NBSIR 88-3829

Technical and Economic Analysis of CFC-Blown Insulations and Substitutes for Residential and Commercial Construction

Stephen R. Petersen

Applied Economics Group
Mathematical Analysis Division
Center for Computing and Applied Mathematics

A. Hunter Fanney

Heat Transfer Group
Building Environment Division
Center for Building Technology

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Gaithersburg, MD 20899

July 1988

75 Years Stimulating America's Progress
1913-1988

Sponsored by

Building Systems Division
Office of the Assistant Secretary for Conservation and Renewable Energy
U.S. Department of Energy
Washington, DC 20234

NBSIR 88-3829

TECHNICAL AND ECONOMIC ANALYSIS OF CFC-BLOWN INSULATIONS AND SUBSTITUTES FOR RESIDENTIAL AND COMMERCIAL CONSTRUCTION

Stephen R. Petersen

Applied Economics Group
Mathematical Analysis Division
Center for Computing and Applied Mathematics

A. Hunter Fanney

Heat Transfer Group
Building Environment Division
Center for Building Technology

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Gaithersburg, MD 20899

July 1988

Sponsored by
Building Systems Division
Office of the Assistant Secretary for Conservation
and Renewable Energy
U.S. Department of Energy
Washington, DC 20234

U.S. DEPARTMENT OF COMMERCE, C. William Verity, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Abstract

Rigid foam insulations blown with chloroflourocarbons (CFC's) are among the most thermally efficient materials available for insulating walls and roofs of buildings. While they are more expensive than traditional insulating materials, their usage where space constraints dictate a more efficient insulator have become commonplace. Increasing concern about the effect of CFC's released to the atmosphere may result in restrictions on the availability of these insulation materials. This report evaluates the thermal performance and economics of rigid foam insulating materials containing CFC's and alternative insulation materials that contain little or no CFC. Residential walls (wood-frame and masonry), commercial wall systems (frame, masonry, and curtain wall) and commercial low-slope roof systems are examined in a wide range of climates in the United States to determine the cost effectiveness of rigid foam insulation materials. Economic substitutes for insulation materials containing CFC exist; however, they are not compatible with all types of wall/window and roof systems and thus may make some wall and roof systems impractical.

Acknowledgments

The authors acknowledge the assistance of all those who helped in preparing and reviewing this report. Douglas Burch and Betty Licitra provided valuable assistance by conducting the finite difference analysis for the commercial walls systems. Douglas Burch, Dr. James Hill, Rosalie Ruegg, Bob Mathey, and Walter Rossiter, (all of NBS), Kathy Wolfgram and Bill Strzepek (Dow Chemical, U.S.A.), George Courville and Jeff Christian (ORNL), Bill Gerkin (formerly of DOE), and Terry Statt (DOE) all provided helpful comments during the preparation of this report. Laurene Linsenmayer and Flora Parsons helped prepare the final manuscript.

CONTENTS

CONTENTS CONTINUED

LIST OF TABLES

Page

LIST OF FIGURES

1. INTRODUCTION

Two of the most efficient insulating products used in new building construction today are polyurethane (including polyisocyanurate) and extruded polystyrene rigid foam insulation. These materials provide a cost-effective means for improving the thermal performance of buildings over a wide range of climates, especially when there are practical or economic limitations to insulation thickness in wall and roof systems. Both of these materials are manufactured with chemicals that contain chloroflourocarbons (CFC's), which contribute substantially to their superior insulating properties. However, CFC's have been implicated as a significant source of atmospheric ozone depletion, and thus their manufacture and/or end use may be curtailed by the Federal Government.

The purpose of this report is to investigate the suitability, cost effectiveness, and potential energy consequences of alternative insulation materials which require lower levels or no CFC's in their manufacture. Three specific building components commonly insulated with CFC-blown rigid foam sheathings are being investigated by NBS: residential wall systems (both wood-frame and masonry), commercial wall systems, and commercial low-slope roof systems. Each of these building components is evaluated over a wide range of climatic conditions and heating/cooling systems types.

The insulation substitutes investigated in this report are expanded polystyrene (EPS) and fiberglass, neither of which contains CFC's. These materials are in fact less costly than polyurethane (and its common form, polyisocyanurate) and extruded polystyrene. However, because they are less efficient insulators, they require greater thicknesses to achieve the same level of overall thermal performance in walls and roofs. Thus the key to the economic analysis of substitutes for CFC-blown insulations is not the cost of the insulation materials themselves but rather the cost of modifying the building components (i.e., walls and roofs) in order to accommodate the thicker insulation.

The general investigative approach used in preparing this report was to identify the current usage of rigid foam insulation in specific building components, identify substitute materials, identify constraints that might make the use of substitutes more costly, and then calculate economic thicknesses for both the CFC-blown insulations and their substitutes in a wide range of climates. Where the economic thickness for the substitute (i.e., the maximum amount that is economically justified on a life-cycle basis) has a lower thermal resistance (R-value) than the economic thickness for the CFC-blown material, the annual energy penalty is calculated, both in Btu terms and their present-value dollar equivalent (i.e., the discounted value of increased energy purchases over the study period).

The construction cost data used in this report were derived from a number of sources. Where possible, cost data for residential construction was taken directly from ASHRAE Research Project 494-RP, "An Economic Data Base in Support of SPC 90.2: Costs of Residential Energy, Thermal Envelope and HVAC Equipment," prepared by the NAHB National Research Center (1986) in support of the draft ASHRAE 90.2 standard "Energy Efficiency Design of New Low-Rise

Residential Buildings." Rigid foam sheathing prices were obtained from at least six sources; ultimately the prices suggested by the Dow Chemical Co. were used, as they provided the most comprehensive and consistent set of price data found. Costs of extension jambs for wood-frame windows came directly from the NAHB National Research Center. All residential construction costs were adjusted to include 25 percent builder overhead and profit. The prices of insulated sheathing provided by Dow Chemical Co. for residential wall systems were also used as the basis for evaluating the costs of insulating commercial wall systems. Costs surveys for commercial buildings (e.g., Means and Dodge) were also consulted, but found to be unrealistically high for insulated sheathing costs.

Cost data for insulating low-slope roof systems were taken directly from ORNL/TM-9904, "Economic Analyses of Insulation Materials Used In Low-Slope, Built-Up Roof Systems," by George Courville and J.O. Kolb at Oak Ridge National Laboratory (1984). That study represents a comprehensive technical and economic analysis of alternative insulating materials suitable for use on steel roof decks. The cost data and analysis in that study represent the consensus of a wide range of roofing experts from government and industry, and could not be duplicated without major funding and time commitment.

The regional energy costs and life-cycle cost procedures used in this report were based on Federal Energy Management Program guidelines, as outlined in NBS Handbook 135, Life-Cycle Cost Manual for the Federal Energy Management Program, (1987).

Estimates of annual energy savings due to the use of insulation in residential wood-frame and masonry walls were based on thermal performance equations developed in support of the ASHRAE Standard 90.2 research program. Estimates of energy savings for commercial walls systems were based on parametric analyses using the ASHRAE "Envelope System Performance Compliance Program" developed in support of ASHRAE Standard 90.1. Corresponding energy estimates for built-up roof systems were taken directly from the ORNL report. Estimates of HVAC equipment efficiencies were taken directly from the corresponding ASHRAE and ORNL sources in order to maintain as much consistency as possible with these sources.

Because the energy prices used in this study are règional, rather than site-specific, the resulting economic thicknesses or R-values of insulation reported here should be regarded as representative of the general climatic location rather than the specific city used in analysis.

2. INSULATED SHEATHING FOR RESIDENTIAL WALLS

2.1 Wood-Frame Walls

Three types of rigid foam sheathing for insulating exterior walls are typically used in the United States: polyurethane (mostly of the polyisocyanurate variety), extruded polystyrene and expanded polystyrene (EPS). In residential wood-frame construction these insulating sheathings typically range in thickness from 0.5 to 1.0 inch, usually replacing non-insulating sheathings which range from 0.125 to 0.5 inches in thickness. Rigid foam sheathing currently represents about 25-30 percent of the wall sheathing market on a square foot basis for single-family housing[1], although major manufacturers claim that the number of new houses built with these materials is between 40 and 50 percent[2]. In fact, the economic analysis conducted in this section concludes that insulating sheathing used in conjunction with wood-frame walls and R-13 fiber glass is generally cost effective on a life-cycle-cost basis in most regions of the continental United States except southern Florida and the southern California coast.

Most of the conventional (referred to in this report as "non-insulating") sheathing used with wood-frame walls in the United States is 0.5 inch plywood or fiberboard, and 0.125 inch aluminum-foil-faced hard board, with the latter growing increasingly common. In general, these non-insulating sheathings have better structural characteristics than the rigid foam sheathings. As a result, corner bracing or plywood sheathing at the corners is often required when rigid foam sheathings are substituted for the non-insulating sheathings in wood-frame construction.

Table 2-1 shows the thermal conductivity (k-value) of each of the three insulating sheathings types examined, along with the corresponding thermal resistance (R-value) per inch and the estimated price per square foot for one inch of thickness (uninstalled) and per unit of thermal resistance (R). Data are shown for two different densities of EPS: the 1.0 lb per cubic foot is most commonly available, but the 1.5 lbs per cubic foot sheathing is also available and can be manufactured using the same equipment by simply using more feedstock (beads). None of these three sheathing types has an advantage from a structural standpoint and all can perform adequately from a moisture migration standpoint in above-ground applications. While EPS is typically a more fragile sheathing product than the other foam sheathings, and more susceptible to ultraviolet degradation while exposed, it is available with foil and/or vinyl facings to make it less vulnerable to damage.

---

[1] LSI Systems, Inc., "Survey of Builder Usage of Building Materials for the Construction of New Houses: Sheathing," Crofton, Md, August 1986.

[2] Because rigid foam sheathing is not typically installed at corners or on walls adjacent to unheated areas (e.g., garages and roof gables), the ratio of rigid foam to total sheathing in houses insulated with rigid foam sheathing is likely to be considerably less than 1.0, explaining some of the discrepancy between these estimates.

Table 2-1. Insulating Sheathing for Exterior Walls in New Housing Units

	Polyurethane (Polyisocyanurate)	Polystyrene		
		Expanded		Extruded
		1.0 lbs/ft^3	1.5 lbs/ft^3	
k-value (Btu-inch/h-ft^2-F)[a]	0.1389	0.2597	0.2398	0.2000
R per inch	7.2	3.85	4.17	5.00
typical cost per sq.ft.[b]:				
per R	$0.046	$0.031	$0.038	$0.052
per inch	$0.33	$0.12	$0.16	$0.26

[a] Based on ASHRAE Handbook Of Fundamentals, 1985.

[b] These costs are representative of builder costs for the sheathing material only, at 1 inch thickness. Costs vary by region, local supply conditions, and volume of purchase.

The prices shown in table 2-1 for the four rigid foam sheathing products are representative of builder costs at the national level. These prices vary regionally and may vary significantly with the volume of purchase and the degree of competition among suppliers and producers in a given market. While the price per R of extruded polystyrene sheathing tends to be slightly higher than that of polyisocyanurate, competitive pressures in some locations will often bring the prices of these two sheathing types closer together, so that the selection of one over the other will often be based more on perceived product differences and availability than price difference, per se.

Two important relationships can be derived from table 2-1: (1) Polyurethane insulation provides the most insulation effect for a given thickness, making it the most thermally efficient of the three, while its price per unit of thermal resistance is approximately 25 percent more per resistance unit (R) than that of EPS, and (2) EPS has the lowest insulation efficiency of the three; however, it also has the lowest price, both per unit of thermal resistance and per unit thickness, at either of the densities shown.

Therefore, if the design objective is to insulate a wall of a given thickness to the greatest degree possible, polyurethane would likely be the insulating sheathing of choice. On the other hand, when space is not a constraint, and there are no costs related to increasing the wall thickness to accommodate more insulation, the lower density EPS sheathing is likely to be the most cost-effective insulating sheathing.

These latter observations are crucial to establishing the cost penalties related to the use of substitute insulation materials, such as EPS or fiber glass, for CFC-blown insulation materials. That is, any cost penalties must be based on increased energy consumption or the cost of expanding the wall thickness to accommodate more insulation, since the substitute materials themselves cost less than the CFC-blown materials.

Options to accommodate more insulation in wood frame walls can take two distinct paths: (1) use of insulating sheathing at various thicknesses, or (2) use of 2x6 in. framing, in place of 2x4 in. framing, in order to accommodate more fiber glass insulation (usually R-19 batts), with or without the use of insulated sheathing. Superinsulation techniques (e.g., double walls with more than 6 inches of fiber glass insulation sandwiched in the resulting cavity) can be used to insulate wood-frame walls beyond these levels. However, these are not representative of common construction practice in the United States and will not be examined in this report.

2.1.1 Base-Case Wall System

In this report, 0.5 in. conventional fiberboard sheathing over a 2x4 in. wood-frame wall with R-13 fiber glass insulation will be used as the primary reference point for calculating the cost of adding insulated sheathing to wood-frame walls. R-13 is the maximum amount of fiber glass insulation that can be installed in a conventional 2 x 4 in. wood-frame wall. R-13 fiber glass is used in the base case wall rather than the more typical R-11 because its additional cost (approximately $0.06 per sq.ft. relative to R-11) is generally less than the cost of an equivalent (R-2) amount of insulated sheathing product. Moreover, the R-13 fiber glass requires no additional space and therefore does not increase the overall thickness of the wall.

The use of fiberboard sheathing in the base case will result in conservative estimates of the energy savings from the substitution of insulating sheathing products. While fiberboard sheathing has been the traditional sheathing product used with wood-frame construction, it has been losing some of its share of the market to 0.125 in. aluminum foil-faced board, which has somewhat lower insulating properties. The savings from insulating sheathings are somewhat greater when substituted for foil-faced board rather than for the fiberboard. However, the economic thickness of insulated sheathing will not change significantly as a function of the choice of the base-case sheathing.

2.1.2 Insulated Wall Sheathings and Estimated Costs

Table 2-2 shows the U-values for walls systems having either typical 0.5 in. fiberboard sheathing or rigid foam insulating sheathing at several thicknesses. Heat loss and gain through the opaquè portion of exterior walls are assumed to be proportional to these U-values for any given wall type.

One-half inch is the conventional sheathing thickness for which most basic wood-frame window and door systems are designed. Insulated sheathing is assumed to replace fiberboard sheathing. To accommodate sheathing thicker than 0.5 inch, window and door jambs must be expanded. (While some wood-frame windows can be extended slightly further without requiring extension jambs, the implications of this thickness constraint are the same. That is, extension jambs will be required to accommodate less efficient sheathings, e.g., EPS, in order maintain the same thermal performance as the most efficient of the CFC-blown insulations, e.g., polyisocyanurate.)

The cost of expanding a wood-frame wall to accommodate thicker sheathing is primarily related to extending the window and door jambs so that they will remain flush with the inside wall surface. For wood-frame windows the cost of jamb extensions can be substantial. Jamb extensions provided by the window manufacturer for an average size wood-frame window typically cost $12-$25, depending on the thickness. The average house has 14 windows[3] and 2 wooden doors, so that the total cost for any increase in sheathing thickness up to 1.5 inches total is estimated at $200 [16x12, rounded], plus builder overhead and profit. For thicknesses between 1.5 and 2.5 inches, a total cost of approximately $300 [16x19, rounded], plus builder overhead and profit, is estimated for this same house. (The cost of wood window and door jamb extensions are typically based on their thickness, rounded up to the next inch.)

For metal windows, however, there is likely to be no cost penalty for jamb extensions, because the inside window openings (sometimes referred to as "returns") are typically finished with gypsum board, which can be extended an inch or two at no appreciable incremental cost in terms of either material or labor. The door frames will still likely require jamb extensions at a similar cost to those of windows, for a total of approximately $25 (up to one inch), plus builder overhead and profit. For houses with metal windows, only this smaller $25 cost will be assumed.

A cost credit can be attributed to the use of EPS sheathing substituted for polyisocyanurate or extruded polystyrene since its cost per R is significantly lower. The builder cost for 0.5 inch polyisocyanurate (R-3.7) is approximately $200 per 1000 sq. ft.[4] EPS with the same R-value (approximately 0.86 inches) has a cost of approximately $155. In an average 1650 sq.ft. single-family house[5] the gross exterior wall area ranges from 1300-1900 sq.ft., depending on the configuration and number of stories. Assuming a gross wall area of 1600 sq. ft., the material savings from substituting EPS for polyisocyanurate would be approximately $72 [($200-155)x1.6], not including builder overhead and profit. The material cost for 0.5 in. extruded polystyrene (R-2.5) is approximately $170 per 1000 sq. ft., while R-2.5 EPS (0.6 in.) costs approximately $125 per 1000 sq. ft., for a savings of approximately $72 [(170-125)x1.6], the same as that for EPS substituted for polyisocyanurate.

---

[3]LSI Systems, Inc., "Survey of Builder Usage of Building Materials for the Construction of New Houses: Windows," Crofton, Md, August 1986.

[4]All costs per square foot for residential construction used in this report are based on gross wall area rather than net wall area as this is common cost-estimating practice. However, the heat loss/gain calculations are based on opaque wall area only. In comparing costs of insulation versus energy costs, an assumption of 15 percent window and door area is assumed.

[5]The median floor area of new single-family houses sold in the United States in 1986 was 1650 sq. ft. Approximately half of all new houses are one story and half two or more stories. Source:U.S. Departments of Commerce and Housing and Urban Development joint publication "Characteristics of New Housing: 1986," Construction Reports C25-86-13, Washington, D.C.,June 1987.

Table 2-2. Thermal Transmittances (U) for Exterior Wood-Frame Walls (Btu/ft^2-h-F)

Wall construction/ Fiber glass blanket plus sheathing thickness	Thermal Transmittance (U)			
	Conventional Fiberboard Sheathing	Rigid Foam Sheathing		
		Polyurethane (Polyisocyanurate)	Polystyrene	
			Expanded[b]	Extruded
2x4 wall (16 in. centers)/				
R-13 fbrgls + 0.5 in.	0.0710	0.0603	0.0669	0.0650
R-13 fbrgls + 1.0 in.	n/a	0.0490	0.0582	0.0553
R-13 fbrgls + 1.5 in.	n/a	0.0415	0.0515	0.0483
2x6 wall (24 in. centers)/				
R-19 fbrgls + 0.5 in.	0.0524	0.0464	0.0502	0.0491

[a] Wood frame wall U-values are based on 2x4 in. studs (R=4.38) with 15 percent frame-to-wall area ratio or 2x6 in. (R=6.88) studs with 12 percent frame-to-wall area ratio. Other assumptions include the use of 0.5 in. gypsum wallboard (R=0.45), 0.5 in. asphalt-impregnated fiberboard sheathing (R=1.32), and 0.5 in. wood bevel lapped siding (R=0.81), outside surface R=0.17, inside surface R=0.68. U-values are for opaque wall areas only. The fiberboard sheathing is replaced by the thermal sheathing in these calculations. All U-values shown here are based on parallel heat transfer calculation methods.

[b] 1.5 lbs/ft^3 EPS

Because the foam sheathing is added to the outside of the house, no inside space is lost and thus there is no cost penalty for lost space. Theoretically, slightly more siding will be needed at each corner of the house. However, for one or two inches this cost is likely to be trivial, since it would not likely require the ordering of additional materials.

Thus the cost of substituting EPS sheathing for 0.5 in. polyisocyanurate or extruded polystyrene sheathing, at a thickness sufficient to maintain equivalent thermal performance, can either increase or decrease construction costs, depending on the type of window and door systems used. Where metal windows are used, a potential materials cost savings of $72, plus 25 percent builder overhead and profit, could result in a total savings of approximately $90 for a typical single-family house. In houses with wood-frame windows, the materials cost could increase by $128 per house [$200-$72], plus 25 percent builder overhead and profit, for a total increase of approximately $160.

Once the wood extension jambs have been added to windows and doors, no additional jamb cost is assumed for sheathing thicker than 0.5 inches, until 1.5 inches is reached. Thus EPS (1.5 lb/ft^3 density) can be substituted for 0.625 or 0.75 in. polyisocyanurate or extruded polystyrene sheathing, maintaining the same R-value at little or no increase in wall-expansion costs, and at some savings in terms of material costs.

2.1.3 2 x 6 in. Wood-Frame Walls

The second design option that is evaluated in this section is the substitution of 2x6 in. framing, R-19 fiber glass batts, and conventional sheathing for 2x4 in. framing with R-13 fiber glass and 0.5 in. polyisocyanurate sheathing. Structurally, 24 in. stud centers can be used with the 2x6 wall instead of the 16 in. centers used with the 2x4 framing, although 0.625 in. gypsum board (in place of 0.5 in.) may be needed to maintain the rigidity of the inside wall surface. The 2x6 wall described here is approximately equivalent to the 2x4 wall in terms of its overall thermal transmittance (U). (Any difference in U-value is more likely to be due to construction anomalies than theoretical differences.) However, the construction cost and value of lost interior space for the former is considerably greater than that for the latter.

The additional framing and fiber glass costs, plus the substitution of conventional fiberboard sheathing for the thermal sheathing results in a net construction cost increase of approximately $.10 per sq. ft. of gross wall area, or $160 for the average 1650 sq.ft. house with 1600 sq. ft. of exterior walls. Two important adjustments must be made to this cost: (1) the cost of window and door jamb adjustments and (2) the cost of the foregone interior space due to the extension of the wall inward instead of outward.

(1) Because the wall thickness is increased by a full two inches, the cost of the jamb extensions for wood windows and doors will be approximately $20 per unit. Again assuming 14 windows and two wood doors in an average size house, this amounts to $320 per house. However, if metal windows are used and the window frames are finished with drywall, this cost will be inconsequential. Then only the cost of extending the door jambs will be considered, at an estimated total of $40 for two doors.

(2) Since the exterior walls are two inches thicker, every six linear feet of wall occupies one square foot of interior space. The cost of extending the walls of the house to maintain equivalent indoor space can serve as a reasonable proxy for the cost of this foregone area. A detailed cost analysis of the additional foundation, flooring, wall, and roof costs suggests that the incremental cost of unfinished floor space is approximately $7.00 per sq. ft., including 25 percent builder overhead and profit.[6] (The average cost per square foot for a new house is not a good proxy for this cost, since the end walls, interior finishing costs, windows and doors, wiring, plumbing, etc., remain unchanged.) This is equivalent to approximately $0.12 [(7/1.25)/(6x8)] per square foot of gross wall area before overhead and profit (to make this compatible with the other cost estimates), or approximately $200 for the 1600 sq. ft. of exterior wall area in the average house.

Thus the total cost estimate of 2x6 in. wood frame walls with R-19 fiber glass

---

[6] Petersen, S.R., Economics and Energy Conservation in the Design of New Single-Family Housing, NBSIR 81-2380, National Bureau of Standards, Gaithersburg, Md, August 1981, page 44.

insulation and 0.5 fiberboard sheathing substituted for 2x4 walls with R-13 and 0.5 in. polyisocyanurate sheathing is estimated at $680 if wood windows are used and $400 if metal windows are used. Adjusted for 25 percent builder overhead and profit, these estimates are $850 and $500, respectively.

2.1.4 <u>Economic Thickness of Insulating Sheathing</u>

Economic thicknesses of rigid foam sheathing used in place of fiberboard sheathing are shown for three heating system types and 12 cities in table 2-3. These thicknesses are shown in inches rather than thermal equivalents (R-values) so that the reader will see how jamb extension costs affect the determination of economic thickness. Economic thicknesses were calculated both with and without jamb extension costs; where the latter differ from the former they are shown in parentheses. Climate factors and the DOE region for each of these cities are shown in Appendix A. The various thicknesses of insulation evaluated and corresponding costs and wall U-values are shown in tables C-1 through C-3 of Appendix C.

The economic sheathing thickness is defined here as that thickness with the greatest net present-value savings, i.e., the present value of energy savings, in dollars, over a specified time horizon, less the installed insulation cost. Energy savings were calculated for both space heating and cooling, using the PEAR regression coefficients for wood-frame walls[7]. (Cooling savings are relatively small except in Dallas, Orlando, and Phoenix.) The present value (i.e., discounted value) of these energy savings over 25 years were then calculated using regional DOE energy price forecasts (in 1987 constant dollars) for natural gas and electricity and a seven percent real (i.e., net of general inflation) discount rate.[8] These prices and the corresponding uniform present worth factors used in this analysis are shown in Appendix B.

One alternative economic criteria to the life-cycle cost approach is the "two-years-to-positive-cash-flow" approach used as a benchmark in the development of the ASHRAE 90.2 Residential Energy Standard. In this alternative approach, the annual energy savings are compared with the increase in annual mortgage costs, on an after-tax basis, as of the end of the second year. (The second year is used because income tax savings may not be realized until that time. The conservation features are assumed to be financed over thirty years at nine

---

[7]PEAR (Program for Energy Analysis of Residences) is a microcomputer program developed at Lawrence Berkeley Laboratory for the Department of Energy. The regression equations used here were derived from this PEAR program to support the development of the draft ASHRAE 90.2 Residential Energy Standard. Thus the savings calculated here are compatible with the energy savings estimated in this draft standard.

[8]These are general data requirements for use in energy conservation studies for DOE. DOE rules for the analysis of energy conservation investments in Federal buildings do not allow the use of a study period longer than 25 years. However, the use of a seven percent discount rate with a study period longer than 25 years would have no practical affect on the results of this analysis.

percent interest, with no down payment. The marginal tax bracket is assumed to be 30 percent, combined Federal and state.) No discounting or projecting of energy costs beyond the second year is required in this approach. If the savings are greater than the increased mortgage cost (after taxes) by the end of the second year, the investment is assumed to be cost justified from a homeowner standpoint.

This second economic criterion for cost effectiveness may appear more attractive to many homeowners than one based on a 25 year life-cycle cost analysis. In this analysis both criteria give almost identical results in terms of determining optimal sheathing thicknesses. (However, this relationship will not always hold in performing engineering-economic analyses, and therefore two-years-to-positive-cash-flow should not be used as general test for determining cost effectiveness.) In a few cases, where an additional increment of sheathing thickness was justified on the two-years-to-positive-cash-flow basis but had a small net loss on a life-cycle cost basis, that increment was included in the table of economic thicknesses.

The results in table 2-3 are quite useful in the analysis of EPS as a substitute for polyisocyanurate and extruded polystyrene sheathings. When natural gas is used as a heating fuel, and jamb extension costs for wood windows and doors are on the order of those discussed above, the economic level of sheathing does not exceed 0.5 inches in any of the 12 cities. If the 0.5 in. EPS is substituted for the more thermally efficient sheathings, there will be an energy penalty as well as a construction cost savings.

When a heat pump is used for heating, economic thicknesses of sheathing exceed 0.5 inches only in the coldest two cities (Boston and Minneapolis). In these two locations, the use of EPS at a thickness thermally equivalent to the 0.5 to 1.0 inches of polyisocyanurate or extruded polystyrene typically used will be cost effective. However, heat pumps do not have a large market share in these locations, and thus the number of houses in this category will be small. In the other 10 locations, only the 0.5 inch EPS can be economically justified.

Table 2-3. Economic Thickness for Insulating Sheathing (inches)
(For Wood-Frame Walls with R-13 Fiber Glass Insulation)

HEATING SYSTEM[a]/ SHEATHING TYPE	BOSTON	WASHINGTON	ATLANTA	ORLANDO	MINNEAP	KANS CITY
NATURAL GAS/						
Polyisocyanurate	0.5(1.0)[b]	0.5	0.5	0.0	0.5(1.0)	0.5
EPS	0.5(1.5)	0.5(1.0)	0.5(0.87[c])	0.5	0.5(1.5)	0.5(1.0)
Extruded Polys.	0.5(1.0)	0.5	0.5	0.0	0.5(1.0)	0.5
HEAT PUMP/						
Polyisocyanurate	1.5(1.5)	0.5	0.5	0.0	1.5(1.5)	0.5(1.0)
EPS	1.5(2.0)	0.5(1.5)	0.5(0.87)	0.5	2.0	0.5(1.5)
Extruded Polys.	1.5(1.5)	0.5	0.5	0.0	1.5	0.5(1.0)
ELECTRIC/						
Polyisocyanurate	1.5(2.0)	0.5(1.5)	0.5	0.0	1.5(2.0)	1.5
EPS	2.5	1.5(2.0)	0.5(1.5)	0.5	2.5	1.5(2.0)
Extruded Polys.	1.5(2.0)	1.5	0.5(1.0)	0.5	1.5(2.0)	1.5

	DALLAS/FW	DENVER	PHOENIX	SEATTLE	OAKLAND	LOS ANGELES
NATURAL GAS/						
Polyisocyanurate	0.5	0.5	0.5	0.5	0.0	0.0
EPS	0.5	0.5(1.0)	0.5(0.87)	0.5(0.87)	0.5	0.5
Extruded Polys.	0.5	0.5	0.5	0.5	0.5	0.0
HEAT PUMP/						
Polyisocyanurate	0.5(1.0)	0.5	0.5	0.5	0.5	0.0
EPS	0.5(0.87)	0.5(2.0)	0.5(0.87)	0.5(0.87)	0.5(0.87)	0.5
Extruded Polys.	0.5	0.5(1.0)	0.5	0.5	0.5	0.0
ELECTRIC/						
Polyisocyanurate	0.5	1.5	0.5	0.5	0.5	0.5
EPS	0.5(1.5)	2.0(2.5)	0.5(1.0)	0.5(1.5)	0.5(1.5)	0.5
Extruded Polys.	0.5	1.5	0.5	0.5	0.5(1.0)	0.5

[a]Electric air conditioning assumed in all cases.
[b]Values in parentheses represent levels computed without jamb extension costs if diffe than value calculated with jamb extension costs.
[c]0.87 inches of EPS is approximate thermal equivalent of 0.5 inches of polyisocyanurat

When electric resistance heating is used, economic thicknesses exceed 0.5 inches in Washington, D.C., Kansas City, and Denver as well as Boston and Minneapolis. Levels of EPS which are thermally equivalent to the typical 0.5 to 1.0 inches of polyisocyanurate and extruded polystyrene can be justified over a wider area when electric heat is used. However, electric resistance heat is more prevalent in the moderate climates than in these colder climates, so that again the relative number of houses in this heating category will be small.

Table 2-4 shows the current number of housing completions in the United States by region and heating system type. It is apparent that the vast majority of new houses fall into those categories where costly extension jambs make the use of sheathing thicknesses greater than 0.5 inches economically unjustified.

The energy penalties corresponding to the use of 0.5 in. EPS as a substitute for the same thickness of polyisocyanurate or extruded polystyrene are shown in table 2-5. These penalties were calculated for a 1650 sq. ft. house with 1360 sq. ft. of net (opaque) wall area, equivalent to 1600 sq. ft. of gross wall area with 15 percent windows and doors. Also included in table 2-5 are the present-value dollar equivalents of these energy penalties over 25 years, discounted at seven percent (net of general inflation).

If no jamb extension costs are incurred when using sheathing thicker than 0.5 inches, the economic thickness of EPS sheathing is greater than 0.5 inches in most cases. As a result, EPS equivalents of the polyisocyanurate or extruded polystyrene sheathings are cost effective for the typical 0.5 to 1.0 in thickness. No energy penalty or dollar cost will be incurred if the thermal equivalent is used. However, some builders accustomed to using 0.5 sheathing may be reluctant to switch to the greater thicknesses required.

2.1.5 Implications for CFC Substitutes for Wood-frame Walls

The use of rigid foam sheathing of at least 0.5 in. thickness, in place of conventional (non-insulating) sheathing, appears to be cost effective in almost every region of the United States, with the possible exceptions of southern Florida and the southern California coast. However, at present, only 40 to 50 percent of all new houses are constructed with this product. Because the long-term energy savings attributable to this product are substantial, especially in the northern climates and in electrically heated houses, its usage should be encouraged from an energy conservation standpoint. Studies conducted in this country and abroad, however, suggest that CFC agents currently used to expand rigid foam insulation may damage the earth's ozone layer, and that the usage of these agents should be curtailed. This would require either new blowing agents for polyurethane and extruded polystyrene products, or the increased usage of EPS, which does not contain CFC's.

No non-CFC chemical substitutes for blowing agents currently used in the manufacture of polyurethane sheathing are currently available. There is some potential for reducing the amount of CFC used per unit volume of foam, or using a less environmentally harmful CFC agent, without significantly affecting the thermal conductivity of the foam. The resulting product would be more costly. However, a modest increase in the installed cost would not significantly affect the economic thicknesses of this material shown in table 2-3.

A chemical substitute for the CFC blowing agent used in the manufacture of extruded polystyrene has been identified which promises the same or better thermal performance without negative side effects at a slight increase in end-product cost. However, this chemical is not currently available in quantity, and toxicity testing has not been completed. Ten years may be required before complete replacement of current CFC-based blowing agent could be accomplished.[9] Again, the economic thicknesses would not likely differ substantially from those shown in table 2-3.

Table 2-4. Housing Completions in 1986 by Region and Heating System Type

	Single-Family Housing (Thousands of units)			
	Census Region			
Heating System	Northeast	Midwest	South	West
Natural Gas	80	132	153	162
Oil	47	0	0	0
Heat Pump	28	15	231	47
Electric Resist.	30	15	104	27

	Multi-Family Housing (Thousands of Buildings)			
	Census Region			
Heating System	Northeast	Midwest	South	West
Natural Gas	6	5	5	14
Oil	0	0	0	0
Heat Pump	1	1	12	4
Electric Resist.	8	10	17	19

[9] "Regulatory Impact Analysis: Protection of Stratospheric Ozone, Volume III: Addenda to the Regulatory Impact Analysis Document, Part 1B: Rigid Foam - Polystyrene and Miscellaneous Foam," Radian Corporation, August 1987.

Table 2-5. Energy Penalty for Substituting 0.5 in. EPS (R-2.2) for 0.5 in. Polyisocyanurate (R-3.6) or 0.5 in. Extruded Polystyrene (R-2.5) (1600 sq.ft. Single-Family Detached House with 1360 sq.ft. Opaque Wall Area)

HEATING SYSTEM/ BASE SHEATHING	MILLION BTU/YR AND PRESENT VALUE DOLLARS OVER 25 YEARS[a]					
	BOSTON	WASHINGTON	ATLANTA	ORLANDO	MINNEAP.	KANSAS CTY
NATURAL GAS/						
Polyisocyanurate	1.62	1.35	0.86	0.15	2.25	1.46
	$225	$121	$77	$13	$195	$121
Extruded Polys.	0.47	0.39	0.25	0.04	0.65	0.42
	$65	$35	$22	$4	$56	$35
HEAT PUMP/						
Polyisocyanurate	0.64	0.51	0.29	0.05	1.03	0.56
	$199	$111	$56	$9	$238	$127
Extruded Polys.	0.18	0.15	0.08	0.01	0.30	0.16
	$57	$32	$16	$2	$6	$37
ELECTRIC/						
Polyisocyanurate	1.10	0.92	0.58	0.10	1.53	0.99
	$342	$202	$112	$19	$355	$226
Extruded Polys.	0.32	0.26	0.17	0.03	0.44	0.29
	$99	$58	$32	$6	$102	$65
COOLING SYSTEM: ELECTRIC AC						
Polyisocyanurate	0.02	0.03	0.04	0.10	0.03	0.05
	$6	$8	$8	$19	$6	$11
Extruded Polys.	0.01	0.01	0.01	0.03	0.01	0.01
	$2	$2	$2	$5	$2	$3
	DALLAS/FW	DENVER	PHOENIX	SEATTLE	OAKLAND	LOS ANGELES
NATURAL GAS/						
Polyisocyanurate	0.66	1.70	0.39	1.48	0.82	0.42
	$51	$126	$31	$139	$65	$33
Extruded Polys.	0.19	0.49	0.11	0.43	0.24	0.12
	$15	$36	$9	$40	$19	$10
HEAT PUMP/						
Polyisocyanurate	0.22	0.68	0.12	0.57	0.28	0.13
	$53	$151	$27	$72	$61	$29
Extruded Polys.	0.06	0.20	0.04	0.16	0.08	0.04
	$15	$43	$8	$21	$18	$8
ELECTRIC/						
Polyisocyanurate	0.45	1.16	0.26	1.00	0.56	0.28
	$109	$255	$58	$128	$123	$63
Extruded Polys.	0.13	0.33	0.08	0.29	0.16	0.08
	$31	$73	$17	$37	$35	$18
COOLING SYSTEM: ELECTRIC AC						
Polyisocyanurate	0.10	0.03	0.20	0.01	0.00	0.00
	$25	$6	$45	$1	$0	$0
Extruded Polys.	0.03	0.00	0.06	0.00	0.00	0.00
	$7	$2	$13	$0	$0	$0

[a]Present values based on DOE energy price projections over 25 years, discounted at 7% (real).

It is difficult to estimate the aggregate energy and economic impact of the substitution of EPS sheathing for CFC-blown materials. This is because the economic choice of thermally equivalent sheathing thicknesses is governed to a large extent by the choice of wood- or metal-framed windows. If the costs associated with extending the jambs of windows and doors are small, there is no cost to the substitution of EPS for the CFC-blown products; in fact there may be a material cost savings. When wood-framed windows are used, however, the cost of extending the jambs to accommodate the increased thickness of sheathing can be significant (on the order of $160, net, per house). If the increased thickness is not installed, the energy penalty can be substantial, as shown in table 2-5. In general, if the present value of the energy penalty is shown to be higher than the cost of the increased insulation thickness, the increased thickness is considered to be cost effective, and vice versa.

2.1.6 Potential Impact of ASHRAE Standard 90.2

Figure 2-1 shows the U-value requirements for above-grade wood-frame walls as proposed in the draft ASHRAE Standard 90.2, "Energy Efficiency Design of New Low-rise Residential Buildings." When adopted, this new standard would require a maximum U-value for wood-frame walls of 0.065 (Btu/ft^2-h-F) almost uniformly across the contiguous United States, with the exception of the Atlantic coastal areas below Charleston, SC, the Gulf coast, and parts of southern Arizona and southern California. Compliance would require the equivalent of R-13 fiber glass insulation plus an insulating sheathing, either 0.375 in. polyisocyanurate, 0.5 in. extruded polystyrene, or 0.75 in. EPS. In the coldest regions of the country (e.g., northern Minnesota and parts of Alaska) the U-value requirement is 0.043 (Btu/ft^2-h-F). This requirement could be met by utilizing R-13 fiber glass insulation plus an insulating sheathing of either 1.5 in. polyisocyanurate, 2.0 in. extruded polystyrene, or 2.5 in. EPS. Alternatively, a U-value of 0.043 could be attained by constructing 2x6 walls with R-19 fiber glass insulation and 0.75 in. polyisocyanurate, 1.0 in. extruded polystyrene, or 1.25 in. EPS sheathing.

The ASHRAE standard has served as the basis for the CABO Model Energy Code used by the three major building code authorities (ICBO, BOCA, and SBCCI). The Model Energy Code, in turn, is the basis of the energy conservation requirements referenced in the building codes of the majority of states, with the exceptions typically adopting even more stringent standards.

The draft ASHRAE Standard 90.2 is likely to be approved by CABO in 1988. The wall performance requirements of this standard will likely minimize the energy impact of a change in the availability of specific insulating sheathings, since they can be achieved by alternative material specifications. If this standard is adopted as presently drafted, there will likely be a substantial increase in the amount of insulating sheathing used in the U.S., some of which would likely be manufactured using CFC's. If the production of CFC-blown rigid foam insulation is curtailed, this standard will expand the market for substitute insulating materials significantly.

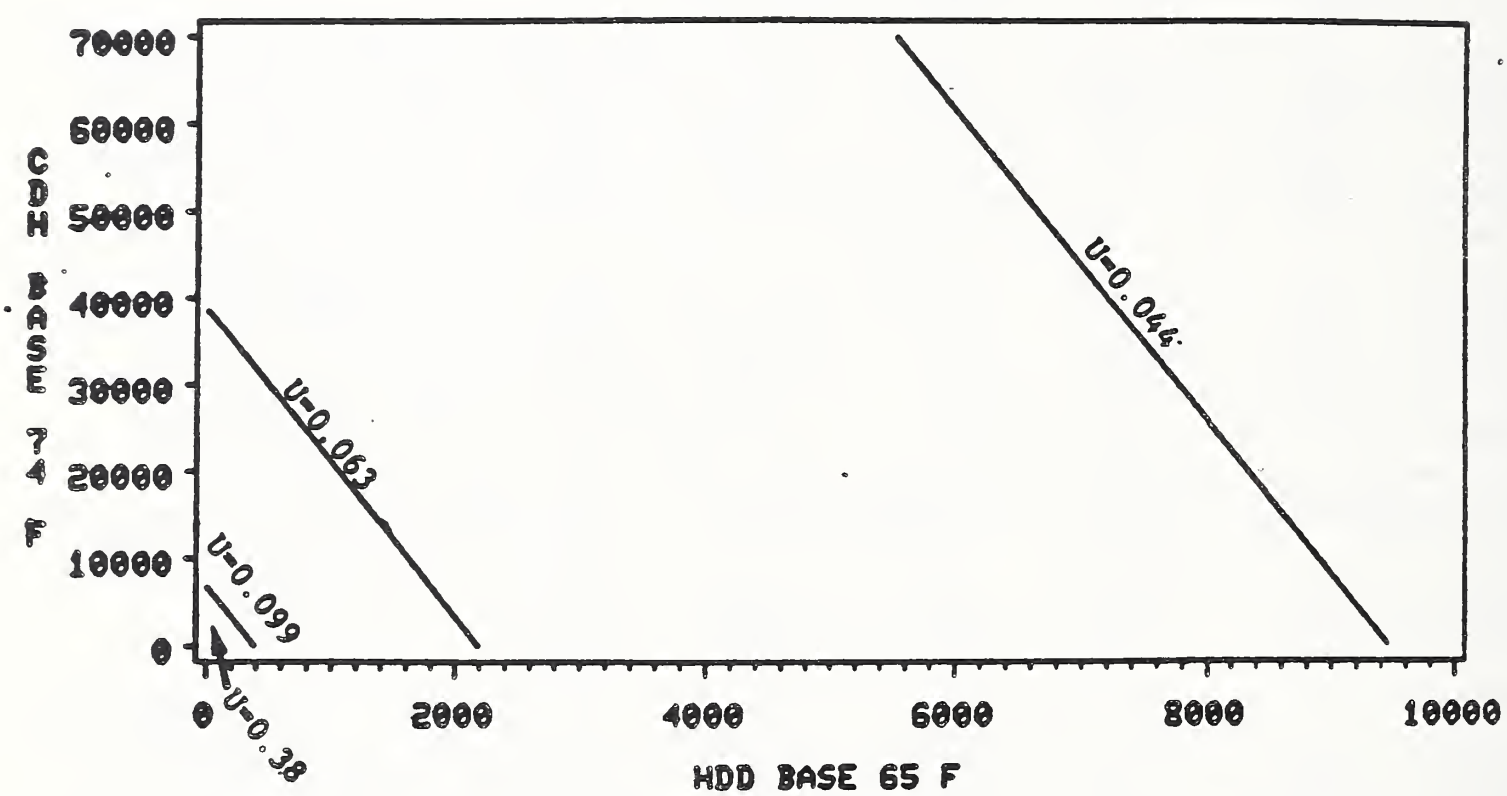

Figure 2-1. Proposed U-Value Requirements for Wood-Frame Wall in Single-Family Houses (Draft ASHRAE Standards 90.2).

2.2 Rigid Foam Insulation in Residential Masonry Wall Construction

New houses with concrete-masonry exterior walls are built primarily in the South and Southwest regions of the United States. These walls are typically constructed of eight inch concrete block, sometimes covered with stucco, or, less often, four inch block and four inch brick (referred to here as cavity wall construction). In general, placing insulation on the exterior of a masonry wall, or even in the air space in a cavity wall, improves the energy-related performance of these walls several percentage points more than the same amount of insulation placed on the inside of the wall.[10] This is because insulation on the exterior surface emphasizes the mass effect of these walls while insulation on the interior surface in effect isolates the mass from the conditioned space. However, insulation on the outside surface requires a protective covering, such as stucco, which increases the effective cost of this technique (unless the wall was to be covered even without insulation).

The space available for the placement of insulation in conventional masonry wall construction is considerably more constrained than in wood-frame walls. Fiberglass blankets can only be used if the wall is framed out on the inside; this involves considerable expense not only from the cost of the otherwise unnecessary framing but from the lost interior space as well. As a result, if any insulation is used at all it is most likely to be rigid foam sheathing, which has a much higher thermal efficiency per inch than the fiberglass insulation typically used in wood frame construction. However, rigid foam insulations, especially the most efficient types blown with CFC's, have a much higher cost per unit of resistance than fiberglass. As a result, the economic level of insulation, in terms of overall R-value, is significantly lower for masonry walls than for wood frame walls. (Economic insulation levels for masonry walls are discussed further below.)

Two approaches to insulating masonry walls are investigated further in this study: (1) rigid foam insulation on the interior surface, covered with wallboard; and (2) rigid foam insulation on the exterior wall, covered with stucco. In both cases, a reflective 0.75-inch air space adjacent to the wallboard is assumed (i.e., at least one surface has a foil face). Cavity wall construction (brick exterior, cavity, and concrete clock interior) is not explicitly treated here. However, the economic level of insulation for cavity wall construction would be nearly identical to that of case (1).

The steady-state U-values of an eight-inch block wall, insulated to several levels of thermal resistance using polyisocyanurate, EPS, and extruded polystyrene sheathing, are shown in table 2-6. These U-values are essentially identical whether the sheathing is inside or outside, since the stucco has no significant insulating effect and an equivalent air space is assumed in both cases. (U-values do not reflect the mass effect of the wall; however, the equations used to estimate the energy savings from insulation are sensitive to

---

[10] Petersen, S.R., Barnes, K.A., and Peavy, B.A., Determining Cost-Effective Insulation Levels for Masonry and Wood-Frame Walls in New Single Family Housing, NBS Building Science Series 134, U.S. Department of Commerce, National Bureau of Standards, Gaithersburg, MD, 1981.

the placement of the insulation.)

2.2.1 Economic Thickness of Insulation

The prices for rigid foam sheathing used in this analysis of masonry walls are the same as those used in section 2 for wood-frame walls. However, unlike the wood-frame wall analysis, no conventional sheathing (e.g., fiberboard) is replaced by the insulated sheathing. Thus the net cost of the first 0.5 inches of foam sheathing is significantly higher in the masonry wall analysis than in the wood frame analysis. No allowance for window and door extension jambs is made in the masonry wall analysis, since the window and door returns are assumed to be fabricated from gypsum board at no significant increase in cost over the non-insulated wall cost. (Metal windows are typically used in masonry construction. Wood-framed windows must be substantially modified to fit a 9.25 inch or greater overall wall thickness.)

If the insulation is applied to the interior wall surface, an adjustment should be made to account for the lost floor space, as was done for 2x6 in. wood-frame wall. A slightly higher cost adjustment factor, $8.25 per square foot of net floor area (including builder overhead and profit), is used because extending masonry walls is more expensive than extending wood-frame walls. This is equivalent to approximately $0.07 [(8.25/1.25)/(8x12)] per inch of additional wall thickness per square foot of gross wall area before profit and overhead, or approximately $80 per inch of increased wall thickness for a one-story 1200 square masonry foot house. (Masonry houses tend to be smaller than average in size, thus a smaller house is used in this example than the median 1650 square foot house used in the wood-frame analysis.)

When insulation is applied to the outside wall, no interior space is lost, and as a result no adjustment is made to the insulation cost. Moreover, the cost of the exterior finish is not included here, based on the assumption that it would have been added with or without the insulation. (If the finish would be used only with insulation, then its cost must be added to the insulation cost in the economic analysis. This is likely to make exterior insulation less cost effective than interior insulation.) While fastener costs can be expected to increase as thicker insulation is used, either outside or inside, these costs are relatively low and are not likely to affect the economic level of insulation significantly.

The same methodology for calculating energy savings and their present value in dollar terms used for wood-frame walls was used to calculate the optimal insulation levels for masonry walls. The estimating equations used to determine energy savings for masonry walls result in somewhat higher savings than those used for wood-frame walls, however, reflecting the mass effect of the masonry walls. The various thicknesses of insulation evaluated are shown in table 3 of Appendix C, along with their corresponding costs and U-values.

Table 2-7 shows the economic levels of rigid foam insulation applied to the inside wall for five Southern and Southwestern locations, with three different heating system types. Table 2-8 shows the corresponding estimates of economic insulation thickness for exterior applications. These calculations were made at 0.25 inch intervals of thickness, rather than in terms of resistance, since sheathing is sold by thickness, not R-value. Corresponding resistance values are shown in table 2-6. Economic levels tend to be higher for exterior sheathing applications (table 2-8) than for interior applications (table 2-7) because exterior insulation improves the mass effect of the walls and no penalty for loss of inside space is incurred. Including the cost of the protective coating would not change these economic levels, since its cost does not vary with insulation thickness.

In general, the economic level of insulation in masonry walls is low compared to that of wood-frame walls in the same climate, especially for houses heated with gas or a heat pump. The R-values corresponding to these economic thicknesses run from zero in the mildest climates to a high of only R-8.3, although an additional R-3 reflective foil surface on either the wallboard or the insulation is cost effective in all cases. These relatively low R-values are not due to the thermal performance of masonry walls, per se, but rather to the higher cost of insulating them. Note also that only building locations in the South and Southwest are shown in these tables; substantially more insulation would be cost effective in northern climates where this type of construction is less frequently used.

2.2.2 Implications for CFC Substitutes for Residential Masonry Walls

High-efficiency rigid foams are generally the insulation of choice from a practical and economic standpoint when constructing masonry walls for new houses because of inherent space limitations. If the insulation is installed on the inside wall surface, covered with wallboard, or in a wall cavity, any space occupied by the insulation reduces the interior living space by a corresponding amount. Exterior insulation may be preferred, both from a thermal performance basis and because it does not intrude into the interior space. However, it must be covered with a protective finish, which adds considerably to its initial cost and possibly to maintenance costs as well. As a result, interior insulation is usually the more cost effective alternative.

The substitution of EPS for polyisocyanurate or extruded polystyrene rigid foam insulation to near-equivalent R-values appears to be cost effective in most of the applications shown in tables 2-7 and 2-8. While the EPS does require more space than the latter materials, the resulting insulation thicknesses are quite low relative to the overall thickness of these walls, at least in these mild climates. Even when the adjustment for the cost of foregone interior space is made, the substitution of EPS for polyisocyanurate or extruded polystyrene is unlikely to increase initial construction costs significantly. Framing out the interior wall and insulating with fiberglass does not appear to be a cost-effective substitute for rigid foams when the cost of the foregone interior space is considered.

Table 2-6. Exterior Wall U-Values for 8-Inch Block with Rigid Foam Insulation[a] (Btu/ft^2-hr-F)

No insulation, non reflective air space (0.75 in.): 0.2799
No insulation, reflective air space (0.75 in.): 0.1928

Insulation Thickness	Rigid Foam Sheathing[b]					
	Polyurethane (polyisocyanurate)		Polystyrene			
Inches			Expanded		Extruded	
	R	U	R	U	R	U
0.5	3.6	0.1129	2.09	0.1365	2.5	0.1291
0.75	5.4	0.0937	3.13	0.1193	3.75	0.1111
1.0	7.2	0.0801	4.17	0.1060	5.0	0.0974
1.25	9.0	0.0700	5.21	0.0954	6.25	0.0868
1.5	10.8	0.0622	6.26	0.0867	7.5	0.0782
1.75	12.6	0.0559	7.30	0.0795	8.75	0.0712
2.0	14.4	0.0507	8.34	0.0734	10.0	0.0654

[a]Masonry wall U-values are based on nominal 1x2 in. (actual 0.75x1.5 in.) furring strips (R-0.94) with 12 percent frame-to-wall area ratio. An emissivity of 0.03 is assumed for foil-faced sheathings or wall board. All U-values shown are based on the parallel heat transfer calculation method.

[b]R-values shown are for the insulation only; U-values are for the total wall, including the surface conductances.

These conclusions are based on masonry wall construction in the South and Southwest where this is most common; in northern climates the substitution of EPS or other insulating materials at the same level of thermal performance as the CFC-blown insulations would be less acceptable from a practical and economic standpoint.

Table 2-7. Economic Thickness for Rigid Foam Insulation in Masonry Walls - Interior Insulation[a]

HEATING SYSTEM[b]/ SHEATHING TYPE	Economic Thickness in Inches				
	ATLANTA	ORLANDO	DALLAS/FW	PHOENIX	LOS ANGELES
NATURAL GAS/					
Polyisocyanurate	0.75	0.0	0.5	0.0	0.0
EPS	1.0	0.0	0.75	0.0	0.0
EXTRUDED POLYS.	0.75	0.0	0.0	0.0	0.0
HEAT PUMP/					
Polyisocyanurate	0.75	0.0	0.75	0.0	0.0
EPS	1.25	0.0	0.75	0.0	0.0
EXTRUDED POLYS.	0.75	0.0	0.75	0.0	0.0
ELECTRIC/					
Polyisocyanurate	1.25	0.0	1.0	0.75	0.75
EPS	2.0	0.0	1.75	1.25	1.25
EXTRUDED POLYS.	1.5	0.0	1.5	0.75	0.75

[a]Reflective air space assumed in all cases, including zero insulation.

[b]Electric air conditioning assumed in all cases.

Table 2-8. Economic Thickness for Rigid Foam Insulation in Masonry Walls - Exterior Insulation[a]

HEATING SYSTEM[b]/ SHEATHING TYPE	Economic Thickness in Inches				
	ATLANTA	ORLANDO	DALLAS/FW	PHOENIX	LOS ANGELES
NATURAL GAS/					
Polyisocyanurate	0.75	0.0	0.75	0.0	0.0
EPS	1.75	0.0	1.25	0.0	0.0
EXTRUDED POLYS.	0.75	0.0	0.75	0.0	0.0
HEAT PUMP/					
Polyisocyanurate	0.75	0.0	0.75	0.75	0.75
EPS	1.75	0.0	1.50	0.75	0.75
EXTRUDED POLYS.	1.25	0.0	0.75	0.0	0.0
ELECTRIC/					
Polyisocyanurate	1.5	0.0	1.5	1.0	1.0
EPS	2.0	0.0	2.0	1.75	2.0
EXTRUDED POLYS.	2.0	0.0	2.0	1.0	1.25

[a]Reflective air space assumed in all cases, including zero insulation.

[b]Electric air conditioning assumed in all cases.

3. EXTERIOR WALLS FOR COMMERCIAL AND HIGH-RISE RESIDENTIAL BUILDINGS

In this section, typical insulation practices for the exterior walls of commercial buildings will be examined, and the substitutability of non-CFC blown insulations (particularly expanded polystyrene, EPS) for CFC-blown insulations will be addressed both from an economic and building code standpoint. For the purposes of this report, the exterior walls of commercial and high-rise residential buildings are divided into three primary categories: concrete-masonry walls; wood or steel studs (load or non-load bearing, with wood, stucco, metal, or brick exterior finish); and non-load-bearing curtain walls, including composite foam-core panels and flat panels (often of honeycombed metal, concrete, or stone) which are attached directly to the superstructure. Rigid foam materials are widely used to insulate all of these wall system types. Polyisocyanurate, extruded polystyrene, and expanded polystyrene (EPS) are all used in concrete-masonry and stud wall systems. Composite foam-core panels are typically manufactured with polyurethane or polyisocyanurate foam, although some manufactured panels covered with a stucco-type finish are insulated with expanded polystyrene (EPS). Fiberglass batts or boards, foamed-in-place polyurethane, and sprayed cellulosic insulation, are most commonly used on the interior side of flat-panel curtain wall systems.

In general, economic R-values for wall insulation in commercial and high-rise residential buildings will be somewhat lower than in single-family dwellings for a number of reasons: (1) heating and cooling loads in commercial buildings tend to be dominated by internal heat gains, so that the energy savings potential of exterior wall insulation is significantly smaller than in a single-family dwelling; (2) interior space generally has a much higher rental value for commercial buildings, so that increasing the wall thickness inward to accommodate insulation is often economically unattractive; (3) exterior walls in commercial buildings have a large (often greater than 50 percent) ratio of glass to gross wall area, making thicker wall systems less effective relative to the lost floor space and making window selection a more critical design variable; (4) income tax rules favor operating costs which can be written off in the year of occurrence (e.g., energy), rather than capital costs (e.g., insulation) which must be depreciated over a long period of time (currently 31.5 years); and (5) mortgages for commercial buildings are usually limited to 15 years, which increases the positive cash flow requirements in the earlier years of the building's life. Furthermore, design aesthetics may be the most important consideration in choosing an exterior wall system, and the choice of the wall system itself will often determine the type and amount of insulation that can be economically used.

Aesthetics and energy considerations are not the only driving forces in exterior wall design; fire safety and related building code provisions must be considered as well. The three major model building codes in the United States have specific provisions for limiting the amount of plastic foam insulation on the exterior side of walls in multistory buildings in order for the wall to be considered non-combustible[11]. The Uniform Building Code and Standard Building Code limit the amount of plastic foam insulation, by its potential fuel contribution, to 6000 Btu/sq ft of exterior wall area. The Basic Building Code limits the thickness of plastic foam insulation to four inches of thickness, regardless of the foam type or its fuel content. A multistory flame test may also be required for some wall systems, further restricting the choice of insulation materials. Polyurethane and polyisocyanurate are considered to be "thermoset" materials; that is, they have a tendency to char when exposed to flame, but do not loose their shape. Expanded and extruded polystyrenes are "thermoplastic" materials, which melt and burn when exposed to high heat or flame.

Table 3-1 shows the approximate limit on thickness imposed by a limit on potential fuel contribution of 6000 Btu/ft^2, along with the corresponding R-value, for the most common types of foam plastic insulation. It is apparent that polyurethane and polyisocyanurate can be installed at significantly greater thicknesses (with significantly greater total R-values) than are permissible for the polystyrene insulation materials under these same code provisions. While foam insulation in thicknesses greater than two inches is not common in conventional construction at this time, these thickness constraints could impose restrictions on exterior wall design as insulation standards for new buildings are upgraded over time if the availability of polyurethane and polyisocyanurate insulations (both containing CFC's) is curtailed.

Other important considerations in selecting an insulation material for exterior wall applications are (1) the dimensional stability of the material, (2) thermal conductivity (time rate of heat transmission per unit thickness per unit area), (3) moisture permeability, (4) its ability to fit snugly into irregular cavities, and (5) in certain applications, its adherence to other surfaces. In some applications, such as use with some stucco or similar textured coatings, some "give" on the part of the insulation is desirable, while in composite panels, rigidity is important. Low conductivity is especially important for applications which may reduce inside usable space, since commercial office space tends to have a high cost per square foot of usable area in terms of the rent that it commands. Low conductivity may also be important if it allows a given level of thermal performance to be achieved without violating building code restrictions on the walls fuel content or thickness. The ability of the insulation to seal and insulate irregular shapes is important in curtain wall systems which are mounted on metal bracing on the outside of the building superstructure. Adhesion properties are important in this latter application and in the manufacture of composite foam-core panels for use in curtain wall construction.

---

[11]This restriction on fuel contribution is related to the containment of flame spread on the exterior of the building, not in the interior spaces. In general, exterior walls containing plastic foam insulation must be covered on the inside by a thermal barrier of 0.5 in. gypsum wallboard or equivalent.

Table 3-1. Approximate Thickness Limitations on Plastic Foam Insulation Consistent with 6000 Btu/ft^2 Fuel Content

Insulation Type	Fuel Content[a] (Btu/pound)	Typical Density (pounds/ft^3)	Allowable Thickness (Inches)	Approximate R-value
Polyurethane	10,000	1.5	4.8	30
Polyisocyanurate	10,000	2.0	3.6	26
Extruded Polystyrene	17,000	2.0	2.1	11
Expanded Polystyrene	17,000	1.0	4.2	16
		1.5	2.8	12

[a]Approximate fuel content; actual fuel content may vary by manufacturer.

3.1 The High Cost of Lost Space

The high thermal performance of CFC-blown foam insulations is particularly beneficial in commercial buildings if the thicker walls needed to accommodate insulation intrude into the usable area. The relatively high rental cost of interior office space ($5.00 to $50.00 per year per square foot of usable area, and even higher for premium locations in some major cities) imposes a significant penalty for every inch of wall intrusion. For each 12 feet of running exterior wall on each floor, one inch of increased wall thickness translates to one foot of lost floor space. Using a 25 year life, a five percent inflation rate, and a 12 percent nominal discount rate, the present value of the rent paid for each square foot of usable area is approximately $120 per $10 of annual rent. This is equivalent to two dollars per inch thickness per square foot of opaque wall area per $10 of annual rent, assuming ten foot high walls per story and 50 percent window to wall area. (The uniform present worth factor is equal to 12.01; each 12 running feet of exterior wall are assumed to have 120 square feet of gross wall area, or 60 square feet of opaque wall area, per story. Any cost attributable to the insulation must be allocated to the opaque wall area, not to the window area.)

In assessing the cost of lost interior space in commercial buildings, it is assumed in this report that the rentable floor space is of prime consideration in the design of the building. If the exterior walls can be extended outward to accommodate thicker insulation without changing the foundations and superstructure, the impact of insulation thickness on rentable area is likely to be negligible. If the exterior wall system has a large interior space for wall supports, wiring, and/or HVAC pipes and ducts, insulation thickness may also be irrelevant from a cost standpoint as well. However, whenever there is a direct tradeoff between insulation thickness and rentable floor area (i.e, the insulation intrudes inward from the wall supports), the rental value of the lost floor area must be included in the true cost of the insulation.

When rentable space must be given up to accommodate wall insulation, the most thermally efficient foam insulations (polyurethane and polyisocyanurate) will generally be the insulation material of choice from an economic standpoint. If these insulation materials are not available, requiring that a less efficient insulation material be substituted, design economics will generally dictate that the wall thickness remain unchanged and the thermal performance be reduced accordingly.

Energy conservation provisions in existing building codes and in the proposed ASHRAE 90.1 energy efficiency standards for commercial buildings typically require a specified minimum energy performance for exterior walls. These provisions may override design decisions based on purely economic criteria in some cases. However, these provisions are usually stated in terms of thermal performance of the overall wall, including both window and opaque wall areas. If high efficiency insulation materials (i.e., rigid foams blown with CFC's) were not available, adjustments to the exterior wall design to comply with these standards would more likely to be made to the size and U-value of the windows than to the thickness of the opaque wall area if this required the wall to intrude into the occupied space. While this cost may be significant, especially in terms of design freedom, it is likely to vary widely in response to site-specific considerations and is not estimated in this report.

3.2 Simulation Procedures and Methods of Economic Analysis

The heating and cooling loads for a representative commercial building were computed using the Envelope System Performance Compliance Calculation Program[12] developed to support the proposed ASHRAE Standard 90.1. The computations are based on a building module consisting of a single story of a multistory building with a square floor plan. The module consists of four perimeter zones of identical geometry surrounding an interior zone. The floor and ceiling are modeled as adiabatic surfaces (i.e., having no heat loss or gain), which is a realistic assumption for multistory buildings. The walls at each end of the four perimeter zones are also modeled as adiabatic surfaces. The four perimeter zones were oriented to four cardinal points of the compass. Each exterior wall is 100 feet in length and has a height of 12 feet resulting in an exterior wall area of 1200 ft^2. Fenestration comprises 27 percent of the total wall area on the north, east, and south walls while accounting for 32 percent on the west wall. Shading coefficient and visible transmittance values of 0.48 and 0.36, respectively, were used in the computer simulations. The glazing U-value which includes the mullion factors was maintained at 0.8 Btu/hft^2F for the analysis. The equipment and lighting loads were assumed to be 0.5 $watts/ft^2$ and 1.73 $watts/ft^2$ respectively.

Parametric runs were conducted for each city by varying the opaque wall U-value for each wall system considered in this analysis. The resulting data was used to generate curves of heating and cooling loads for this building in each city as a function of its opaque wall U-value. Sensitivity analyses were performed in which changes in glazing area and internal heat gains were made

---

[12]Envelope System Performance Compliance Calculation Program, Version 1.0, DOE Report No. CE-0166, November 1986.

to this representative building. It was found that while total space heating and cooling loads change significantly with these two variables, changes in the space heating and cooling loads which are directly attributable to reductions in the U-value of the opaque wall changed very little.

Changes in space heating and cooling loads were converted to corresponding changes in annual energy consumption using steady-state estimates of heating and cooling system performance. A seasonal efficiency of 70 percent was used for natural gas heating and 95 percent for electric resistance heating; a seasonal COP of 2.0 was used for air conditioning. Electric heat pump HSPFs (heating season performance factors) range from 5.1 to 7.7, depending on the severity of the winter climate[13]. Corresponding reductions in electricity consumption by air-handling equipment were not estimated, but are assumed to be small. It should be noted that energy savings due to changes in wall insulation levels are sensitive to equipment efficiency, and that equipment efficiency varies widely from building to building, depending on the type of equipment, its age, and how well it has been maintained.

Energy prices and projected rates of increase over time used in the economic analysis were based on regional projections by the U.S. Department of Energy, as published by the National Bureau of Standards[14]. These factors are shown in Appendix B. Life-cycle cost guidelines consistent with both NBS Handbook 135, Life-Cycle Costing Manual for the Federal Energy Management Program and ASTM Standard Practice E-917, "Measuring Life-Cycle Costs of Buildings and Building Systems" were used to compute economic levels of insulation. The economic level of insulation is defined here as that level with the lowest total present-value life-cycle cost, including initial costs, operating and maintenance costs, resale value, and tax considerations. A twelve percent nominal after-tax discount rate was used to convert future savings to present value[15]. A study period of 25 years and a straight-line depreciation period of 31.5 years were used in the analysis. Half of the real value of the insulation is assumed to remain at the end of the 25 year study period; however, when this value is discounted to present value it is relatively insignificant in comparison to its initial cost.

Insulation costs used to compute economic levels are the same per-square-foot costs used in section 2 for residential analysis, except that costs for commercial wall insulation are applied directly to the opaque wall area while

---

[13]HSPFs used are as follows: Phoenix 7.38, Los Angeles 7.34, San Francisco 6.74, Denver 5.77, Orlando 7.67, Atlanta 6.80, Boston 5.88, Minneapolis 5.10, Fort Worth 7.04, Seattle 6.05, Washington 6.41, Kansas City 6.07.

[14]Lippiatt and Ruegg, Energy Prices and Discount Factors for Life-Cycle Cost Analysis, NBSIR 85-3273-2, U.S. Department of Commerce, National Bureau of Standards, Gaithersburg MD, 1987.

[15]A twelve percent nominal discount rate is approximately equivalent to a seven percent real discount rate plus a five percent rate of general inflation. The seven percent real discount rate is used in analysis of energy conservation investments in Federal buildings.

costs for residential wall insulation are applied to the gross wall area. It should be recognized that installed insulation costs can vary significantly from installer to installer depending on a number of factors, including union or non-union status, location, timing, job size and other site-specific characteristics.

It should also be noted that the life-cycle cost criteria for determining the economic level of insulation used in this report may be considered unrealistic by many building owners more concerned with year-to-year cash flows than long term economics. As a result, the economic R-values shown in this section should be considered only as design benchmarks for assessing the substitutability of insulation materials and not as design guidelines for new buildings.

3.3 Insulation Analysis by Wall Type

In this subsection, common uses of insulation materials in exterior commercial and high-rise residential walls systems are explored and economic thicknesses estimated for a wide range of locations and fuel prices. The substitution of non-CFC-blown insulations for CFC-blown foams in these same applications is investigated.

3.3.1 Concrete-Masonry Walls

Concrete-masonry walls can be insulated on the outside or inside surfaces, in the cores of concrete blocks, or in the cavity of a composite brick and block wall. Rigid foam insulation is the most common material for this purpose, although some loose-fill materials (e.g., perlite) are sometimes used to fill cavities and molded plastic inserts (or more loose-fill insulation) are sometimes placed in core sections. The three rigid foam sheathings discussed in section 2 for residential wall construction are most typical for insulating masonry walls in commercial buildings: polyurethane (including polyisocyanurate), extruded polystyrene, and expanded polystyrene (EPS). The analysis of concrete-masonry walls will be limited to these three materials in the cavity of a brick and block cavity walls and on the outside surface of concrete block walls. The use of insulation in the cores of concrete blocks will not be evaluated for two reasons: the insulation materials used in cores does not generally contain CFCs; and, more importantly, the insulation of cores has serious shortcomings from a thermal performance standpoint because of the thermal bridging effects of the solid portions of the concrete blocks. As a result, this insulation technique should only be used to supplement rigid foam insulation.

3.3.1.1 Brick and Block Cavity Walls:

In commercial buildings cavity wall construction typically consists of eight inch concrete block, an air space (cavity), and four-inch face brick. The cavity can be expanded to accommodate up to four inches of insulation. The rigid foam insulations shown in table 3-1 are all satisfactory for this application. Since they are protected from fire on both the inside and outside they are not subject to the thickness constraints shown in this table. In general, the major economic considerations in selecting among insulation types and in determining economic thickness are based on the cost of the insulation per resistance unit and an assessment of wall expansion costs. If the cavity can be expanded to accommodate thicker insulation by moving the face brick outward at minimal cost, the substitution of EPS for a rigid foam insulation blown with CFC to the same level of overall thermal performance will have little impact on the construction cost or energy cost of the building. If the inside surface of the wall must be moved inward to accommodate the increased thickness of insulation required to maintain thermal performance, the added cost, in terms of lost interior space, will likely discourage the additional insulation, resulting in a significant energy penalty over the life of the building.

Economic levels of rigid foam insulation in a brick and block cavity wall were calculated for a commercial office building in twelve locations in the United States. DOE regional energy price projections for both electricity and natural gas were used in a life-cycle cost analysis. A study period of 25 years and a real (net of general inflation) after-tax discount rate of seven percent were used in the analysis. Results are shown in table 3-2 for three different heating systems in each location: electric heating, natural gas, and heat pump; electric air conditioning was assumed in all buildings. These results are reported for rigid foam insulation in general, without identifying the particular insulation type, as the costs and results (in terms of economic R-values) are similar for all three types examined. The corresponding insulation thicknesses range from 0 to 2 inches for polyisocyanurate, 0 to approximately 3.5 inches for EPS, and 0 to 3 inches for extruded polystyrene.

In general, the economic levels of insulation shown in table 3-2 are quite low compared to those for residential walls. This result is primarily due to the relatively small energy savings attributable to the insulation of commercial wall systems in comparison to residential construction. Not only do heating savings tend to be smaller in the former, but insulation actually tends to increase cooling loads in commercial buildings with brick and block cavity walls (except in Phoenix), offsetting some or all of the savings in the heating mode.

As a result of this analysis, it is estimated that there is no economic or energy penalty incurred in switching from polyisocyanurate or extruded polystyrene to EPS for brick and block cavity walls.

3.3.1.2 Concrete Block Walls--Exterior Insulation:

Rigid foam sheathing on the exterior surface is the most effective method of insulating concrete block walls from a thermal performance standpoint, since it helps realize the full potential of the thermal storage properties of such walls. Insulation of the outside surface also has no effect on usable interior space, unless the outside dimensions of the building are strictly limited and the block walls must be moved inward to compensate for the insulation. Exterior insulation does require that a protective coating be applied. A stucco or similar coating is typically used. At a cost of $2.00 to $4.00 per square foot, this significantly reduces the cost effectiveness of exterior insulation, unless this coating is to be applied for reasons other than insulation protection (e.g., for design aesthetics). All three types of rigid foam insulation materials are used for this purpose, although the choice is narrowed somewhat by the type of exterior coating used. Hard coatings, being more rigid, require a more rigid foam sheathing such as extruded polystyrene, while soft coatings tend to be more yielding, which is more compatible with a less rigid foam sheathing such as EPS.

The economic R-values shown for brick and block cavity walls in table 3-2 are approximately valid for concrete block walls with an exterior insulation and finish system. (This does not imply that the walls perform equally well, but only that the additional energy savings from additional increments of insulation are similar in both walls.) EPS appears to be a viable substitute for CFC-blown insulation materials in exterior wall insulation systems, despite the requirement for thicker insulation, since the wall and window sill expansion costs will likely be quite small. In fact, EPS is the most commonly used rigid foam insulation in these applications. However, there have been complaints about failures of the soft-coat exterior finish systems related to water leakage and subsequent damage, which may require a more rigid standard for EPS in these systems. And the manufacturers and installers of the hard-coat systems will be negatively impacted by the non-availability of extruded polystyrene unless they are able to modify their product to improve its compatibility with less-rigid foam sheathings.

Table 3-2. Approximate Economic R-values for Brick-and-Block Cavity Walls in Commercial Buildings[a]

Location	HDD65	CDH74	Electric Furnace	Natural Gas	Heat Pump
PHOENIX	1382	55998	R-4	R-3	R-3
LOS ANGELES	1494	01193	R-0	R-0	R-0
SAN FRANCISCO	3237	00835	R-4	R-0	R-0
DENVER	6083	07510	R-7	R-5	R-7
ORLANDO	0531	27247	R-0	R-0	R-0
ATLANTA	3069	11892	R-5	R-4	R-3
BOSTON	5775	05094	R-14	R-7	R-10
MINNEAPOLIS	8059	06946	R-14	R-10	R-12
FORT WORTH	2354	28048	R-5	R-0	R-3
SEATTLE	5280	01260	R-7	R-5	R-4
WASHINGTON DC	4228	09952	R-10	R-5	R-5
KANSAS CITY	5201	13730	R-12	R-5	R-7

[a]Based on a 25-year life-cycle cost analysis.

3.3.1.3 Concrete Block Walls--Interior Insulation:

The economic R-values shown in table 3-2 are also reasonably representative for rigid-foam insulation on the inside of concrete block walls, covered with minimum half-inch gypsum board, but only when no cost is attributed to the lost interior space. (Again, this does not imply that the walls perform equally well.) In fact, this cost can be quite high, depending on the use of the building, making the real cost of insulation prohibitively high in many instances. In general, if insulation must be used on the inside surface, only the most efficient insulation materials (e.g., polyisocyanurate) can be justified. If those materials were no longer available, and EPS were to be substituted, the insulation thickness required to achieve the same thermal performance would increase by approximately 70 percent (assuming 1.5 lb density EPS at R-4.17 per inch versus polyisocyanurate at R-7.2 per inch). In most installations, it could be expected that the insulation thickness would be held constant, with a corresponding reduction in thermal performance. Where energy standards require a specified thermal performance for exterior walls, it is likely that a combination of window and wall design changes would be met to comply with the standard, rather than simply increasing the thickness of the insulation to maintain the same insulation R-value.

3.3.1.4 Wood and Steel Stud Wall Systems:

The exterior walls of both load- and non-load-bearing walls can be framed with wood or steel studs. Stucco or similar coatings, wood, brick, or other siding materials are typically used to cover the exterior surface. The cavity between the studs is often insulated with R-11 or R-13 fiberglass batts. If thermal performance beyond that typically achieved with the fiberglass batts is desired, rigid foam insulated sheathing can be attached to the exterior side of the studs, under the outer surface. In the case of the stucco-type coatings, insulated sheathing is often used as the base on which the coating is applied. All of the rigid foam insulations examined in this section are appropriate for use with wood or steel stud systems. However, some types of stucco-type coating systems are more compatible with certain types of sheathing. For example, so-called "soft" coating systems (e.g., the Dryvit system) require sheathing with a lower modulus of elasticity, such as EPS, while harder coatings may require a more rigid sheathing, such as extruded polystyrene.

The costs of rigid foam insulation used as sheathing with wood and metal stud walls is similar to those used for residential wood-frame walls in section 2. Metal window and door systems are most prevalent in commercial and high-rise residential buildings. Thus there is little additional cost in terms of the window and door jamb expansion to accommodate the additional thickness of EPS when substituted for the CFC-blown insulation materials. It is unlikely that rigid foam insulation used to augment fiberglass insulation in the wall cavity would approach a thickness prohibited by the fire-safety provisions of the building codes.

Table 3-3 shows economic R-values of insulated sheathing used with stud wall systems in commercial office buildings, assuming that R-13 fiberglass batts are installed in the stud space. (Since fiberglass batts are generally less costly per resistance unit than foam insulation, it is more economical to start with the former.) These economic thicknesses are calculated using a 25-year life-cycle cost analysis. In general, the insulated sheathing is only cost effective in these applications in northern climates with electric heat. Designers using a more stringent economic criteria (e.g., seven-year payback or positive cash flow in early years) would find the foam sheathing to be uneconomical in most applications (again, assuming that R-13 fiberglass is used in the stud space.)

It should be noted that in the case of stucco-type exterior finish systems, one-inch foam sheathing is typically required as the base for the exterior coating. In the milder climatic regions, this exterior finish system may be used without fiberglass batts. In such cases, a desired increase in insulation would more likely be accomplished by adding fiberglass batts rather than increasing the thickness of the foam sheathing.

It is concluded that for wood- and steel-stud wall systems, the substitution of a non-CFC blown rigid foam insulation for a thermally equivalent CFC-blown material would have little or no economic cost or energy penalty in terms of building construction or operating costs. However, as noted above, some buildings with a "soft" stucco-type finish system using EPS have had problems with water damage. Consideration should also be given to the manufacturers and installers of those exterior coating systems which require a more rigid surface than that provided by EPS. A reduction in the availability of extruded polystyrene would force these manufacturers to modify their coating system or go out of business.

3.3.1.5 Curtain Wall Systems:

Two types of curtain wall systems are considered for analysis is this report: composite foam-core panels, in which the insulation is installed at the factory, and flat panels, to which the insulation is attached after the panels are installed.

Composite foam core panels with metal skins are typically manufactured with polyurethane (or polyisocyanurate) foam. These panels are available in several standard thicknesses, with two inch thickness being the most common. Other thicknesses can be manufactured, although for some manufacturers this may require that assembly lines be modified at substantial cost. For some systems, a redesign of curved corner panels would also be required. Compatible window systems are manufactured to be used with standard panel thicknesses. However, these same window systems can be used with thicker panels using modified sill adapters.

Manufacturers of the metal-skin composite panels state that polyurethane or polyisocyanurate foams are the only viable candidates for this application for several reasons. (1) These panels can be manufactured rapidly on an assembly line where the chemicals are poured into the panel, expanding and adhering firmly to both surfaces in less than a minute. The alternatives must be glued to the inside surfaces and cured under pressure, greatly increasing the amount of manufacturing time. (2) The polyurethane/polyisocyanurate

Table 3-3. Economic R-values for Foam Sheathing in Wood and Steel Stud Walls[a] (Assumes R-13 fiberglass batts in stud space)

Location	HDD65	CDH74	Electric Furnace	Natural Gas	Heat Pump
PHOENIX	1382	55998	R-0	R-0	R-0
LOS ANGELES	1494	01193	R-0	R-0	R-0
SAN FRANCISCO	3237	00835	R-0	R-0	R-0
DENVER	6083	07510	R-6	R-0	R-0
ORLANDO	0531	27247	R-0	R-0	R-0
ATLANTA	3069	11892	R-0	R-0	R-0
BOSTON	5775	05094	R-10	R-0	R-0
MINNEAPOLIS	8059	06946	R-12	R-0	R-6
FORT WORTH	2354	28048	R-0	R-0	R-0
SEATTLE	5280	01260	R-0	R-0	R-0
WASHINGTON DC	4228	09952	R-0	R-0	R-0
KANSAS CITY	5201	13730	R-0	R-0	R-0

[a]Based on 25-year life cycle cost analysis.

materials are the most thermally efficient foams suitable for this purpose and result in high-efficiency panels at practical thicknesses. (3) Neither the expanded nor extruded polystyrene products can satisfy the fire protection provisions of the model building codes with regard to exterior flame spread for multistory buildings. The polystyrene materials melt when exposed to heat from a fire and the panels then offer little resistance to flames from below.

For these reasons, it is concluded that expanded polystyrene is not an acceptable substitute for the polyurethane/polyisocyanurate materials currently used in the manufacture of metal-skin composite foam-core panels. New blowing agents for these latter materials are being investigated which have lower or zero levels of CFC's, with some degradation in terms of thermal performance (approximately 15 percent according to industry estimates). This loss in thermal performance could be compensated by making thicker panels, at a relatively small increase in the overall manufacturing cost of the panel (although some one-time costs related to the modification of the assembly line may be significant). In the milder climates, it is more likely that the same thicknesses will be maintained, with slightly reduced thermal performance, since the additional cost of the thicker insulation will not be cost justified in these installations. In the colder climates, some adjustment to thicker insulation levels might be expected over time. However, even if these alternate blowing agents and the resulting foams are found to be acceptable environmentally, much additional research will be needed to demonstrate their suitability from the standpoint of the fire-safety and adhesion properties needed for these applications.

Table 3-4 shows estimates of economic thicknesses for composite foam-core curtain wall panel insulation in 12 locations, by heating system type. These estimates were calculated using the same energy costs and insulation costs used in table 3-2. (This assumes the incremental cost per inch of polyisocyanurate insulation is approximately $0.40 per square foot; incremental costs of the composite panels will likely vary substantially from manufacturer to manufacturer, depending on the set-up costs involved in changing the product thickness.)

Table 3-4. Economic Thicknesses of Composite Foam-Core Curtain Wall Panel Insulation[a]

			Electric Furnace		Natural Gas		Heat Pump	
Location	HDD65	CDH74	Inches	R	Inches	R	Inches	R
PHOENIX	1382	55998	1.5	11	1.0	7	1.0	7
LOS ANGELES	1494	01193	0	0	0	0	0	0
SAN FRANCISCO	3237	00835	1.0	7	1.0	7	1.0	7
DENVER	6083	07510	2.0	14	1.5	11	1.5	11
ORLANDO	0531	27247	1.0	7	0	0	0	0
ATLANTA	3069	11892	1.5	11	1.0	7	1.0	7
BOSTON	5775	05094	2.5	18	1.5	11	2.0	14
MINNEAPOLIS	8059	06946	2.5	18	2.0	14	2.5	18
FORT WORTH	2354	28048	1.5	11	1.0	7	1.0	7
SEATTLE	5280	01260	1.5	11	1.0	7	1.0	7
WASHINGTON DC	4228	09952	2.0	14	1.5	11	1.5	11
KANSAS CITY	5201	13730	2.0	14	1.5	11	1.5	11

[a]Polyisocyanurate insulation (R-7.2/inch), based on 25 year life-cycle cost analysis.

Flat curtain wall panels are typically insulated on the inside after they are attached to the building. Installation of rigid foam insulation on the inside surface of these wall systems is often impractical due to the irregular shapes of the cavities that result from the interface of these panels with the supporting members and window systems. Fiberglass boards and batts are most frequently used for this purpose; sprayed cellulosic insulation is also used in some installations. However, foamed-in-place polyurethane has a particular advantage for this application, in that it completely fills the cavities, while its superior adherence properties provide an improved seal against air infiltration. Polyurethane has more than twice the thermal resistance per inch of fiberglass batts, making a significantly higher levels of overall wall performance achievable in a limited-depth wall cavity. If the use of polyurethane for these curtain wall applications were curtailed, it is likely that the same thickness of fiberglass insulation would be used, but at a considerable energy penalty.

Another approach to the insulation of manufactured composite panel systems is to attach rigid foam sheathing to the outside surface of non-combustible board stock and apply the same exterior stucco-type exterior finishing system used with the wood- and steel-stud wall system. These panels can then be attached to the superstructure of a building without the need for scaffolding. A non-combustible fire rating can be attained, even with EPS, if the exterior coating system provides sufficient protection to the insulation. Economic R-values similar to those shown in table 3-4 (but with approximately twice the thickness) would be appropriate for this latter system.

3.4 Conclusions for Commercial/High-Rise Wall Systems

The choice of an exterior wall system for commercial buildings and high-rise residential buildings is much wider than that for a typical single-family residence. As with the latter, the choice of a wall system can have a significant effect on the appropriate insulation type and its economic thickness.

For most masonry and stud wall systems, EPS, which contains no CFC agent, can be used in place of CFC-blown rigid foam insulation with no economic or energy penalty, provided that the exterior wall surface can be expanded outward at little or no increase in construction cost in order to maintain the same level of thermal performance. Exceptions to this conclusion are (1) concrete-masonry walls with insulation installed on the interior surface, (2) hard-coat exterior finish and insulation systems which require the more rigid surface provided by extruded polystyrene, and (3) buildings for which the outside wall dimensions are strictly limited at the building site. In general, the cost of rental space in commercial buildings is so high that any intrusion into the occupied space to maintain the thermal performance of the insulation will be uneconomical.

For some curtain wall systems, the choice of insulation material is determined more by fire codes than by economics, per se. The polyisocyanurate or polyurethane insulation currently used in metal-skinned foam-core panels cannot be replaced with EPS in non-combustible wall construction. The elimination of CFC-blown foam insulation would have a significant negative impact on the design of many new commercial buildings and the industry manufacturing this product.

In flat-panel curtain wall systems (e.g., metal, stone, and aggregate panels), where the insulation is typically added to the inside surface after the panels are attached to the building, fiberglass is the most commonly used insulation material. Foamed-in-place polyurethane is also used in this latter application with superior results, not only because of its improved thermal performance but because it is able to seal the wall to reduce air infiltration. While this latter insulation system is not as prevalent as fiberglass, a reduction in the availability of CFCs for foam insulation will have a negative impact here as well, primarily in terms of increased energy usage. It is unlikely that fiberglass would be used at the thickness required to achieve a level of thermal performance equivalent to foamed-in-place polyurethane in such installations.

Curtain wall panels are also manufactured using EPS insulation with a protective stucco-like coating on the outside. These panels could be substituted for those containing CFC-blown insulation materials in some new buildings where a stucco-like exterior is acceptable.

4. LOW-SLOPE ROOF SYSTEMS FOR COMMERCIAL BUILDING APPLICATIONS

4.1 Alternatives Examined

The energy data and economic analysis reported here are derived for the most part on a recent Oak Ridge National Laboratory report entitled "Economic Analyses of Insulation Materials Used in Low-Slope, Built-Up Roof Systems.[16]" That report provides a comprehensive summary of currently marketed rigid-board insulation materials for use below membranes of low-slope, above-deck, built-up roof systems on U.S. Air Force Facilities. The primary requirements of that study were to compare, on a 20-year life-cycle cost (LCC) basis, currently available insulation materials as alternatives to fiber glass insulation, and to determine economically optimal levels for built-up roof (BUR) systems on a LCC basis. Only insulation systems recommended by the National Roofing Contractors Association were included in that study, and for each insulation type, a system design was selected with a strong likelihood of a long (approximately 20 year), trouble-free, life.

While the NBS analysis is based on ORNL data for built-up roofing systems, similar conclusions can be drawn for other low-slope roof systems in which the rigid insulation boardstock is covered by a protective membrane. However, "protected-membrane" systems, in which the insulation is placed over a water-tight membrane, usually require a water-resistant and durable rigid foam insulation such as extruded polystyrene, which in turn is covered with ballast to hold it in place. For this reason the results of this analysis cannot be extrapolated to protected-membrane systems. However, these latter systems make up only a small percentage of the total number of low-slope roofing systems installed in the United States.

Calculations of heating and cooling energy requirements attributable to roofs with a wide range of insulation values were performed at ORNL using the DOE-2.1A building energy analysis program for a 60,000 square foot building in six cities. Differences in energy usage attributable to wet insulation over part of the roof life and differences caused by the effect of aging on thermal conductivity for gas-filled, closed cell foam insulations were incorporated into the calculations. In addition, the transient heat transfer characteristics of the various roof systems were considered in the ORNL analysis. A sensitivity analysis with respect to roof area did not show any significant variation in energy usage per square foot over a wide range of roof sizes.

Seven different types of insulation were analyzed in the ORNL report for use under BUR membranes: fiber glass, perlite, wood fiberboard, cellular glass, expanded polystyrene (EPS) composite, polyisocyanurate composite, and polyurethane composite. Extruded polystyrene was not analyzed because this insulation type is not recommended for use under BUR membranes by the National Roofing Contractors Association (NRCA). A perlite composite underlayment and

---

[16]Courville, G.E., and Kolb, J.O, "Economic Analyses of Insulation Materials Used in Low-Slope, Built-Up Roof Systems," ORNL/TM-9004, Oak Ridge National Laboratory, Oak Ridge, TN, 1984.

fiberboard cover were assumed for all of the rigid foam insulations.

Table 4-1 summarizes the initial thermal conductivities and corresponding insulation thicknesses for a range of design R-values for each of these insulation types used. Note that the values used for unfaced polyurethane and polyisocyanurate foams (k = 0.17 Btu-inch/ft^2-h-F, or R-5.8 per inch) were selected by the authors of the ORNL report to represent the average value for the first year of use on the basis of work reported by Muhlenkamp and Johnson.[17]

ORNL obtained price quotes for installing each of these seven insulation types at several different thicknesses from 40 roofing contractors in 37 states. Maintenance and inspection costs were estimated for each type of insulation based on past U.S. Air Force experience. Energy prices were based on the then current DOE energy prices. Insulation salvage values were calculated as a percentage of their initial cost. An eight percent real discount rate was used in the ORNL study to determine the present value of energy and maintenance costs and salvage values so that a total present-value life-cycle cost could be determined for each installation.

This study will focus on only three of these insulation types -- fiber glass, EPS composite, and polyisocyanurate composite -- since these are the most thermally efficient materials for roof deck insulation, i.e., the insulation types with the lowest k values. (Polyisocyanurate will be used in this analysis to represent polyurethane composites as well, since the thermal conductivity is the same for both, while the cost of the latter is slightly higher than the former.) Table 4-2 shows the installed insulation costs and annual maintenance and inspection costs used for these three insulation types. The total installed cost per 100 sq. ft. is also shown graphically as a function of R-value in figure 4-1. These initial costs include an adjustment for energy equivalence over time (recognizing a slight increase in the thermal conductivity of the polyisocyanurate foam as it ages over 20 years), an adjustment for long term durability (by the inclusion of a cover board for the EPS and fiber glass insulations and a bottom board for the latter as well), and an adjustment for the length of the required nailers. These costs do not include any adjustment for rooftop HVAC equipment clearance; thus in retrofit applications where limited clearance below existing equipment prevents the use of the optimal R-value, the most thermally efficient insulation material (i.e., polyurethane or polyisocyanurate) will generally be the economic choice.

---

[17]Muhlenkamp, S.P. and Johnson, S.E., "In-Place Thermal Aging of Polyurethane Foam Roof Insulation," Paper No. 11, 7th Conference, Proceedings of the NRCA-NBS Conferences on Roofing Technology, April 1983.

Table 4-1. Insulation Conductivity and Thicknesses[a]

Insulation Type	Initial Thermal Conductivity[b] (k) (Btu-inch/ft²-h-F)	Insulation Thickness (inches)				
		R-10	R-15	R-20	R-25	R-30
Fiber Glass	0.25	2.50	3.75	5.00	6.25	7.50
Perlite	0.36	3.60	5.40	7.20	9.00	10.80
Fiberboard	0.36	3.60	5.40	7.20	9.00	10.80
Cellular Glass	0.38	3.80	5.70	7.60	9.50	11.40
EPS Foam	0.26	2.60	3.90	5.20	6.50	7.80
Polyisocyanurate foam	0.17	1.70	2.55	3.40	4.25	5.10
Polyurethane foam	0.17	1.70	2.55	3.40	4.25	5.10

[a]Source:ORNL/TM-9004.

[b]For first year, dry condition.

Table 4-2. Installed Insulation and Annual Maintenance Costs[a]

	Installed Cost ($/100 ft^2)	Annual Maint ($/100 ft^2)
Fiber Glass		
R-10	158	10
R-20	268	0
R-30	378	10
EPS Composite		
R-10	179	9
R-20	210	9
R-30	241	9
Polyisocyanurate composite		
R-10	165	9
R-20	216	9
R-30	268	9

[a]Source: ORNL/TM-9004. Note: all installation costs have been adjusted for energy equivalence, longevity, and wood nailer costs. Costs have been adjusted to 1987 dollars from 1984 dollars using a 12 percent cumulative inflation factor.

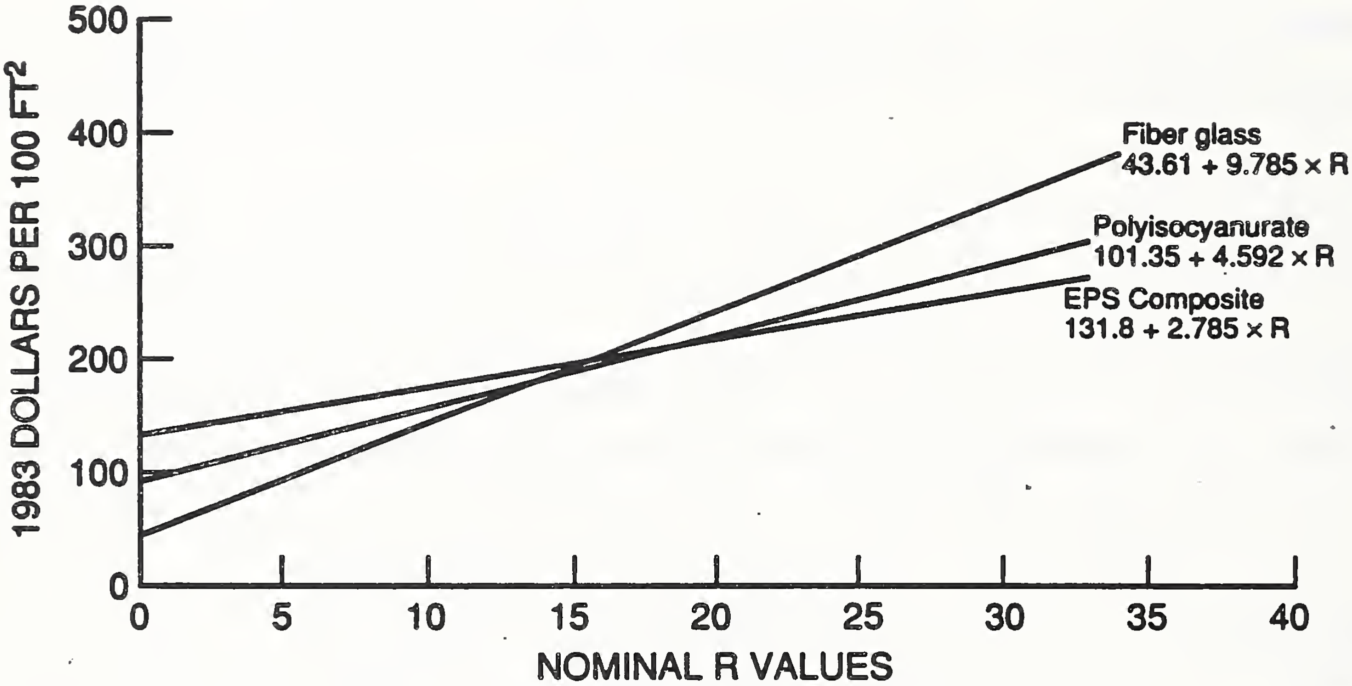

Figure 4-1. ORNL Installed Insulation Costs for Built-Up Roofs (per 100 ft^2, 1983 dollars).

All insulation was assumed to be installed on an existing steel deck roof with 1/4 in.-per-foot minimum slope. A three-ply fiberglass membrane was assumed to be installed over the insulation or cover board in all cases; however, the cost of this membrane is not included in these installed insulation costs.

4.2 Economic Thickness of Insulation

In order to make the results of the ORNL study consistent with the methodology used in other sections of this NBS report, their economic analyses have been recomputed using current DOE energy price projections and a 7 percent real discount rate. Optimal levels of insulation in each location for three heating system types were recomputed for each of the six locations and three heating system types. These results are shown in table 4-3.

The results reported in table 4-3 are consistent with the ORNL findings, except that the optimal levels for built-up roof insulation tend to be slightly lower now than in 1984. This is because current DOE projections of energy price increases are somewhat less steep than similar projections made by DOE at the time that the original study was completed. In addition, a more conservative insulation salvage value was used in the new analysis (50 percent rather than the 90 percent used in the ORNL study).[18] In general, because the EPS composite has the lowest incremental cost per unit of R-value, its optimal R-values are slightly higher than those computed for polyisocyanurate and considerably higher than those for fiber glass insulation. For insulation levels between R-10 and R-15, all three systems have similar life-cycle costs; for levels above R-15, the two foam insulations have nearly identical life-cycle costs and are somewhat less than those for the fiber glass.

Table 4-3 shows optimal R-values for these same installations based on the premise that insulation costs are financed over 15 years and that positive cash flow must be reached by the end of the second year. Energy, maintenance, and depreciation costs are all assumed to be tax deductible in this analysis. While these optimal R-values are generally somewhat lower than those shown in table 4-3, they are more indicative of the economic criteria that would be used for many commercial and industrial applications. As a result, these R-values will generally be closer to what is often installed in such buildings than the levels determined using 20-year life-cycle costs.

---

[18]In the ORNL study, it was assumed the insulation could be left in place after roof membrane failure, with a new membrane over the top, since a protective fiberboard cover was assumed to be installed with the insulation. Note that the present value of this "salvage value" is quite small since it is discounted over 20 years.

Table 4-3. Optimal R-Values for BUR Insulation Based on 20-Year LCC

Insulation/ Heating System[a]	Location					
	Minot N.D.	Indiana-olis IN	Orlando FL	San Anto-nio TX	Phoenix AZ	Bakers-field CA
Fiber Glass						
Natural gas	R-15	R-15	R-10	R-10	R-10	R-10
Heat Pump	R-20	R-15	R-10	R-10	R-10	R-10
Electric Furn.	R-25	R-20	R-10	R-15	R-15	R-15
EPS Composite						
Natural gas	R-30	R-25	R-15	R-20	R-20	R-20
Heat Pump	>R-30	R-30	R-15	R-20	R-20	R-20
Electric Furn.	>R-30	>R-30	R-15	R-20	R-20	R-20
Polyisocyanurate Composite						
Natural gas	R-20	R-20	R-10	R-15	R-15	R-15
Heat Pump	R-30	R-30	R-10	R-15	R-15	R-15
Electric Furn.	>R-30	>R-30	R-10	R-20	R-20	R-25

[a]Heating system efficiencies used: natural gas=70 percent, electric resistance=95 percent; heat pump HSPF: Minot=4.7, Indianapolis=5.9, Orlando=7.7, San Antonio=7.3, Phoenix =7.4, Bakersfield = 7.1; Cooling system SEER=6.8 in all locations.

Table 4-4. Optimal R-Values for BUR Insulation Based on Cash Flow Analysis at End of Second Year[a]

Insulation/ heating System[a]	Location					
	Minot ND.	Indiana-polis IN	Orlando FL	San Anto-nio TX	Phoenix AZ	Bakers-field CA
Fiber Glass	------------ R-10 or less in all applications --------					
EPS Composite						
Natural gas	R-15	R-15	R-10	R-10	R-10	R-10
Heat Pump	R-20	R-15	R-10	R-10	R-15	R-15
Electric Furn.	R-25	R-20	R-15	R-15	R-15	R-15
Polyisocyanurate Composite						
Natural gas	R-10	R-10	R-10	R-10	R-10	R-10
Heat Pump	R-15	R-15	R-10	R-10	R-10	R-10
Electric Furn.	R-20	R-15	R-10	R-10	R-15	R-15

[a]Assumes 15 year mortgage at 10 percent interest, depreciation over 31.5 years, energy and maintenance as deductible expenses, and marginal income tax rate of 25 percent.

4.3 Implications for CFC Substitutes in Commercial Roof Systems

The implications of both the original ORNL research and this new NBS economic analysis, with regard to substitutes for insulation materials blown with CFC's, are the same: Both fiber glass and EPS composites are cost effective substitutes for polyisocyanurate (and by implication, polyurethane) roof deck insulation. However, both of these substitutes will require significantly thicker insulation to achieve a given R-value. Thus the exception to this conclusion lies in those retrofit applications where rooftop HVAC equipment constrains the thickness of the insulation to a level lower than that required to achieve the desired R-value. (For new buildings the clearance under HVAC equipment can generally be increased at little or no additional cost if the designer is aware of this constraint.) Table 4-5 shows the energy penalties per 1000 ft^3 of roof area that can be attributed to the substitution of EPS (k=0.26) for polyisocyanurate (k=0.17) when the insulation thickness constraint is 2 inches. These would be substantial losses, enough to justify some modification of the clearances in many cases.

In general, the EPS/perlite composite will be a more economical choice as a substitute for polyisocyanurate than fiber glass insulation because higher R-values can be economically justified. It should also be recognized that the density of the EPS material can be increased above the 1.0 lbs/ft^3 used in the ORNL study to improve its thermal conductivity. An increase to 1.5 lbs/ft^3 will reduce its thermal conductivity by eight percent, so that the thermal performance equivalent to the polyisocyanurate board can be achieved with a 40 percent increase in thickness. This will lessen any energy penalty attributable to the substitution of EPS for polyisocyanurate when thickness constraints are present.

4.4 Potential Impact of ASHRAE Standard 90.1

The draft ASHRAE 90.1 standard for energy conservation in commercial building design specifies an overall thermal transmittance (U) for a roof system to be less than or equal to a specified value. This design value is computed by a relationship which takes into account the heating and cooling degree days at a base of 65F, and the cooling degree hours at a base of 80F. Table 4-6 shows the equivalent R-value requirement for each of the six locations evaluated in this section. In addition, table 4-6 shows the corresponding thickness for the three types of insulation considered: fiber glass, EPS composite, and polyisocyanurate composite.

The minimum R-values shown in table 4-6 compare reasonably well with the optimal R-values shown in table 4-3 for the polyisocyanurate composite on the roofs of buildings heated with natural gas, considering that the optimal values were computed at R-5 intervals rather than continuously. The exception here is for Phoenix, where the draft ASHRAE standard requires R-21.5, and the economically optimal level for gas and heat pump is R-15 (although R-20 is optimal with electric resistance).

Table 4-5. Energy Penalty for Substitution of 2 in. EPS (R-7.7) for 2 in. Polyisocyanurate (R-11.8) per 1000 ft^2 of Roof Area

Location:	Minot N.D.	Indiana polis IN	Orlando FL	San Anto- nio TX	Phoenix AZ	Bakers- field CA
	Energy Penalty in Million Btu/Yr					
Annual heating load:	10.9	7.4	2.1	2.9	2.9	4.0
Annual cooling load:	0.4	0.8	1.8	2.8	3.1	2.0
	Increased Present-Value Cost of Energy over 20 Years:[a]					
Natural gas	$992	$815	$368	$545	$585	$591
Heat Pump	$1570	$978	$322	$584	$570	$584
Electric Furn.	$2270	$1720	$545	$949	$907	$1040

[a]All energy cost calculations assume electric air conditioning. (See efficiency assumptions in table 4-3.)

Table 4-6. Minimum R-Values and Corresponding Insulation Thicknesses for Commercial Roof Deck Systems

Location	Standard 90.1 Minimum R-Value	Required Thickness (inches) Fiber Glass	EPS	Polyisocyanurate
Minot, N.D	22.8	5.7	5.9	3.9
Indianapolis	17.2	4.3	4.5	2.9
Orlando	13.1	3.3	3.4	2.2
San Antonio	15.7	3.9	4.1	2.7
Phoenix	21.5	5.4	5.6	3.7
Bakersfield, CA	16.3	4.1	4.2	2.8

These draft ASHRAE requirements could not be met economically with fiber glass board. However, the optimal R-value for EPS composite, from an LCC standpoint, is well above the ASHRAE requirements in all locations except for Phoenix. The use of EPS composite in built-up roof systems provides a more cost-effective means of achieving the minimum ASHRAE requirements, and in fact makes it cost-effective, again from a LCC standpoint, to exceed the standard in most of these locations.

5. SUMMARY

Substitutes for CFC-blown rigid foam insulations were evaluated for use in three distinct building components: residential walls systems (both wood-frame and masonry), commercial walls systems, and commercial low-slope roof systems. It was found that the most suitable substitutes, expanded polystyrene (EPS) and fiber glass, typically have a lower cost per resistance unit than most commonly used CFC-blown foams (polyisocyanurate and extruded polystyrene), but that greater thicknesses of these substitutes are required to attain the same thermal performance as the latter materials. As a result, any economic costs attributable to such substitutions are related to expanding the walls and roofs to accommodate the thicker insulation rather than to the materials themselves.

EPS rigid foam sheathing is the most suitable substitute for polyisocyanurate or extruded polystyrene sheathings for wood-frame walls. The EPS specifically evaluated has an R-value of 4.17 per in. at a density of 1.5 lbs/ft^2, and has a protective facing to improve its handling characteristics and reduce ultraviolet degradation while exposed. The costs of using a thicker EPS sheathing than the polyisocyanurate or extruded polystyrene on wood-frame walls was found to be determined primarily by the cost of extension jambs for wood-framed windows and doors. For an average size (1650 ft^2 of floor area) house the net cost of adding wood extension jambs (after subtracting the savings in material costs) to accommodate sheathing thicknesses greater than 0.5 in. is approximately $160. In new houses with metal windows no significant cost for increasing the depth of the window jambs is expected, since these extensions are typically gypsum board finish. In general it was found that substituting 2x6 in. studs for 2x4 in. studs and insulated sheathing, in order to accommodate an equivalent amount of fiber glass insulation, is not a cost effective means of reducing the usage of CFC-blown insulation.

The cost of increasing the thickness of an exterior masonry wall to accommodate a thermally equivalent amount of EPS rigid foam insulation in place of polyisocyanurate or extruded polystyrene on the inside surface or in the wall cavity is primarily related to lost interior space. This cost is approximately the same as the reduction in cost attributable to the usage of EPS in place of the CFC-blown insulations, so that there is no significant net increase in cost for using EPS. If the EPS insulation is installed on the exterior wall, no wall expansion cost is expected. Insulation on the exterior surface is actually more energy efficient than an equivalent amount on the inside surface. However, insulation on the exterior surface must be covered with a protective finish, which makes this an overall more costly alternative.

The choice of an exterior wall system for commercial buildings and high-rise residential buildings is much wider than that for typical single-family residence; as with the latter, the choice of a wall system can have a significant effect on the appropriate insulation type and its economic thickness. For most masonry and stud wall systems, EPS can be used in place of CFC-blown rigid foam insulation with no economic or energy penalty, provided that the exterior wall surface can be expanded outward at little or no increase in construction cost in order to maintain the same level of thermal performance. Exceptions to this conclusion are (1) concrete-masonry walls with insulation installed on the interior surface, (2) hard-coat exterior finish and insulation systems which require the more rigid surface provided by extruded polystyrene, and (3) buildings for which the outside wall dimensions are strictly limited at the building site. In general, the cost of rental space in commercial buildings is so high that any intrusion into the occupied space to maintain the thermal performance of the insulation will be uneconomical.

For some curtain wall systems, the choice of insulation material is determined more by fire codes than by economics, per se. The polyisocyanurate or polyurethane insulation currently used in metal-skinned foam-core panels cannot be replaced with EPS in non-combustible wall construction. The elimination of CFC-blown foam insulation would have a significant negative impact on the design of many new commercial buildings and the industry manufacturing this product.

In flat-panel curtain wall systems (e.g., metal, stone, and aggregate panels), where the insulation is typically added to the inside surface after the panels are attached to the building, fiberglass is the most commonly used insulation material. Foamed-in-place polyurethane is also used in this latter application with superior results, not only because of its improved thermal performance but because it is able to seal the wall to reduce air infiltration. While this latter insulation system is not as prevalent as fiberglass, a reduction in the availability of CFCs for foam insulation will have a negative impact here as well, primarily in terms of increased energy usage. It is unlikely that fiberglass will be used at an equivalent level of thermal performance for those installations currently using foamed-in-place polyurethane.

Curtain wall panels are also manufactured using EPS insulation with a protective stucco-like coating on the outside. These panels could be substituted for those containing CFC-blown insulation materials in some new buildings where a stucco-like exterior is acceptable.

Both fiber glass board and EPS rigid foam were found to be cost-effective substitutes for polyisocyanurate or polyurethane rigid foam in insulating built-up roofs on commercial buildings. The exceptions, which are difficult to quantify in terms of frequency of encounter, are those existing installations where roof-top equipment has insufficient vertical clearance to allow the use of a thicker insulation material. If the same thickness of EPS or fiber glass is used instead of the more efficient polyisocyanurate or polyurethane, the energy penalty will be significant.

Appendix A. Climatic Data and DOE Regions for Locations Evaluated

1. Wall Analysis:

CITY	HDD65	CDH74	DOE REGION
BOSTON	5775	5094	1
WASHINGTON	4828	9952	3
ATLANTA	3069	11892	4
ORLANDO	531	27247	4
MINNEAPOLIS	8059	6946	5
KANSAS CITY	5201	13730	7
DALLAS/FT WORTH	2354	28048	6
DENVER	6083	7510	8
PHOENIX	1382	55998	9
SEATTLE/TACOMA	5280	1260	10
SF/OAKLAND	2922	342	9
LOS ANGELES	1494	1123	9

2. Roof Analysis:

MINOT ND	9177	4584	8
INDIANAPOLIS IN	5620	7639	5
ORLANDO FL	531	27247	4
SAN ANTONIO TX	1578	30394	6
PHOENIX AZ	1382	55998	9
BAKERSFIELD CA	2194	28514	9

Appendix B. DOE Regional Price Projections and Uniform Present-Worth Factors[1]

Table B-1. Residential Analysis (Walls)

Energy prices (1987) and corresponding UPW based on 25 years and 7% discount rate plus DOE energy price projections for residential sector:

REGION	ELECTRICITY		NAT GAS	
	PRICE	UPW	PRICE	UPW
1	29.15	10.69	7.34	18.96
2	26.25	11.22	6.86	14.65
3	20.03	10.97	6.10	14.63
4	19.20	9.98	5.46	16.53
5	22.86	10.13	5.34	16.16
6	19.36	12.52	4.92	15.60
7	21.21	10.77	4.74	17.54
8	21.29	10.36	4.55	16.29
9	21.31	10.36	4.88	16.34
10	10.29	12.43	5.58	16.86
Avg. U.S.	20.54	10.75	5.50	15.78

Table B-2. Commercial Analysis (Roof and Walls)

Energy prices (1987) and corresponding UPW based on 20 years and 7% discount rate plus DOE energy price projections for commercial sector:

REGION	ELECTRICITY		NAT GAS	
	PRICE	UPW	PRICE	UPW
1	29.07	9.75	6.10	14.05
2	25.44	10.18	5.52	13.88
3	19.79	9.95	5.40	13.16
4	19.38	9.12	4.73	14.89
5	22.63	9.24	4.72	14.58
6	18.82	11.3	4.18	14.41
7	20.71	9.7	3.93	16.02
8	20.71	9.4	4.25	14.44
9	21.12	9.4	5.64	12.06
10	10.26	11.1	4.44	16.00
Avg. U.S.	20.80	9.7	4.85	14.17

[1]Source: Lippiatt, B.C., and Ruegg, R.T., Energy Prices and Discount Factors for Life-Cycle Cost Analysis, NBSIR 85-3273-2 (Rev. 6/87), National Bureau of Standards, Gaithersburg, MD, 1987

Appendix C. Installed Insulation Costs and U-Values Used in Analysis

The following tables contain the insulation R-values and corresponding U-values and installed costs used in to determine the economic thicknesses or R-values for insulation in each building component evaluated in this report. All costs were adjusted to include 25 percent builder overhead and profit. All costs are in 1987 dollars.

Table C-1. Residential Wood-frame Walls, With Extension Jamb Costs

WALL NO.	WALL U	SHEATHING R	COST /FT^2	WALL DESCRIPTION
1	0.0781	1.320	$0.36	3.5" WALL WITH R-11 FIBERGLASS
2	0.0710	1.320	$0.43	3.5" WALL WITH R-13 FIBERGLASS
3	0.0538	1.320	$1.33	5.5" WALL WITH R-19 FIBERGLASS 16" CENTERS
4	0.0524	1.320	$1.05	5.5" WALL WITH R-19 FIBERGLASS 24" CENTERS
5	0.0603	3.600	$0.51	R-13 + 0.5" POLYISOCYANURATE
6	0.0490	7.200	$0.90	R-13 + 1" POLYISOCYANURATE
7	0.0415	10.800	$1.13	R-13 + 1.5" POLYISOCYANURATE
8	0.0669	2.090	$0.38	R-13 + 0.5" EPS
21	0.0644	2.610	$0.56	R-13 + 0.625"EPS
24	0.0603	3.600	$0.60	R-13 + 0.86" EPS
9	0.0582	4.170	$0.65	R-13 + 1" EPS
22	0.0546	5.210	$0.71	R-13 + 1.25" EPS
10	0.0515	6.255	$0.77	R-13 + 1.5" EPS
23	0.0488	7.300	$0.92	R-13 + 1.75" EPS
11	0.0463	8.340	$0.97	R-13 + 2" EPS
12	0.0650	2.500	$0.46	R-13 + 0.5" EXT. POLYS
13	0.0553	5.000	$0.81	R-13 + 1" EXT. POLYS
14	0.0483	7.500	$0.99	R-13 + 1.5" EXT. POLYS
15	0.0464	3.600	$1.13	R-19 + 0.5" POLYISOCYANURATE
16	0.0395	7.200	$1.45	R-19 + 1" POLYISOCYANURATE
25	0.0488	2.610	$1.11	R-19 + 0.625"EPS
17	0.0451	3.850	$1.16	R-19 + 1" EPS
26	0.0430	5.210	$1.26	R-19 + 1.25" EPS
18	0.0426	5.775	$1.29	R-19 + 1.50" EPS
27	0.0393	7.300	$1.47	R-19 + 1.75" EPS
19	0.0491	2.500	$1.08	R-19 + 0.5" EXT. POLYS
20	0.0434	5.000	$1.36	R-19 + 1" EXT. POLYS

Table C-2. Residential Wood-frame Walls, Without Extension Jamb Costs

WALL NO.	WALL U	SHEATHING R	COST /FT^2	WALL DESCRIPTION
1	0.0781	1.320	$0.36	3.5" WALL WITH R-11 FIBERGLASS
2	0.0710	1.320	$0.43	3.5" WALL WITH R-13 FIBERGLASS
3	0.0538	1.320	$1.08	5.5" WALL WITH R-19 FIBERGLASS 16" CENTERS
4	0.0524	1.320	$0.79	5.5" WALL WITH R-19 FIBERGLASS 24" CENTERS
5	0.0603	3.600	$0.51	R-13 + 0.5" POLYISOCYANURATE
6	0.0490	7.200	$0.74	R-13 + 1" POLYISOCYANURATE
7	0.0415	10.800	$0.97	R-13 + 1.5" POLYISOCYANURATE
8	0.0669	2.090	$0.38	R-13 + 0.5" EPS
21	0.0644	2.610	$0.40	R-13 + 0.625"EPS
24	0.0603	3.600	$0.44	R-13 + 0.86" EPS
9	0.0582	4.170	$0.49	R-13 + 1" EPS
22	0.0546	5.210	$0.55	R-13 + 1.25" EPS
10	0.0515	6.255	$0.61	R-13 + 1.5" EPS
23	0.0488	7.300	$0.66	R-13 + 1.75" EPS
11	0.0463	8.340	$0.72	R-13 + 2" EPS
12	0.0650	2.500	$0.46	R-13 + 0.5" EXT. POLYS
13	0.0553	5.000	$0.64	R-13 + 1" EXT. POLYS
14	0.0483	7.500	$0.83	R-13 + 1.5" EXT. POLYS
15	0.0464	3.600	$0.87	R-19 + 0.5" POLYISOCYANURATE
16	0.0395	7.200	$1.10	R-19 + 1" POLYISOCYANURATE
25	0.0488	2.610	$0.77	R-19 + 0.625"EPS
17	0.0451	3.850	$0.81	R-19 + 1" EPS
26	0.0430	5.210	$0.92	R-19 + 1.25" EPS
18	0.0426	5.775	$0.95	R-19 + 1.50" EPS
27	0.0393	7.300	$1.03	R-19 + 1.75" EPS
19	0.0491	2.500	$0.95	R-19 + 0.5" EXT. POLYS
20	0.0434	5.000	$1.01	R-19 + 1" EXT. POLYS

Table C-3. Insulation in Masonry Walls (residential)[1]

WALL NO.	WALL U	SHEATH R	COST/FT² INTERIOR	COST/FT² EXTERIOR	WALL DESCRIPTION
1	0.2799	0.000	$0.00	$0.00	NON-REFLECTIVE AIRSPACE
2	0.1928	0.000	$0.05	$0.05	3/4 IN REFLECTIVE AIR SPACE
3	0.1129	3.600	$0.48	$0.43	0.5 IN POLYISOCYANURATE (FOIL FACING)
4	0.0937	5.400	$0.60	$0.52	0.75 IN POLYISOCYANRURATE (FOIL FACING)
5	0.0801	7.200	$0.76	$0.66	1.0 IN POLYISOCYANURATE (FOIL FACING)
6	0.0700	9.000	$0.90	$0.77	1.25 IN POLYISOCYANURATE (FOIL FACED)
7	0.0621	10.800	$1.04	$0.88	1.5 IN POLYISOCYANURATE (FOIL FACING)
8	0.0559	12.600	$1.18	$1.00	1.75 IN POLYISOCYANURATE (FOIL FACING)
9	0.1366	2.090	$0.35	$0.30	0.5 IN EPS (FOIL FACING)
10	0.1194	3.130	$0.42	$0.34	0.75 IN EPS (FOIL FACING)
11	0.1060	4.170	$0.52	$0.41	1.0 IN EPS (FOIL FACING)
12	0.0954	5.210	$0.60	$0.47	1.25 IN EPS (FOIL FACING)
13	0.0867	6.260	$0.68	$0.53	1.5 IN EPS (FOIL FACING)
14	0.0795	7.300	$0.76	$0.58	1.75 IN EPS (FOIL FACING)
15	0.0734	8.430	$0.85	$0.65	2.0 IN EPS (FOIL FACING)
16	0.1291	2.500	$0.49	$0.44	0.5 IN EXTRUDED POLYS (FOIL WALLBOARD)
17	0.1110	3.750	$0.58	$0.51	0.75 IN EXTRUDED POLYS (FOIL WALLBOARD)
18	0.0974	5.000	$0.72	$0.62	1.0 IN EXTRUDED POLYS (FOIL WALLBOARD)
19	0.0868	6.250	$0.84	$0.71	1.25 IN EXTRUDED POLYS (FOIL)
20	0.0782	7.500	$0.96	$0.80	1.5 IN EXTRUDED POLYS (FOIL WALLBOARD)
21	0.0713	8.750	$1.08	$0.90	1.75 IN EXTRUDED POLYS (FOIL WALLBOARD)

[1]Cost and U-value do not include exterior finish.

Table C-4. Built-up Roof Insulation

ROOF NO.	ROOF U	INSUL. R	COST /FT^2	WALL DESCRIPTION
1	0.1000	10.0	$1.58	FIBERGLASS R-10
2	0.0667	15.0	$2.13	FIBERGLASS R-15
3	0.0500	20.0	$2.68	FIBERGLASS R-20
4	0.0400	25.0	$3.23	FIBERGLASS R-25
5	0.0333	30.0	$3.78	FIBERGLASS R-30
6	0.1000	10.0	$1.79	EPS COMPOSITE R-10
7	0.0667	15.0	$1.94	EPS COMPOSITE R-15
8	0.0500	20.0	$2.10	EPS COMPOSITE R-20
9	0.0400	25.0	$2.26	EPS COMPOSITE R-25
10	0.0333	30.0	$2.41	EPS COMPOSITE R-30
11	0.1000	10.0	$1.65	POLYISOCYANURATE R-10
12	0.0667	15.0	$1.91	POLYISOCYANURATE R-15
13	0.0500	20.0	$2.16	POLYISOCYANURATE R-20
14	0.0400	25.0	$2.42	POLYISOCYANURATE R-25
15	0.0333	30.0	$2.68	POLYISOCYANURATE R-30
16	0.0850	11.8	$1.74	POLYISOCYANURATE 2"
17	0.1300	7.7	$1.72	EPS COMPOSITE 2"

FORM NBS-114A (REV.11-84)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 88-3829	2. Performing Organ. Report No.	3. Publication Date JULY 1988

4. TITLE AND SUBTITLE

Technical and Economic Analysis of CFC-Blown Insulations and Substitutes for Residential and Commercial Construction

5. AUTHOR(S)

Stephen R. Petersen and A. Hunter Fanney

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

NATIONAL BUREAU OF STANDARDS
U.S. DEPARTMENT OF COMMERCE
GAITHERSBURG, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

Building Systems Division
U. S. Department of Energy
Washington, D.C. 20585

10. SUPPLEMENTARY NOTES

☐ 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)

Rigid foam insulations blown with chloroflourocarbons (CFC's) are among the most thermally efficient materials available for insulating walls and roofs of buildings. While they are more expensive than more traditional insulating materials, their usage where space constraints dictate a more efficient insulator have become commonplace. Increasing concern about the effect of CFC's released to the atmosphere may result in restrictions on the availability of these insulation materials. This report evaluates the thermal performance and economics of rigid foam insulating materials containing CFC's and alternative insulation materials that contain little or no CFC. Residential walls (wood-frame and masonry), commercial wall systems (frame, masonry, and curtain wall) and commercial low-slope roof systems are examined in a wide range of climates in the United States to determine the cost effectiveness of rigid foam insulation materials. Economic substitutes for insulation materials containing CFC exist; however, they are not compatible with all types of wall/window and roof systems and thus may make some wall and roof systems impractical.

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

building economics; building energy performance; building envelope; chloroflourocarbons; energy conservation; thermal insulation

13. AVAILABILITY

☒ Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.
☒ Order From National Technical Information Service (NTIS), Springfield, VA 22161

14. NO. OF PRINTED PAGES

62

15. Price

$13.95

USCOMM-DC 85-6006