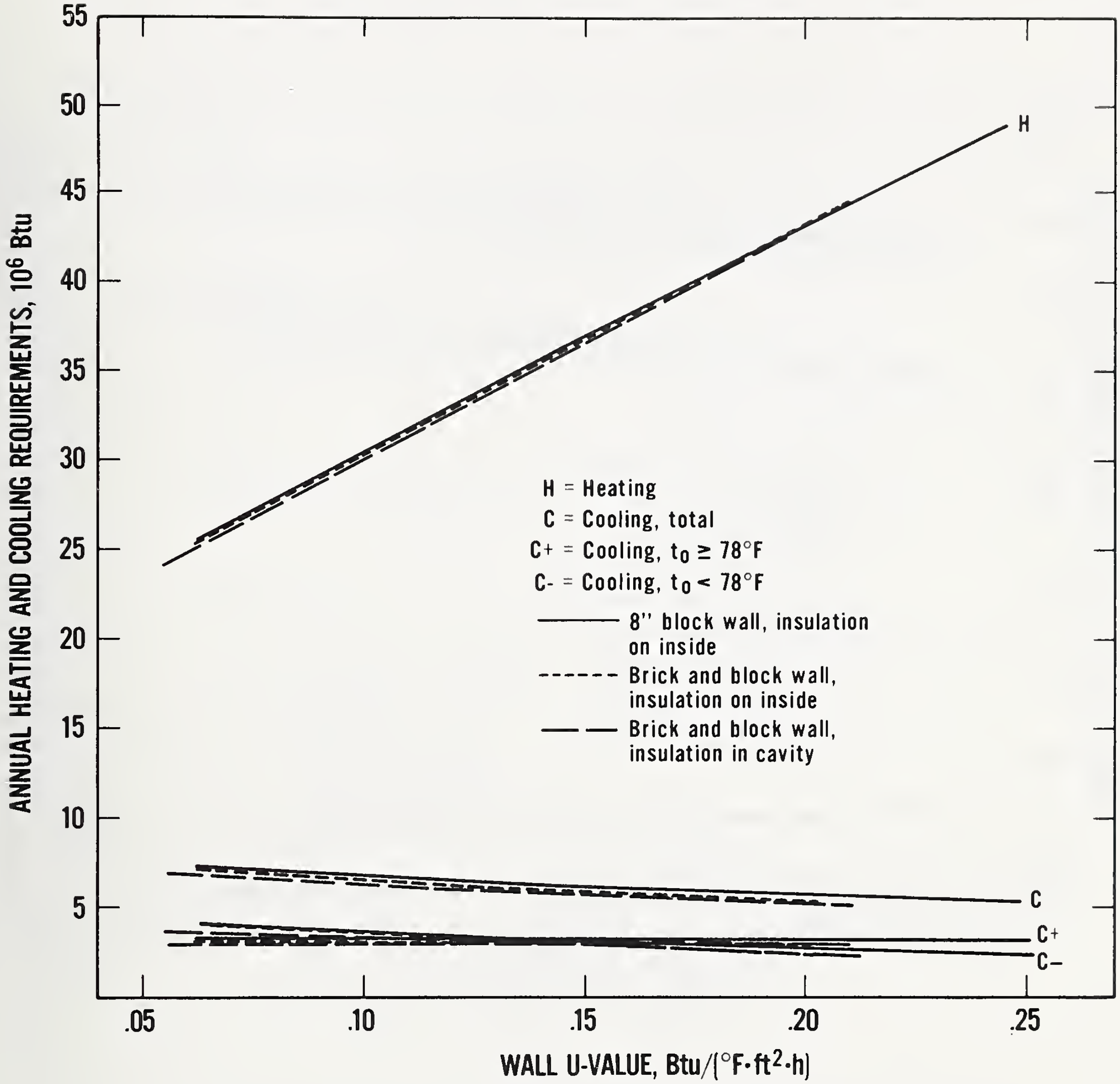

Figure B.16 Madison, Wisconsin: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Brick and Block Walls)

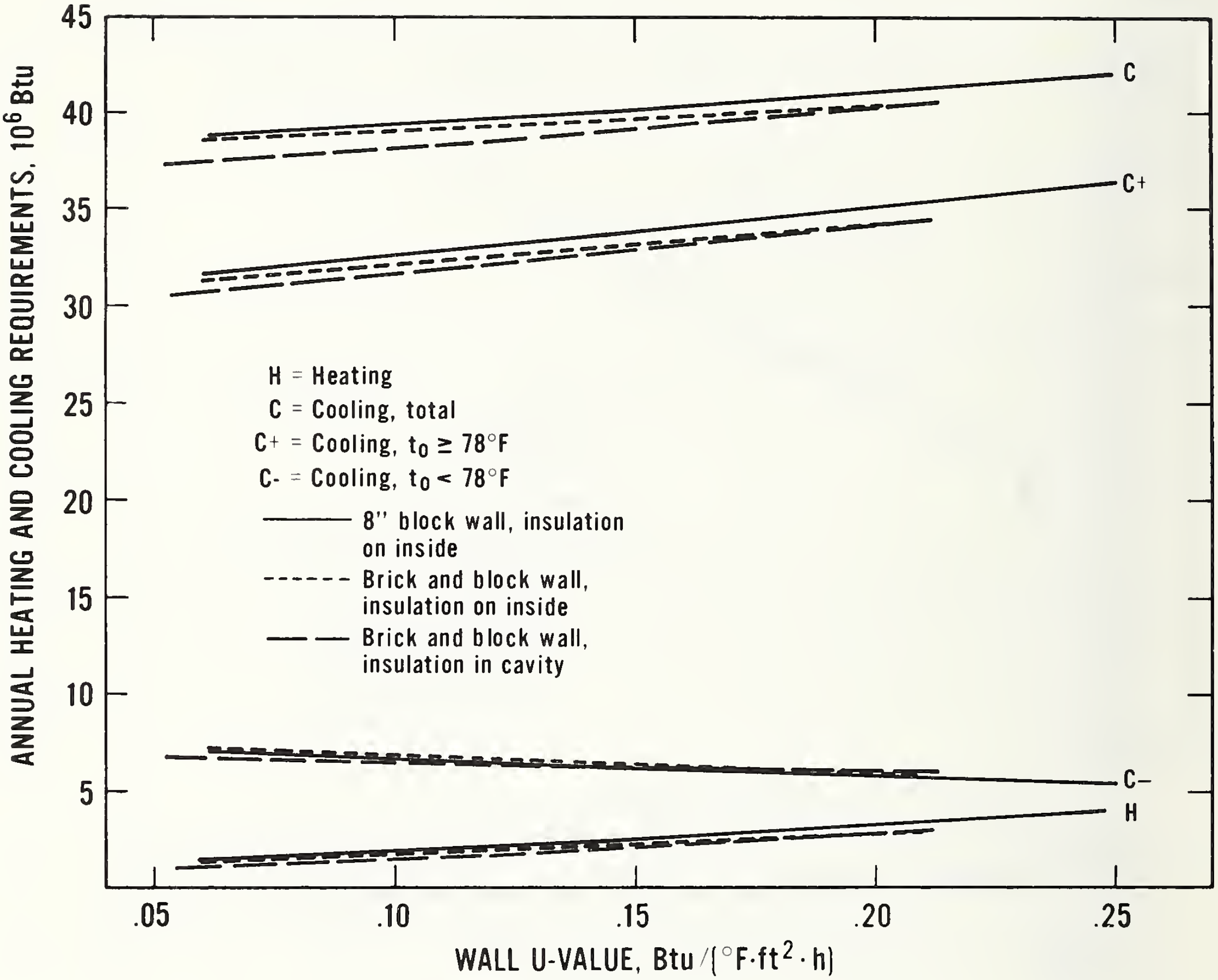

Figure B.17 Phoenix, Arizona: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Brick and Block Walls)

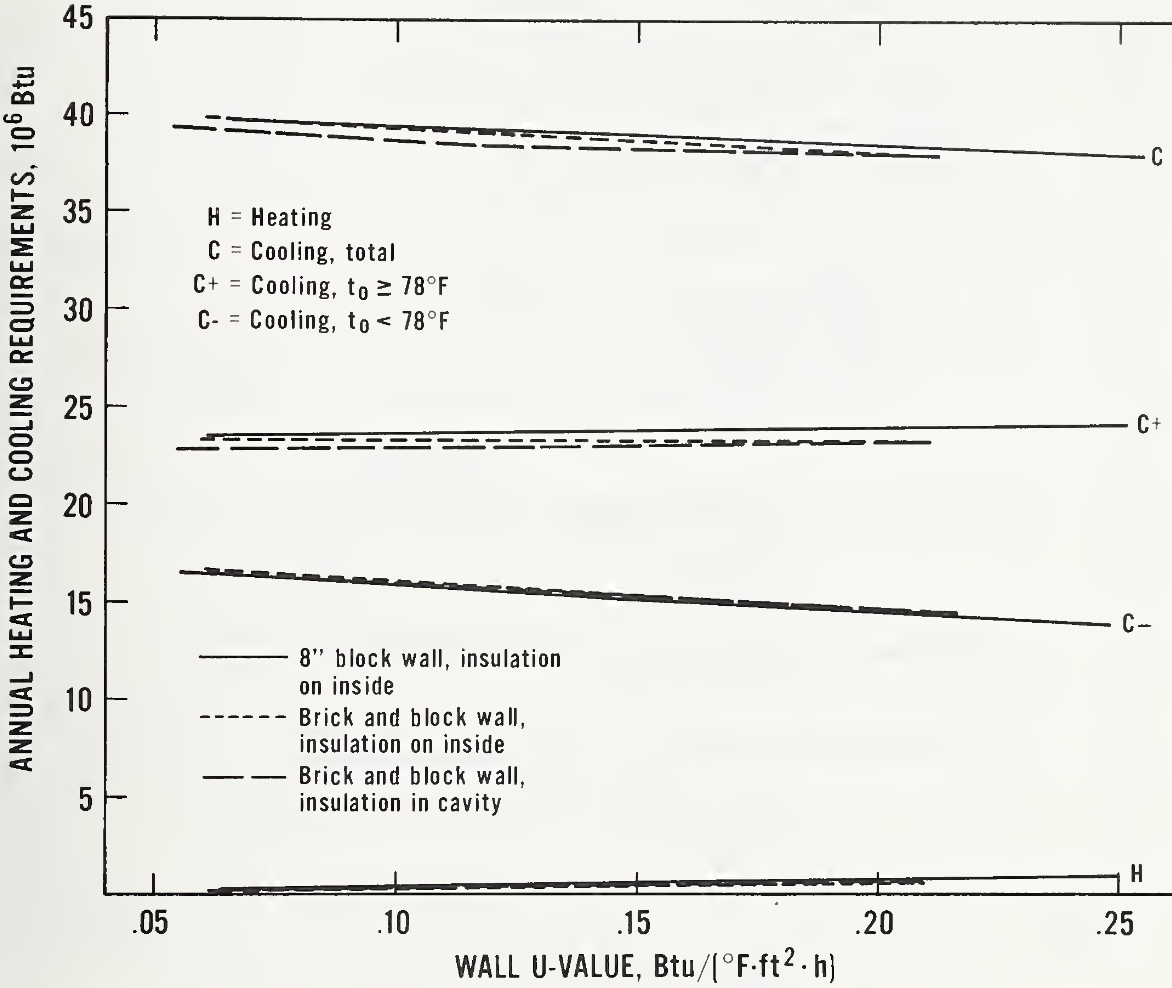

Figure B.18 Tampa, Florida: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Brick and Block Walls)

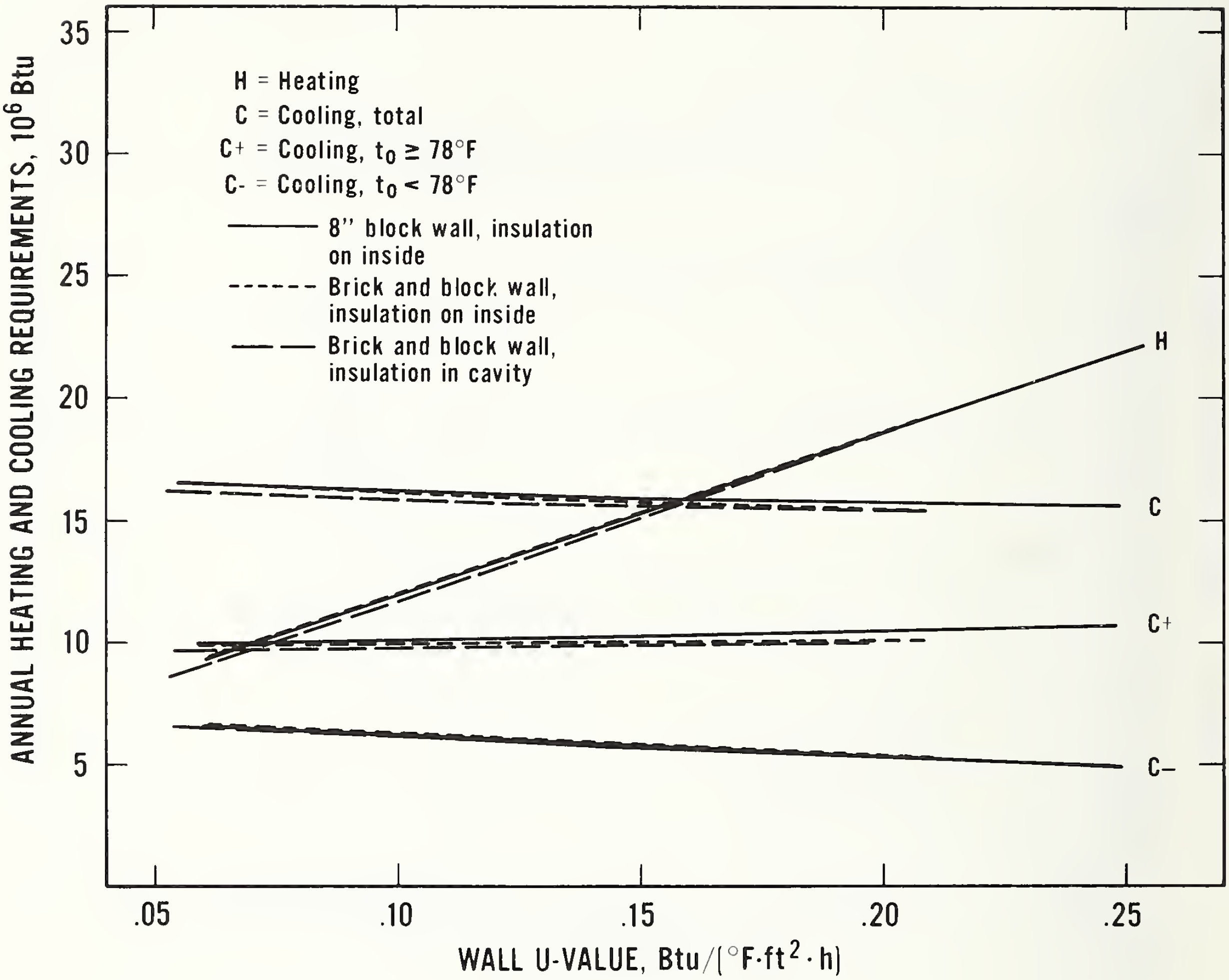

Figure B.19 Washington, D.C.: Relationship Between Annual Heating and Cooling Requirements and Wall U-value for an 1176 ft^2 House (8-in Block Walls and Brick and Block Walls)

APPENDIX C

SOLAR ABSORPTANCES OF WALLS BY COLOR[a]

A. Concrete Masonry Unit

Plain or grey	55-60 percent
Coral	66 percent
Adobe Red	68 percent
Buff	69 percent

B. Brick

Brown	72 percent
Light Red	62 percent
Buff	49 percent
Red	65 percent

C. Painted Concrete Masonry Unit

Bone White	27 percent
Navaho White	28 percent
Pearl White	31 percent
Sea Shell Beige	45 percent
Desert Sand	58 percent

D. Painted Wood Paneling

Avocado Green	85 percent
Sand Dune	74 percent
Beige	60 percent

E. Stained Wood Paneling

Weathered Brown	90 percent
Dark Brown	87 percent

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[a] Source: J. A. Reagan and D. M. Acklam, "Solar Reflectivity of Common Roofing Materials and Its Influence on the Roof Heat Gain of Typical Southwestern Residences," Summer Attic and Whole-House Ventilation, NBS SP 548 (Washington, D.C.: National Bureau of Standards, 1979).

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Determining Cost-Effective Insulation Levels for Masonry and Wood-Frame Walls in New Single-Family Housing

5. AUTHOR(S)

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6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

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10. SUPPLEMENTARY NOTES

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Economically optimal insulation methods and resistance levels for three different types of walls in a one-story, single-family residence are calculated for a wide range of geographic locations, energy prices, heating and cooling equipment efficiencies, and financial evaluation criteria. The three basic wall types examined are 8-in concrete block walls, brick and block walls, and wood-frame walls with lightweight siding. Changes in annual heating and cooling requirements for an 1176 ft^2 prototype house resulting from several different insulation resistances in each wall type are calculated using the NBS Load Determination program and Test Reference Year climate data for a number of geographic locations. Changes in heating requirements are correlated with heating degree days to provide estimates of energy savings in all geographic regions of the continental United States. Cooling requirements are not found to vary significantly with the thermal resistance of the walls under a typical operating profile except in the southwestern desert. An index number system is developed to quickly determine insulation levels based on the data generated in the report.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

building design; building economics; energy conservation; exterior wall; HVAC calculations; insulation; life-cycle cost analysis; masonry; mass.

13. AVAILABILITY

☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

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