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OPTIMUM INSULATION THICKNESSS IN WOOD-FRAMED HOMES

A. E. OVIATT

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
U.S. DEPARTMENT OF AGRICULTURE FOREST SERVICE
PORTLAND, OREGON

Abstract

New design methods must be developed to reduce energy waste in buildings. This study examines an economic approach to the design of thermal insulation in the home and demanstrates graphically that an optimum point of insulation thickness occurs where total costs of insulation and energy over the useful life of a building are a minimum. The optimum thickness thus determined exceeds that recommended by older design criteria and significantly reduces energy requirements for heating and cooling. An engineering heat loss analysis is applied to typical wood-framed wall and roof constructions, and total costs of insulation and energy are graphically shown for various thicknesses of insulation in several climates of the United States. Simple expressions are derived which may be used by designers and contractors to estimate optimum insulation thicknesses for any climate, using a series of curves. This method of design is new and results in greater total cost economy and better energy conservation than previous methods. Other ways of reducing heat loss in the home are also discussed.

Keywords : Wood properties (thermal), construction (wood).

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Introduction

The energy shortage in the United States is now clearly visible, and measures to conserve our existing supplies of energy fuels and to develop new sources are urgently needed., The problem has many facets and implications, but there is an immediate need for effective conservation methods. We must operate within our present means to allow time for the development of other potential energy sources, so that the least disruption in our economy and our way of life will occur.

A very significant reduction in energy use can be made by curtailing the enormous waste of energy we have tolerated in our residential heating systems by inadequate design of thermal insulation. Of some 71 million housing units now existing in the United States, a large majority has insufficient insulation or other thermal treatment.

Thermal insulation, as such, was not widely used in residential buildings until the 1930's. Hence, a large number of older dwellings are without insulation, other than that afforded by the construction itself. Some of these older houses have since been improved, but many remain with grossly inefficient and costly thermal systems. Newer houses are frequently nominally insulated, but a majority do not have adequate thermal protection, either because good standards were not generally known or because so-called "first-cost" was the controlling factor to the builder.

Many of our older buildings would be difficult or costly to significantly improve thermally. Such is the case with many multifamily apartments and the growing number of mobile homes, many of the latter being notoriously difficult to heat. However, simple alterations to the 48 million existing one- and two-family dwellings can be easily and economically made. The installation or improvement of ceiling insulation and the use of storm windows and doors in northern locations can usually save 20 percent or more in heating and cooling costs,

An energy saving of more than 1,400 trillion Btu's per year has been estimated (*7*), if these improvements to existing homes were made. This translates to a saving of some **$3** billion per year, enough to pay for the improvements in a very short time.

A continuing opportunity to conserve our available energy is presented in current and future residential construction, which normally adds some 2 million units each year to our heating and cooling load. If insulation in these units were increased to an optimum level, considerable reduction in energy use would result, with an attendant reduction in total cost, The saving, of course, would be a progressive one as new housing is built, but additional savings of some 6,000 trillion Btu's are possible over a 10-year period due to improved insulation of all new construction. Such a saving would offset present trends toward larger living units and greater use of air conditioning which, if they continue, will increase energy demands per living unit.

Where future construction is concerned, important steps have already been taken to increase insulation requirements, as in Federal Housing Administration Minimum Property Standards, 1974, for FHA insured construction and the Oregon State Building Code, 1974. However, maximum energy savings can only be assured when an individual investing in a home realizes the total economy of adequate insulation, and this study seeks to inform owners as well as designers and builders.

An important side effect of energy conservation is a proportional reduction in air pollution, since pollution occurs in direct proportion to the amount of fuels consumed. It is, therefore, more desirable in reduced air pollution, as well as economy, to curtail the amount of energy used per living unit than to develop new sources or quantities of usable energy.

Design of Insulation

Insulation design involves a choice of material and form, as well as a determination of thickness needed, It is not the purpose of this study to discuss materials and forms in great detail. It is important that the material be fire-resistant, and one that does not produce noxious gases on exposure to heat. It should be resilient enough to prevent compaction and should'not readily absorb or be damaged by water vapor. In typical wood-frame houses, batts or blankets are well suited to fitting between studs or rafters, and loose, fill-type materials may be readily blown over ceiling joists. This type of installation, using glass or rock wool, is in general use and is widely recognized for its economy in wood-frame construction. Therefore, insulation and cost values used in this study will be limited to this material. Other kinds of insulation, such as insulating board sheathing, foamed plastic board types, and vermiculite fill have important applications but are not so widely used.

Insulation Thickness

Given the material and form of insulation most widely used in the typical wood-frame house, how shall we determine how much to use? Most previous methods of design emphasize comfort criteria, i. e, , the essential design requirement being that occupants of a building are entitled to a thermally comfortable environment, It is presumed to follow that this would also be a healthful environment. Among widely used rules of thumb to achieve average comfort conditions are:

1. "All Weather Comfort Standard," as developed by manufacturers, equipment suppliers, and power companies. This standard provides a range of choice of insulation thickness based on three arbitrary weather zones (6), using the degree-day[1] heating requirement to define these zones.

2. Comfort criteria based on the average difference between desired room air temperature and that of enclosing surfaces. An average balance of heat gained by convection and heat lost by radiation is thus obtained, and criteria are applied from experience as to what this difference should be (4).

These standards address the fundamental requirements of comfort and health of the occupants but provide little guidance to the designer or builder on the economic use of insulation or on energy conservation. Illustrations are sometimes provided to show the savings in heating cost which can be made by adding another inch of insulation, but no attempt is made to arrive at an economic optimum.

A 1971 publication of the National Association of Home Builders (5) recognizes the growing use of air conditioning in American homes and provides an excellent guide for the designer or builder in analyzing heat losses and energy costs. It provides heating and cooling worksheets whereby the builder may enter trial combinations of insulation and openings, determining total heat transfer and equipment sizes. Simple cost calculations are provided, establishing heating and cooling costs for a given heat transfer in any part of the United States. It does not, however, identify the optimum economic thickness of insulation which results in the least total cost (insulation plus operating cost) to the owner. Rather, it leaves it to the builder to choose constructions in a manner to result in least first-cost, and to use what he feels is a reasonable level of insulation thickness acceptable to a buyer.

The first-cost approach has never been conducive to the best interests of the typical home buyer, since the few hundred dollars saved by eliminating or minimizing insulation can cost the owner a few thousand dollars over the life of the building in increased energy costs. We can no longer afford this kind of energy waste.

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[1] A degree-day is a unit used to predict seasonal fuel consumption for heating. For 1 day, the number of degree-days is'equal to the number of degrees that the mean temperature for that day is below 65° F. For the heating season, the number of degree-days is the sum of degrees for all days that the mean temperature falls below 65° F. The average seasonal totai of degree-days over a number of years is useful to estimate average annual heating costs for a given locality.

Optimum. Thickness of Insulation

Minimum total costs result when first-cost of insulation plus the corresponding cost in energy over the useful life of the building are a minimum. A relatively simple engineering and cost analysis can be used to identify optimum thicknesses of any kind of insulation for local energy costs in any climate. This is no more than the same cost-effectiveness approach applied to many materials and types of equipment in industry and government. The method is commonly applied in heavy construction to many aspects of design, yet it has not been widely used in insulation design.

A survey of recent literature has revealed few published attempts to approach insulation design on a total cost basis. I made such a study involving cork insulation in a refrigerated building in 1947.[2] The National Research Council of Canada initiated two such analyses in 1964 and 1965 (2, 11). These excellent studies, however, are based on fuel and material costs which are now obsolete and do not consider the wide use of air conditioning in the United States.

Optimum Economy and Conservation

The design of insulation for optimum total cost economy, as applied in this study, does not at first seem to satisfy the objective of maximum conservation. Optimum conservation of energy would seem to imply maximum energy savings, perhaps regardless of costs. In fact, though, cost does enter the picture, As energy becomes less available, its cost will rise, and the development of new energy sources will very probably increase costs. As the cost of ene'rgy increases, so will the thickness of insulation needed to effect minimum total cost, and conservation automatically increases.

The economic method of insulation design presented here results in greater amounts of insulation and greater energy savings than previous methods. It is a practical method of obtaining maximum conservation which is economically realistic, as the fuel conserved per inch of insulation rapidly diminishes beyond the point of optimum economy. This can be readily seen in figure 1, where heat loss in a ceiling is plotted against insulation thickness. The heat saved by the 1st inch of insulation is 3 times that saved by the 2d inch and 75 times that saved by the 10th inch. Excessive quantities of insulation would quickly reach a point of no return, where the energy consumed in insulation manufacture, transportation, and installation, plus that which would be incurred by additional framing, exceeds the energy saved.

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[2] A. E. Oviatt. A frozen food locker plant. Unpublished B. Arch. thesis, Yale University, New Haven, Connecticut, 1947.

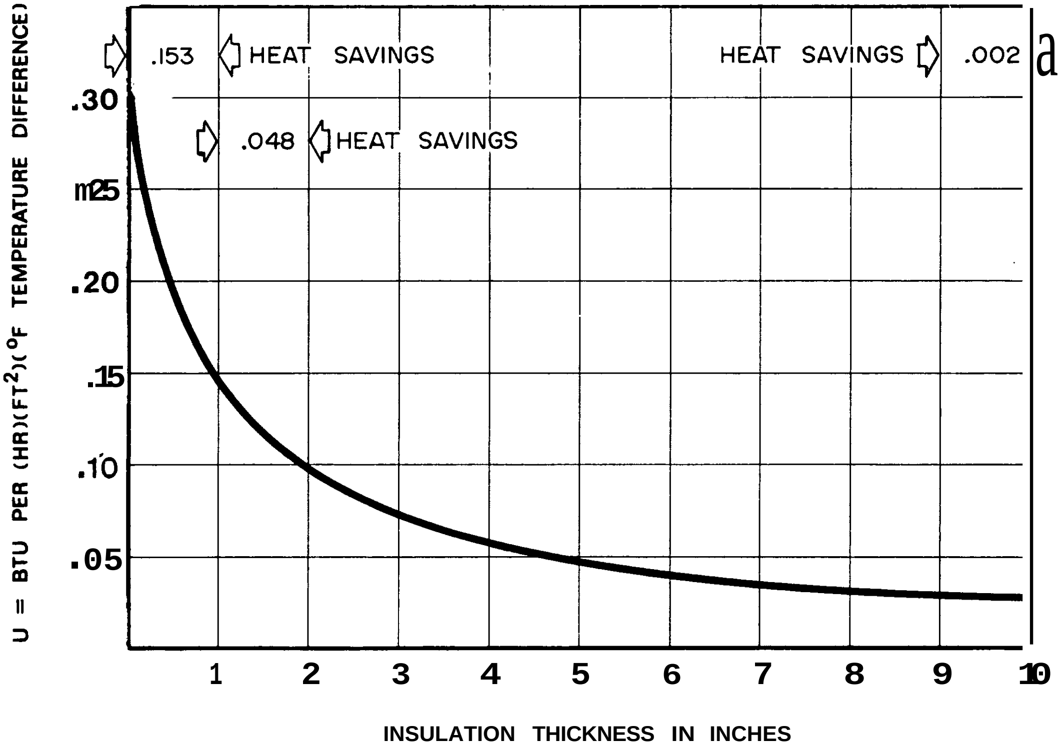

Figure 1.--Effect of increasing insulation thickness on heat losses in a typical roof-ceiling construction.

Method of Analysis

R. K. Beach of the National Research Council of Canada showed that optimum thickness of insulation can be obtained directly by an application of differential calculus familiar to many engineers (2). An equation for total cost must first be developed, including the many pertinent variables, and the first derivative taken to obtain a minimum cost expression. This may then be solved directly for optimum thickness. This method may be preferred by mechanical engineers who are able to develop and manipulate mathematical expressions for their particular area of practice. However, it has the disadvantage of being unintelligible to many architects, builders, and owners who are unfamiliar with the language of mathematics.

This report seeks to present visually the cost-thickness relationship for various areas, using graphs plotted from simple algebraic expressions. The basic engineering and cost relationships and assumptions used are outlined in the appendix, for those who wish to adapt them to special cases. Fuel costs are taken from the National Association of Home Builders Insulation Manual, 1971 (5), for the various local utilities. These costs are currently in a state of escalation at various regional rates, and their future levels cannot now be foreseen. However, possible future effects of inflation on insulation thickness are discussed.

Determing Heat Loss and Gain

The transfer of heat through a material or assembly of materials is measured by its *U* value, expressed in English units in Btu's per hour per square foot per degree Fahrenheit temperature difference between the two surfaces. This gives the heat loss through the construction for a unit area for each degree Fahrenheit temperature difference. Heat losses through each material in an assembly have a relationship based on reciprocals, as is the case in other areas of physics having to do with flow. To greatly simplify the summation of elements of a construction, an *R* value, signifying the resistance of an element or an assembly to the flow of heat, is now generally used. An *R* value is the reciprocal of the *U* value, and these resistance values may be directly summed for each element in a construction, When the total *R* is determined, however, it must be converted to its reciprocal or *U* value to return it to units of heat. *U* and *R* values used in this study, as well as engineering methods of computation, are taken from the authoritative American Society of Heating, Refrigerating and Air Conditioning Engineers "Handbook of Fundamentals" (*1*).

Heat transmission values for a typical wood-frame roof and ceiling construction are listed in appendix I. Although the nature of the construction has some effect on its *U* value, minor substitutions of materials have little ultimate bearing on the *U* value of a well-insulated construction. Thus, for example, it would make little difference whether the roofing is asphalt shingles, wood shingles, or slate, since the small change in *U* value for this element of the construction is dwarfed by the effect of the insulation itself. Similarly, the ceiling material might be gypsum board, plaster, or hardboard without materially affecting insulation requirements. But, if an insulating material, such as a 1-inch acoustical tile ceiling is made part of the construction, then the need for additional insulation would be reduced by nearly 1 inch. Some judgment is needed, therefore, in applying the results of this study to other constructions; but in most cases, variations in individual materials do not have a decisive effect on insulation requirements.

The amount of insulation in ceiling joists in an open attic may be limited by joist depth, due principally to the need to get full insulation depth over the entire ceiling at the eaves without blocking the usual eave ventilators. Normally, joist depths of over 8 inches would be uneconomical for structural purposes in a residential ceiling, so an insulation requirement of more than 7-1/2 inches net could increase construction cost somewhat by requiring deeper ceiling joists or a raised plate at the eaves. When greater insulation is required, as in areas along the northern border of the United States or in much of Alaska, a judgment must be made in trading the heat saving for the increase in construction cost. It may well be satisfactory in many cases to use a maximum of 7-1/2 inches of insulation, since an additional 1 inch, say, would have a negligible effect on heating cost in this range of total insulation thickness. The *U* values of a roof-ceiling system with no insulation and with 1 to 10 inches of insulation are given in tables 1 and 2 to extend total cost curves beyond the optimum point for all climates.

Table 1.--Heating and cooling costs per year per 1,000 square feet of ceiling (various locations)

	0	1	2	3	4	5	6	7	8	9	10
U value construction	0.292	0.147	0.099	0.074	0.060	0.050	0.042	0.037	0.033	0.030	0.028
	Dollars										
Cost per year of insulation, 40-year amortization	0	7.45	8.94	10.43	11.92	13.41	14.90	16.39	17.88	19.37	20.86
San Diego:											
Heating	13.15	6.45	4.33	3.20	2.63	2.19	1.84	1.62	1.45	1.32	1.23
Cooling	2.26	1.11	.75	.56	.45	.38	.32	.28	.25	.23	.21
Total	15.41	7.56	5.08	3.76	3.08	2.57	2.16	1.90	1.70	1.55	1.44
Total insulation and operation	15.41	15.01	14.02	14.19	15.00	15.98	17.06	18.29	19.58	20.92	22.30
Seattle:											
Heating	62.20	30.40	20.50	15.30	12.42	10.35	8.70	7.66	6.83	6.21	5.80
Cooling	.86	.42	.28	.21	.17	.14	.12	.11	.09	.09	.08
Total	63.06	30.82	20.78	15.51	12.59	10.49	8.82	7.77	6.92	6.30	5.88
Total insulation and operation	63.06	38.27	29.72	25.94	24.51	23.90	23.72	24.16	24.80	25.67	26.74
Miami:											
Heating	4.05	1.98	1.34	1.00	.81	.68	.57	.50	.45	.41	.38
Cooling	60.00	29.40	19.80	14.80	12.00	10.00	8.40	7.40	6.60	6.00	5.60
Total	64.05	31.38	21.14	15.80	12.81	10.68	8.97	7.90	7.05	6.41	5.98
Total insulation and operation	64.05	38.83	30.08	26.23	24.73	24.09	23.87	24.29	24.93	25.78	26.84
St. Louis:											
Heating	44.75	21.90,	14.75	11.03	8.95	7.45	6.25	5.52	4.92	4.47	4.17
Cooling	39.90	19.55	13.15	9.85	7.98	6.65	5.58	4.92	4.38	3.99	3.72
Total	84.65	41.45	27.90'	20.88	16.93	14.10	11.83	10.44	9.30	8.46	7.89
Total insulation and operation	84.65	48.90	36.84	31.31	28.85	27.51	26.73	26.83	27.18	27.83	28.75
Chicago:											
Heating	79.80	39.10	26.38	19.70	16.00	13.32	11.18	9.85	8.78	7.98	7.45
Cooling	23.40	11.46	7.72	5.77	4.68	3.90	3.27	2.88	2.57	2.34	2.18
Total	103.20	50.56	34.10	25.47	20.68	17.22	14.45	12.73	11.35	10.32	9.63
Total insulation and operation	103.20	58.01	43.04	35.90	32.60	30.63	29.35	29.12	29.23	29.69	30.49
Duluth:											
Heating	145.00	71.00	47.80	35.80	29.00	24.20	20.30	17.90	15.96	14.50	13.54
Cooling	.78	.38	.26	.19	.16	.13	.11	.10	.09	.08	.07
Total	145.78	71.38	48.06	35.99	29.16	24.33	20.41	18.00	16.05	14.58	13.61
Total insulation and operation	145.78	78.83	57.00	46.42	41.08	37.74	35.31	34.39	33.93	33.95	34.47
Montpelier:											
Total	168.00	82.20	55.30	41.30	33.60	27.90	23.50	20.70	18.47	16.80	15.66
Total insulation and operation	168.00	89.65	64.24	51.73	45.52	41.31	38.40	37.09	36.35	36.17	36.52

Table 2.--Heating and cooling costs per year per **1,000** square feet of ceiling **(even** inches of insulation thickness)

	0	1	2	3	4	5	6	7	8	9	10
	Btu's per hour per square foot per degree Fahrenheit										
U value construction	0.292	0.147	0.099	0.074	0.060	0.050	0.042	0.037	0.033	0.030	0.028
	Dollars										
Cost per year of insulation, 40-year amortization	0	7.45	8.94	10.43	11.92	13.41	14.90	16.39	17.88	19.37	20.86
Energy cost index 41 (2 inches):											
Cost operation	12.30	6.02	4.06	3.03	2.46	2.05	1.72	1.52	1.35	1.23	1.15
Insulation and operation	12.30	13.47	13.00	13.46	14.38	15.46	16.62	17.91	19.23	20.60	22.01
Energy cost index 76 (3 inches):											
Cost operation	22.80	11.17	7.52	5.62	4.56	3.80	3.19	2.81	2.51	2.28	2.13
Insulation and operation	22.80	18.62	16.46	16.05	16.48	17.21	18.09	19.20	20.39	21.65	22.99
Energy cost index 124 (4 inches):											
Cost operation	37.20	18.23	12.28	9.18	7.44	6.20	5.21	4.58	4.09	3.72	3.47
Insulation and operation	37.20	25.68	21.22	19.61	19.36	19.61	20.11	20.97	21.97	23.09	24.33
Energy cost index 165 (5 inches):											
Cost operation	49.50	24.25	16.33	12.20	9.90	8.25	6.92	6.10	5.44	4.95	4.62
Insulation and operation	49.50	31.70	25.27	22.63	21.82	21.66	21.82	22.49	23.32	24.32	25.48
Energy cost index 228 (6 inches):											
Cost operation	68.30	33.50	22.60	16.87	13.70	11.41	9.58	8.43	7.52	6.83	6.38
Insulation and operation	68.30	40.95	31.54	27.30	25.62	24.82	24.48	24.82	25.40	26.20	27.24
Energy cost index 332 (7 inches):											
Cost operation	99.60	48.76	32.83	24.55	19.92	16.60	13.93	12.27	10.94	9.96	9.30
Insulation and operation	99.60	56.21	41.77	34.98	31.84	30.01	28.83	28.66	28.82	29.33	30.16
Energy cost index 427 (8 inches):											
Cost operation	128.00	62.70	42.20	31.60	25.60	21.30	17.90	15.78	14.08	12.80	11.94
Insulation and operation	128.00	70.15	51.14	42.03	37.52	34.71	32.80	32.17	31.96	32.17	32.80

Note: Minimum costs for each energy cost index are underlined to indicate corresponding insulation thickness.

Transmission values for a typical wood-framed wall construction are given in appendix II. These are calculated for an uninsulated wall and with insulation of 1 to 7 inches as listed in tables 3 and 4. Again, minor differences in wall materials would have little effect on the amount of insulation needed, unless such substitutions included such insulating materials as insulation board sheathing, It is important to note that a definite constraint on the thickness of insulation is imposed by the standard stud depth of 3-1/2 inches. To keep comparisons in the same terms, using only batt-type insulation in the stud spaces, any amount of insulation above 3-1/2 inches thick requires deeper studs, such as 2- by 6-inch or 2- by 8-inch. Although somewhat greater spacing between studs can be justified with deeper studs, significant increases in cost do appear here. These include the increased framing costs and an increase in the depth and cost of all window and door frames. These increased costs are added to insulation cost, as noted in appendix 111, and do influence optimum economy. It should be noted, however, that no cost increase is assigned because of the loss in floor area attending a 2-inch increase in stud depth, as no practical method has been found to judge the economic effect of a small decrease in room dimensions in a residence. In many instances, this would have no real effect on the placing of furniture or the use of open spaces; and the common practice of assigning a cost per square-foot value, as in office space, is considered rather arbitrary and inapplicable in residential spaces. Any change in wall thickness, such as would occur with a change to masonry construction, for example, would affect interior area, but this is not normally assigned a value in residential cost comparisons. In individual cases, some allowance may be reasonable for the area factor, but no attempt has been made here to evaluate it for all cases.,

It is thought important to note the effect of the framing members themselves on the overall resistance value of a ceiling or wall construction. Fortunately, wood framing members have a high insulating value, so that heat losses through them, bypassing the insulation, are relatively small. These heat losses have been considered in this study in appendixes I and II, though their effect on average *U* values is small and is often neglected for wood construction. As heat follows the path of least resistance, the major portion of the heat flow will not be through the entire depth of the framing member when some airspace is present. Therefore, a pattern of heat flow as shown in figure 2 has been assumed when insulation is not full depth.,

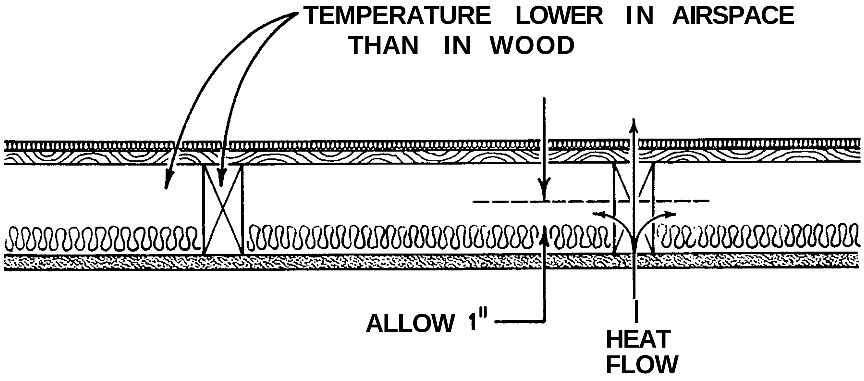

Figure 2.--Assumed heat flow through wood framing members when insulation is not full depth.

Table 3.--Heating and cooling costs per year per 1,000 square feet of wall {various locations)

	0	1	2	3	4	5	6	7
	- - - *Btu's per hour per square foot per degree Fahrenheit* - - -							
U value construction	0.250	0.136	0.093	0.071	0.059	0.051	0.043	0.039
	- - - - - - - - - - - - - - *Dollars* - - - - - - - - - - - - - -							
Cost per year of insulation-- 40-year amortization	0	7.45	8.94	10.43	11.92	13.41	14.90	16.39
Increased construction cost over 2 inches by 4-16 inches center to center	0	0	0	0	5.85	5.85	17.93	17.93
Total construction cost	0	7.45	8.94	10.43	17.77	19.26	32.83	34.32
San Diego:								
Cost heating and cooling	12.10	6.58	4.60	3.44	2.86	2.47	2.08	1.89
Total construction and operation	12.10	14.03	13.54	13.87	20.63	21.73	34.91	36.21
Seattle:								
Cost heating and cooling	52.10	28.30	19.80	14.80	12.30	10.62	8.96	8.12
Total construction and operation	52.10	35.75	28.74	25.23	30.07	29.88	41.79	42.44
St. Louis:								
Cost heating and cooling	58.40	31.80	22.20	16.60	13.80	11.93	10.05	9.12
Total construction and operation	58.40	39.25	31.14	27.03	31.57	31.19	42.88	43.44
Chicago:								
Cost heating and cooling	79.50	43.25	30.20	22.60	18.77	16.23	13.67	12.40
Total construction and operation	79.50	50.70	39.14	33.03	36.54	35.49	46.50	46.72
Duluth:								
Cost heating and cooling	121.20	65.80	46.00	34.40	28.60	24.70	20.80	18.90
Total construction and operation	121.20	73.25	54.94	44.83	46.37	43.96	53.63	53.22
Montpelier:								
Cost heating and cooling	137.70	75.00	52.30	39.10	32.50	28.10	23.70	21.50
Total construction and operation	137.70	82.45	61.24	49.53	50.27	47.36	56.53	55.82
Miami:								
Cost heating and cooling	33.85	18.44	12.86	9.62	8.00	6.91	5.83	5.28
Total construction and operation	33.85	25.89	21.80	20.05	25.77	26.17	38.66	39.60

Table 4.--Heating and cooling costs per year for 1,000 square feet of wall (various insulation thicknesses)

	Insulation thickness (inches)							
	0	1	2	3	4	5	6	7
	- - - Btu's per hour per square foot per degree Fahrenheit- - - -							
U value construction	0.250	0.136	0.093	0.071	0.059	0.051	0.043	0.039
	- - - - - - - - - - - - - - - *Dollars* - - - - - - - - - - - - - - -							
Amortized cost per year insulation	0	7.45	8.94	10.43	11.92	13.41	14.90	16.39
Increased construction cost over 2 inches by 4-16 inches center to center	0	0	0	0	5.85	5.85	17.93	17.93
Total construction cost	0	7.45	8.94	10.43	17.77	19.26	32.83	34.32
Energy cost index 58 (2 inches):								
Cost heating and cooling	14.50	7.89	5.50	4.12	3.42	2.96	2.49	2.26
Operation and insulation	14.50	15.34	14.44	14.55	15.34	16.37	17.39	18.65
Operation, insulation, plus increased construction cost	14.50	15.34	14.44	14.55	21.19	22.22	35.32	36.58
Energy cost index 80 (3 inches):								
Cost heating and cooling	20.00	10.87	7.60	5.67	4.72	4.08	3.44	3.12
Operation and insulation	20.00	18.32	16.54	16.10	16.64	17.49	18.34	19.51
Operation, insulation, plus increased construction cost	20.00	18.32	16.54	16.10	22.37	23.34	36.27	37.44
Energy cost index 123 (3 inches):								
Cost heating and cooling	30.75	16.73	11.68	8.73	7.25	6.27	5.28	4.79
Operation and insulation	30.75	24.18	20.62	19.16	19.17	19.68	20.18	21.18
Operation, insulation, plus increased construction cost	30.75	24.18	20.62	19.16*	25.02	25.53	38.11	39.11
Energy cost index 490 (5 inches):								
Cost heating and cooling	122.50	66.60	46.50	34.80	28.90	25.00	21.07	19.10
Operation and insulation	122.50	74.05	55.44	45.23	40.82	38.41	35.97	35.49
Operation, insulation, plus increased construction cost	122.50	74.05	55.44	45.23	46.67	44.26*	53.93	53.42

Note: Minimum costs for each energy cost index are underlined to indicate corresponding insulation thickness; Asterisks indicate minimum costs are at full 3-1/2-inch or 5-1/2-inch thickness.

When metal framing members are used in an exterior wall, however, they have a very pronounced effect in shunting heat flow around fill-type insulation, so that appreciable reduction in the average resistance value occurs. In cold climates, vertical lines of condensation or frost-can occur. When metal framing members are used in severe climates, any cavity insulation should be supplemented with enough insulation on the outside face of the framing to prevent condensation.

Determining costs

The costs for heating and cooling for a unit area of a construction can be readily calculated from the expressions given in Appendix IV. It should be noted here that this study is concerned primarily with the insulation factor, not with other elements of a building which may contribute substantially to energy requirements. These elements may include windows, air leakage or air change, duct losses, and the heat added by occupants and appliances. Although very important in the entire economy of the heating system, they have no effect on the economical thickness of insulation in wall or ceiling areas. They will be considered as separate factors later,,

The need for heating or cooling varies widely in the United States. Heating is not required in Hawaii, for example; and in the southern parts of Florida and Texas, small unit heaters are used only for short periods. When the degree-day heat requirement is less than 1,000 or so, the economical thickness of insulation for heating may approach zero,, However, in most such cases, there is an appreciable cooling requirement, usually defined by the number of hours annually that temperatures reach or exceed 80" F. The cooling requirement may then control insulation requirements, as is true in Miami (fig. *3)*. Or the cooling requirement may have a large effect on insulation thickness, as in St. Louis (fig. 4). In San Diego (fig. 5) the combined costs of heating and cooling are so low that a small amount of insulation results in optimum total cost, and it can be argued that no added insulation at all is needed in wood-frame construction, since the total cost reduction is very small.

There may be little need for cooling in areas with mild summers, such as Alaska, Northwest coastal areas, and scattered areas at high altitudes. Seattle, for example, has an average of 100 hours per year with temperatures exceeding 80° F. Although the cooling cost per year is very low, the cost of cooling equipment becomes an important element in cost per hour of operation. **A** more economical method of cooling which uses less energy, such as an attic or window fan, may be a better choice here; or an evaporative type cooler, depending entirely on the evaporation of water, works well in arid areas, even when cooling requirements are high. Such a unit requires only enough power for fan operation for air distribution and has a much lower energy requirement than a refrigeration type unit. It does need a reasonable supply of water, sometimes in short supply in arid regions.

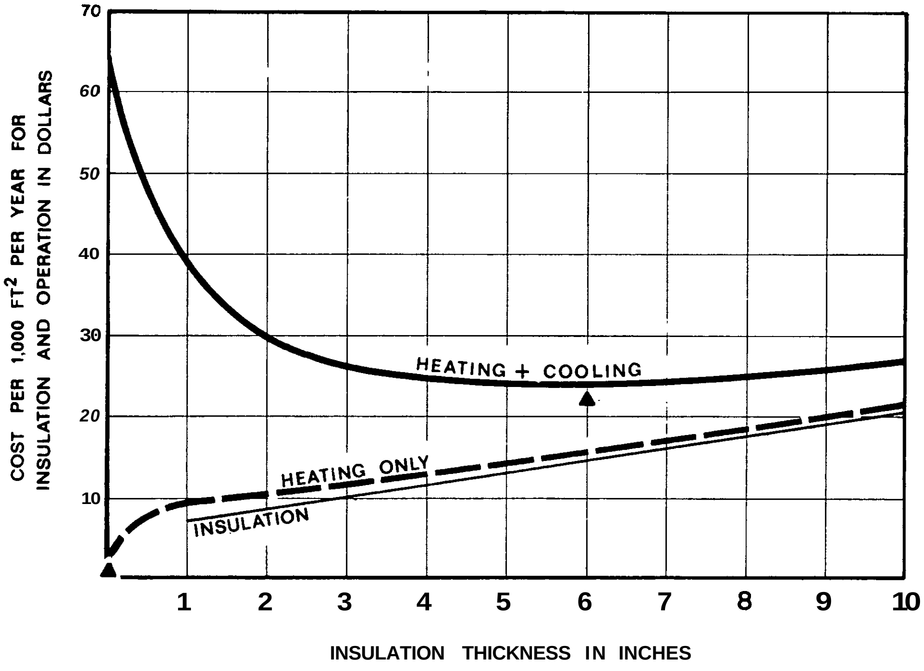

Figure 3.--Roof-ceiling insulation thickness determined principally by cooling cost (Miami).

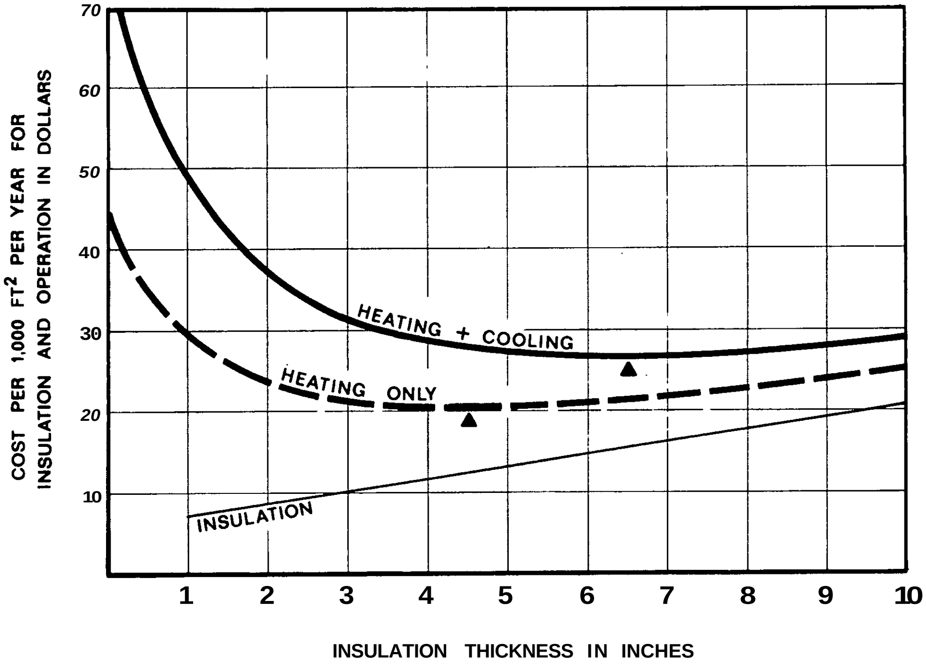

Figure 4.--Roof-ceiling insulation thickness as influenced by cooling cost (St. Louis).

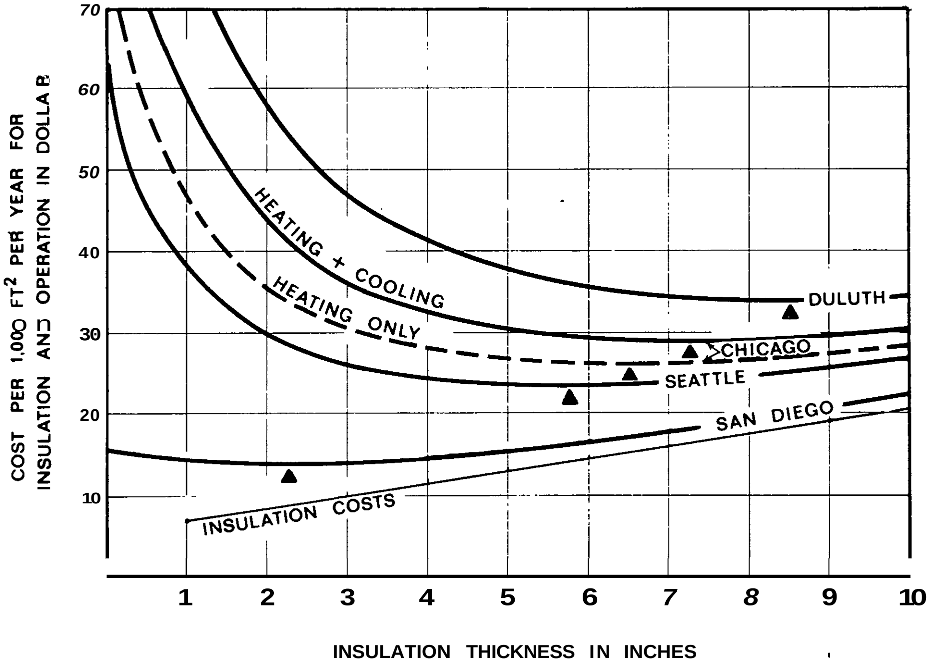

Figure 5.--Optimum roof-ceiling insulation thickness.

The cost of insulation in place, using mineral fiber blankets in the ceiling and batts in wall areas, was calculated with two sources of price data (3, 8). These proved to be a good agreement, indicating a cost of $0.10 per square foot for the first inch, and about $0.02 per square foot for each additional inch, 'These costs are approximate average costs for the 48 contiguous States, with costs in Alaska and Hawaii undoubtedly higher. They are believed to be sufficiently accurate for this study.

When money is invested in a particular material in a home, it usually becomes part of a mortgage, at interest. However, it is of no consequence whether a mortgage actually exists, or what its duration may be. The sum so invested has a value, either in mortgage interest charged or in interest lost on a cash outlay over the entire useful life of the home. This hidden cost is large; and if calculated at a conservative 7 percent per year for 40 years, it has the effect of approximately tripling the original cost. This allowance for amortization is included in the tabulated and plotted costs of insulation, as well as of added stud, window frame, and door frame depths.

Total costs of operation and insulation are tabulated in tables 1 to 4 for all illustrated cost-thickness curves.

Total Cost Curves and Minimums

Cost-thickness curves in figures 3 to 5 for ceilings and figures 6 to 8 for walls are plotted from data in tables 1 and 3, respectively, Figure 5 indicates the optimum cost points on curves for ceiling insulation in four selected cities with varying heating and cooling requirements. Insulation cost is given by the sloping line at bottom, with heating and cooling costs added above to develop the total cost curves. For Chicago, total costs for heating only are indicated by a dotted line, and the addition of cooling increases optimum insulation by three-fourths inch. In Duluth, San Diego, and Seattle, cooling costs have almost no bearing on optimum thickness.

In Miami, though, cooling costs principally determine insulation thickness (fig. 3), and the dotted line indicates no need for insulation for heating alone.

The curves for St. Louis (fig. 4) show a more balanced condition, and the use of cooling would add 2 inches to the optimum insulation requirement for ceilings.

In frame-wall construction, figures 6, 7, and 8 show that generally less insulation is required in walls compared with ceilings. The significant increases in framing costs and frames for openings can be seen in the steps in these curves as the stud depth is increased. For the most part, increases from the standard 2- by 4-inch stud are not economically justified to increase insulation thickness in the continental United States, although a slight advantage is shown for the most severe climate in Montpelier, Vermont, if the loss in floor area is unimportant. San Diego, on the other hand, does not require wall insulation for economic reasons.

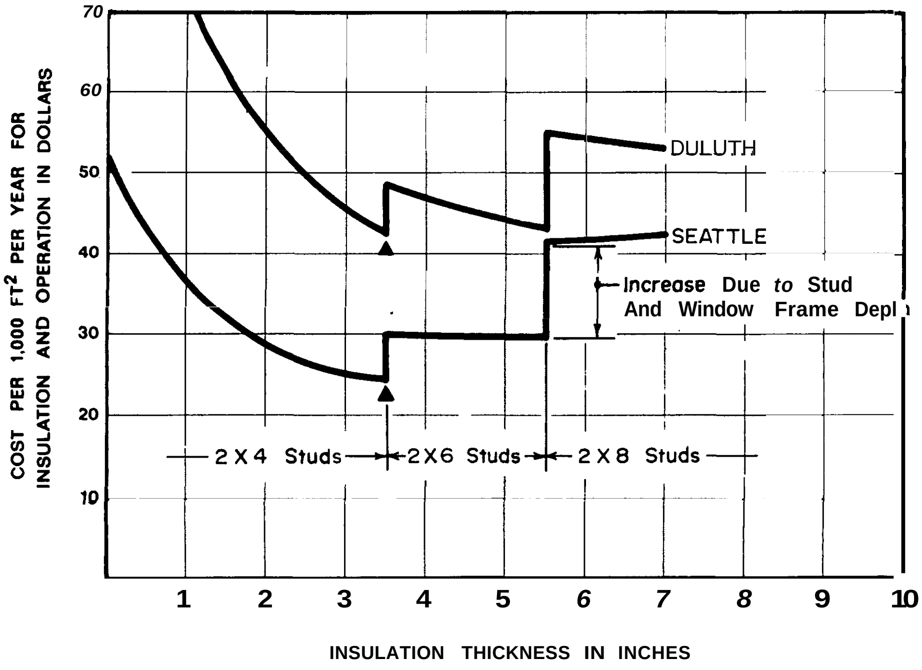

Figure 6.--Optimum thickness in walls.

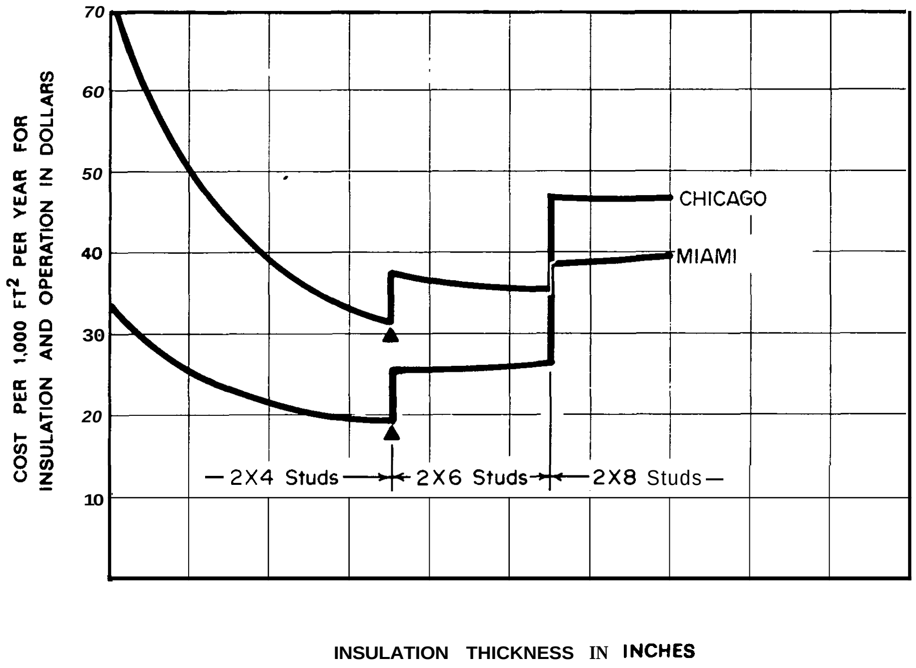

Figure 7.--Optimum thickness in walls.

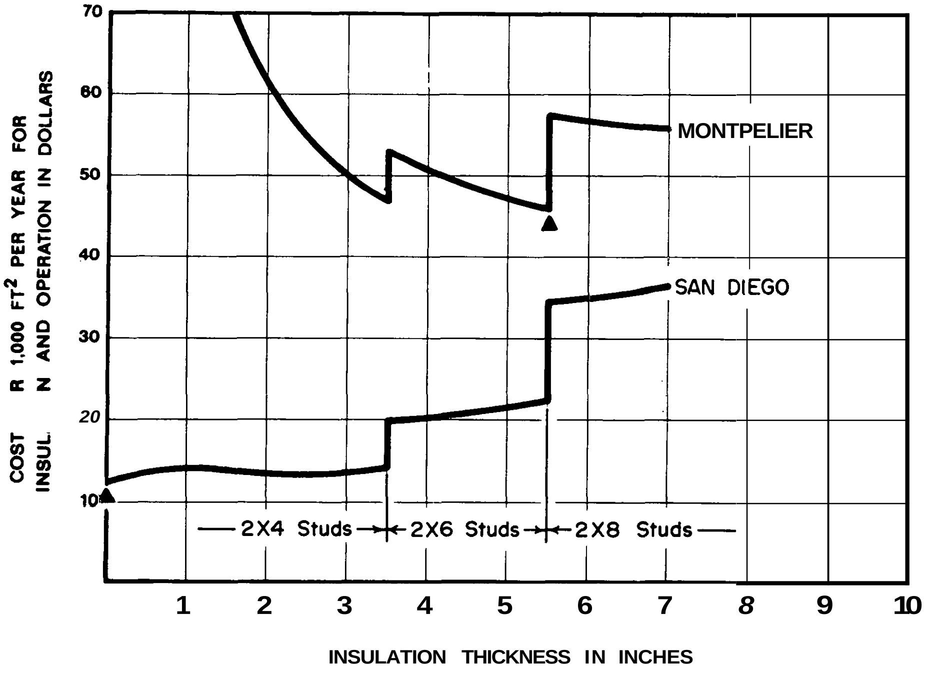

Figure 8.--Range of optimum thickness in walls--continental United States.

The use of 2- by 6-inch studs is not uncommon for the newer residences in many parts of Alaska. They can, in fact, be economically justified in regions with long, cold winters and little sunlight. Also, air change under these conditions is restricted to a minimum, and the moisture generated by humans and by cooking and other activities commonly make interior humidities high. This causes condensation and frosting at the studs, if they are not deep enough to keep the inside face of the wall above the dew point.

Influence of Inflation

Energy costs have increased appreciably since the oil embargo late in 1973. Subsequent increases in well-head costs for crude oil appear to be a continuing influence on our energy costs, and it is evident that our narrowing energy resources will result in gradually increasing costs for energy in all forms. With this outlook, should we not allow for an additional increase in insulation in homes?

Unfortunately, nobody knows how much energy costs may increase'in the next 5 years, much less for the 40-year life of a new home. However, a look at the influence of increased costs on insulation requirements is useful, because balancing factors tend to stabilize the optimum economic thickness.

Figure 9 shows several curves for the thickness of ceiling insulation in St. Louis, based on various assumptions of cost changes. Curve A is the

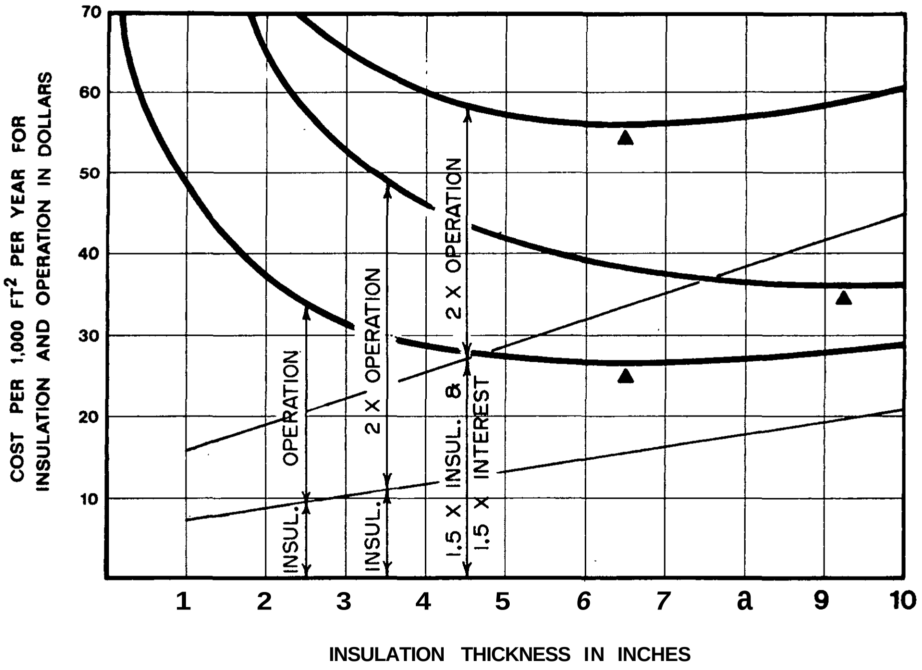

Figure 9.--Optimum roof-ceiling insulation thickness as influenced by inflation (St. Louis).

same as the total cost curve in figure **4,** and the assumption here is one of complete stability of costs for energy, materials, labor, and money (which was assumed at 7-percent interest).

But if energy costs do escalate sharply, what happens to the insulation requirement? Curve B (fig. 9) is plotted on the assumption that energy costs will double over some period of time but that costs of insulation and money remain constant. This produces a marked shift in the point of optimum thickness, adding nearly **3** inches of ceiling insulation.

Of course, energy costs cannot increase in any such magnitude without affecting the costs of all manufactured goods, transporation, services, labor, and money. General inflation accompanies increased energy costs, as at present, and some portion of this inflation is directly attributable to the energy increase. Interest rates depend on the general inflation rate and rise proportionately.

Without pretending to know the future extent of energy costs or accompanying inflation in other costs, an example is shown in curve C (fig. 9) of the balancing effect of increased insulation and financing costs. Here the assumption is that at some future time costs of energy will double and costs for insulation and money will inflate at a lesser rate of 50 percent. This assumption results, coincidentally, in a return to about the same optimum thickness as in curve **A,** though at a higher cost level. Actually, although energy costs have doubled here, the amortized cost of insulation compounded has more than doubled, and a 50-percent increase in insulation cost and in interest rate (10-1/2 percent) results in a much larger total increase. **A** larger proportionate increase in amortized insulation cost as related to energy cost would, of course, reduce optimum insulation thickness; but this is not thought to be likely in the near future.

Our experience indicates that some degree of inflation will always be with us, and recent estimates of our energy resources strongly suggest that increases in energy costs in the future will exceed other inflationary factors. However, we need to consider the balancing effect of increases in other materials and in money, as illustrated in curve C (fig. 9). It is my opinion, therefore, that large increases in insulation thickness should not be provided in anticipation of increased energy costs. The cost-thickness curves characteristically are quite flat at the optimum cost point, and a change of an inch or more in thickness produces a very small change in total cost. Thus, some latitude exists in the choice of thickness, **Also,** an imbalance in inflationary trends will tend to stabilize optimum insulation thickness.

A reasonable approach, considering the foregoing factors, might be to choose insulation thickness to the next higher even inch above the apparent optimum, but judgment should be based on the particular conditions,

An Approximate Method of Estimating Local Energy Costs

We have' considered some examples of optimum insulation thickness in various cities across the country. Let us now see how this analysis may be applied closer to home, in any selected area and in a simplified form.

For total cost of operation for heating and cooling for 1,000 square feet of ceiling or wall per year, the U[3] value of the construction is multiplied by the sum of local heating and cooling costs. If we regard this sum as an energy cost index ***(Ce)*** for the local area, then the total cost of operation for any given U value is equal to U ***Ce.*** It is useful to consider this quantity or cost index as an entity, as it contains all the factors that may vary with location. **A** simple expression from which this local cost index may be determined can be derived from the expressions given in appendix IV, thus:

$$Ce = 0.36\, D\, C_t\, t\, 0.146\, A_T\, CH\, C_k$$

where

Ce = energy cost index
D = degree-days in heating season
C_t = cost of natural gas in dollars per therm
Δ_t = design equivalent sol-air temperature difference, degrees Fahrenheit
CH = summer cooling hours per year
C_k = cost of electricity in dollars per kilowatt-hour

This simplification applies only to natural gas heating and electric cooling, and assumes operating efficiencies for the gas heater of 0. 67 and for the cooling unit of 2.0

The above expression, however, contains an element which may not be readily obtainable by a local owner or contractor. This is the quantity Δ_T, the design equivalent temperature difference, which takes into consideration the radiant effect of the sun on surfaces in the summer. This solar heat gain increases outside design temperatures considerably when the sun is shining, and its effect varies with location and the nature of the surface. The American Society of Heating, Refrigerating and Air Conditioning Engineers Handbook (1) lists these design equivalent temperatures in chapter 22, table 50, and explains their selection. Without this information, however, an intermediate value can be assumed with reasonable accuracy for residential design in most areas, Reasonable accuracy here means that optimum insulation thickness will be in error less than 1 inch plus or minus, even in areas of high cooling requirements such as Miami or Hawaii. However, for final

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[3] Defined on page 6.

design decisions in such hot and dry areas as Arizona, a competent professional should be consulted. If intermediate values of design equivalent temperatures of 38.0° F for ceilings and 20. 5" F for walls are assumed, these approximate expressions for the energy cost index result:

Ceilings: $Ce = 0.36 D C_t t (5.5 CH C_k)$

Walls: $Ce = 0.36 D C_t t (3.0 CH C_k)$

The above formulas are for natural gas heating and electric cooling, as before. For No. 2 oil heating and electric cooling, they would become:

Ceilings: $Ce = 0.256 D C_g + (5.5 CH C_k)$

Walls: $Ce = 0.256 D C_g + (3.0 CH C_k)$

where: C_9 = cost of heating oil in dollars per gallon.

The portion of the formulas in parentheses is the cooling cost index and, if no cooling is needed, may be omitted. With the assumed value of the design equivalent temperature, all elements of these expressions needed for estimating Ce may be obtained locally from utilities, oil dealers, or any competent heating and ventilating contractor.

Determining Optimum Insulation Thickness

Figure 10 contains a family of curves, based on the energy cost index, which covers the range of this index in the continental United States, These curves are for roof-ceiling construction and represent the energy cost indexes which correspond to inches of insulation thickness. Figure 11 is similar for walls, except that the cost indexes correspond to inches up to 3 inches, and actual stud depths of 3-1/2 and 5-1/2 inches. It should be kept in mind that insulation and other construction costs used in these illustrations are at 1973 levels which are believed not to have increased sufficiently to significantly alter the total cost curves at this writing. Energy costs used, however, are at 1971 levels and have increased in varying amounts in different areas. Fortunately, energy cost increases will automatically be reflected in the energy cost index, as locally computed, so that the curves remain valid but the energy cost index may increase. For example, a cost index for roof-ceiling construction in figure 10 computed at 228 for 6 inches of insulation might increase to 280 and indicate an optimum thickness of about 6-1/2 inches,

An example may help clarify how the energy cost index is calculated and used with the cost index curves to determine approximate insulation thickness. St. Louis has a high heating requirement along with a fairly high cooling requirement and provides a check on this simplified method of design when compared with the curve in figure 4, which was previously plotted by the longer method. St. Louis has an average degree-day heating requirement of 5,000 at a cost for natural gas of 0.0832 per therm. Summer cooling hours

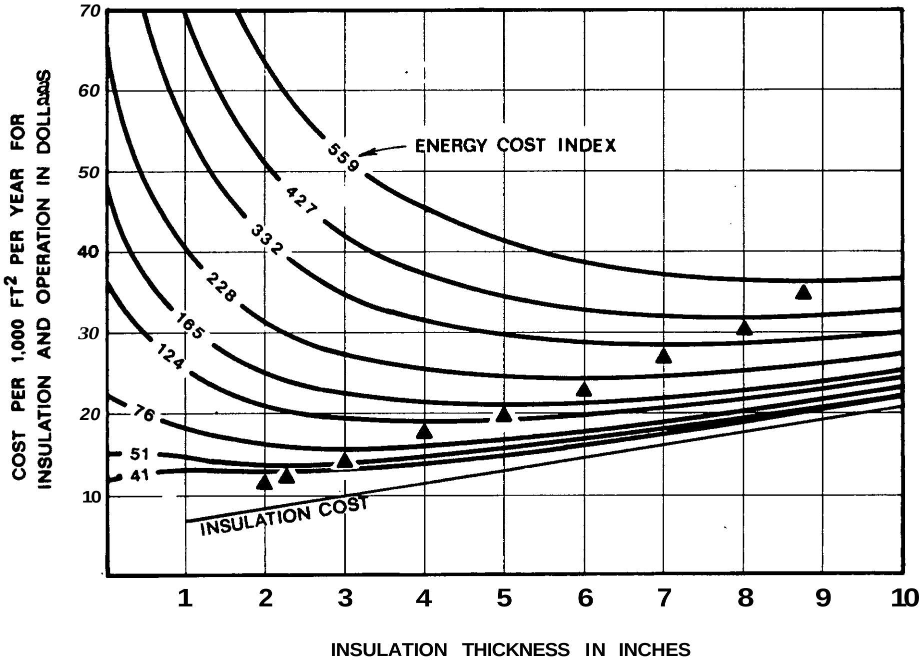

Figure 10.--Range of optimum roof-ceiling insulation thickness--continental United States.

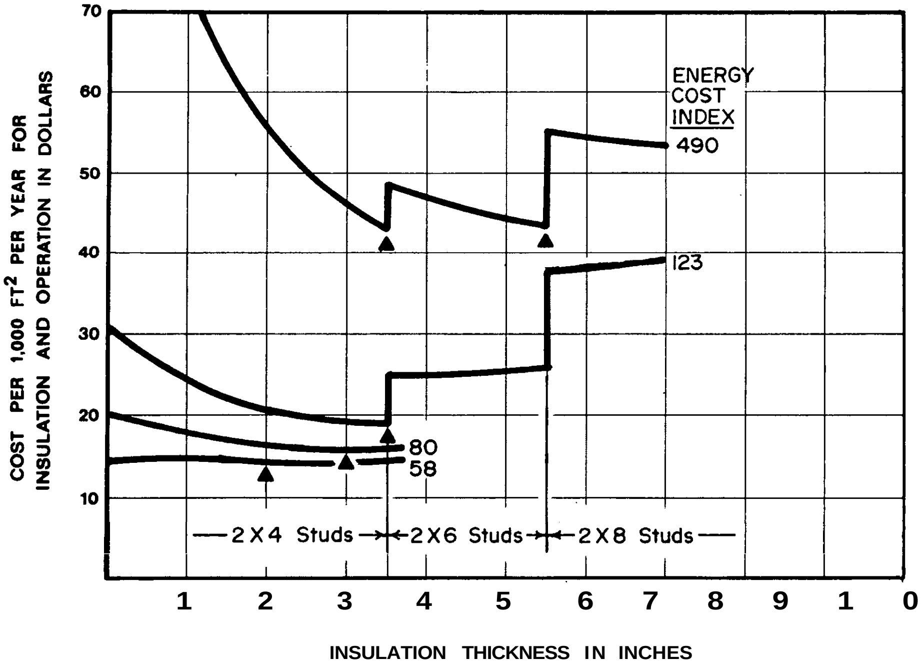

Figure 11.--Range of optimum wall insulation thickness--continental United States.

over 80" F are 1,150, and the cost of electric power is \$0. 0214 per kilowatt-hour. To obtain the energy cost index for a roof-ceiling construction, these values are substituted in the approximate formula for gas heat and electric cooling:

$$
\begin{aligned}
Ce &= (0.36)\,(5{,}000)\,(0.0832)\ \mathbf{t}\ (5.5)\,(1{,}150)\,(0.0214) \\
&= 150\mathrm{t}\ 135 \\
&= 285
\end{aligned}
$$

The cost index of 285 may then be interpolated between the curves for 228 and 332 in figure 10, and the imaginary curve about halfway between those shown would have a minimum total cost point at about 6-1/2 inches of insulation. This checks with the total cost curve in figure 4 and is the optimum insulation thickness for ceiling insulation in St. Louis. This may be increased to 7 inches to provide for future increases in energy cost.

Similarly, optimum thickness of insulation in any area can be determined by computing the energy cost index for the area and comparing it with curves in figures 10 or 11, for ceiling or wall insulation, respectively.

However, it is important to be aware of the limitations on accuracy of the method imposed by inflationary changes. Although energy cost index ***(Ce)***, as locally determined, will reflect energy costs at the time, there is no way to predict insulation cost increases. Therefore, the balancing effect of this factor is lost, and energy cost increases of 100 percent may indicate unreal thicknesses of insulation when applied to figures 10 and 11. For example, the cost of heating oil has doubled in the Seattle area in a little over a year. This nearly doubles the energy cost index for oil heat, since cooling is not an important element. A recalculation of the index will indicate an optimum thickness of insulation in the ceiling of 8 inches, with thickness in the walls remaining at 3-1/2 inches because of the extra costs attending an increase in wall thickness. This increase in the cost of heating oil is general in other areas and will operate to make an increase in insulation thickness economical in most northern areas. Costs of natural gas and electricity have increased at a lesser rate initially, and the increases vary in different areas, but it appears likely that they will eventually parallel increases in oil costs.

In some northern 'areas, energy cost increases may result in an energy cost index higher than the maximum curves shown in figures 10 and 11. When this occurs, I suggest maximum insulation thicknesses which do not incur increases in the framing; that is, 7-1/2 inches for ceilings and 3-1/2 inches for walls. This will result in a thickness very close to optimum in the continental United States and will avoid changes in the framing.

A Comparison of Design Methods

The foregoing method of selecting insulation thickness in a wood-framed home, based on optimum economy, generally results in a greater insulation requirement than methods previously in use. This can be seen in table 5, which compares the minimum thickness of ceiling insulation as determined by several criteria. The method using the difference between air temperature and inside surface temperature gives very inadequate thicknesses for the various locations, although a temperature difference of only 4" F was used here for a relatively high degree of comfort. The Industry All-Weather Comfort Standard results in a range of choices, obviously leaving this judgment to the local designer; but the high end of the range does not result in good economy in most areas. Only the new FHA Minimum Property Standards give reasonable economic thicknesses, though the accuracy of these standards is variable in different locations.

Table 5.--Minimum insulation thickness for a wood-framed ceiling construction under various criteria

(Inches)

Location	San Diego	Seattle	St. Louis	Duluth
Minimum comfort criteria, based on allowable ceiling temperature	1	1	2	3
Industry All-Weather Comfort Standard, National Forest Products Association	2-3	2-3	2-3	3-5
Federal Housing Administration Minimum Property Standards, 1974, new construction	3	5	5	6
Optimum economy (to next higher full inch)	3	6	7	9

Other Sources of Heat Loss

Heat loss and heat gain in a typical, uninsulated wood-framed house are not limited to that passing through wall and ceiling construction's, though the latter may amount to some 50 to 60 percent of total loss or gain. Other sources of loss include floor or ground, windows and doors, ventilators or cracks, and miscellaneous,. such as may occur from ducts, chimneys, and water pipes. The relative percentage of loss occurring from each source, of course, will vary with areas involved and their insulation or sealing.

This study is principally concerned with the insulation of wall and ceiling areas, where optimum conditions of economy in typical constructions are possible. Other sources of loss are generally more difficult to analyze on a typical basis, as they may vary rather widely in individual cases and require local judgments. However, some discussion of these losses may emphasize their importance and guide the builder in their economical treatment.

GROUND LOSSES AND CRAWL SPACES

Several types of construction are used below the first floor of a home, either because of local practice or specific design advantages. With a full or partial basement, minimal heat losses to the basement occur in most climates, and the basement is warmed sufficiently for occasional use for laundry, workshop or storage,' and to protect water pipes in extreme weather. Such a nominally unheated basement does not require insulation in the first floor. However, when the basement is designed for normal occupancy, floor and wall insulation may be required in the basement itself for economical heating. Heat transfer through basement floors and walls depends on their construction, ground temperatures at their outside surfaces, and the heat conductivity of the ground. The latter two factors are variable and may be unknown, and engineering assumptions based on local practice are usually necessary. Lower average wall temperatures in winter will normally require more insulation for walls than for floors. Because the temperature differences between outside and inside surfaces may not be accurately known over the heating season and because insulation costs are generally higher for masonry constructions, a determination of optimum amount is not practical. The objective for masonry walls should be to limit inside surface temperatures to comfort levels.

For concrete floor slabs in contact with the ground, experiments indicate that heat losses occur principally at the edges of the slabs and are negligible in interior areas. Therefore, insulation of the perimeter of the slab is sufficient to reduce heat loss to an economical level. In colder climates, as much as 2 inches of rigid insulation may be used around the perimeter, extending from the top of the slab, down the foundation, and under the slab about 2 feet. An alternate method used in milder climates is to place the insulation vertically on the 'outside of the foundation, extending from the top of the foundation to a point 6 inches below grade, using perhaps 1-inch thickness. Insulation placed in or on the ground in this manner must be waterproof, such as foamed plastic or glass board which does not absorb water. Slabs on the ground may usually be made comfortable enough for children's play by using 4 to 6 inches of gravel under the floor--also desired for moisture control-Lor by such floor surfaces as wood or thick pads and carpets. None of these measures may be needed, however, in milder southern climates where these slabs are most common.

Crawl space construction typically uses floor joists, supported by foundations and interior beams and posts, over a shallow excavation sufficient for access to heating ducts and pipes. A crawl space may be vented to the exterior the year around for moisture control, if ground moisture conditions are severe. However, control of ground moisture is usually possible with a ground cover of polyethylene sheet or roofing felts, so that the ventilating apertures in the outside wall may be closed off during the heating season.

When a closed crawl space can be used, insulation is not used in the floor, and ducts and hot-water pipes need not be insulated,, Small amounts of heat from these sources keep the crawl space reasonably warm in mild winter climates and protect other piping. In severe winter climates, insulation may be needed; this is usually placed vertically on the inside of the foundation walls to limit heat loss. Again, plotting an optimum thickness for typical conditions is not possible, as average ground temperature, the proportion of the wall above grade, and kind of insulation will vary. The University of Illinois Small Homes Council (*10*) recommends 1 inch of foamed plastic or glass fiberboard for climates with an average outside air minimum temperature of -10" F or higher, with greater thickness desired for lower minimum temperature. A greater thickness may well be used to pack the header blocks at the ends of the joists to a depth equal to the optimum wall insulation thickness for the region.

When ground moisture conditions are severe, a crawl space may have to be vented continuously to control humidity and protect the structure. A ground cover can become ineffective if liquid water runs under it and through the laps; it then becomes a liability by retaining pools of water on the top as ground water recedes. Under these conditions, maximum ventilation is desired, and temperatures within the crawl space may approach that of the outside air.

In cold areas, water pipes should be insulated to prevent freezing, and heating ducts to limit heat loss. For comfortable floors and limited loss of heat from the area above, insulation in the floor structure is required. This is usually placed between the floor joists in the form of batts or blankets. In a new house, batts may be placed from above before the subfloor is laid, stapling flanges to the joists much as is done in walls. In existing construction, blankets may be placed from the crawl space, taking care that the moisture-barrier is up, and retained in place by spring clips, chicken wire, or other moisture resistant material nailed to the bottom of the joists.

Heat losses through a floor are not as great as losses through a ceiling, because the average inside-outside temperature difference is less. Average crawl space temperatures are moderated by ground temperature when there is little wind for ventilation and there is no solar load to provide for in summer cooling. Hence, insulation thickness in fully ventilated floors may be somewhat less than that of ceilings,, For new construction where insulation cost would be about the same in each case, I recommend use of optimum ceiling thickness for the climate, less 2 inches. This will result in a thickness close to the optimum for average open crawl space conditions.

STORM WINDOWS AND DOORS

Windows and doors account for a very high percentage of heat loss in a typical residence, which may be as much as 30 percent of the total heating and cooling load, The single-pane window is a particular problem, with very low resistance to the flow of heat through the glass and high transparency to radiant heat from the sun.

Windows, however, offer important amenities which outweigh problems of thermal control, furnishing daylight, ventilation, and an outward view. Windowless buildings have been designed and built but are not successful when continuous human occupancy is involved,, Most building codes require that glass areas be at least 10 percent of floor areas, and the University of Illinois Small Homes Council recommends glass areas of at least 20 percent of floor areas (9).

Thermal problems related to windows may be greatly reduced by good design. Orientation to reduce solar loads is an important factor. If principal window areas face south, greater control of solar heat can be achieved by overhangs or solar shades which permit the entry of low winter rays but shade the window from the high summer sun. East and west windows are more difficult to shade in summer because of the sun's lower inclination, and loads are higher. Although drapes or venetian blinds may be used, these limit outward view and natural lighting. North windows take no advantage of winter sunlight, though they may be preferred in very hot climates to limit summer heating by radiation.

Horizontal windows high in the wall are often easier to shade than vertical windows extending lower, Moreover, they give better light from the sky with greater privacyand allow greater freedom in the placement of furniture.

Trees may be an important means of shading openings. Deciduous trees, in particular, have the advantage of shading in summer while allowing warming by the sun's rays in winter.

FHA Minimum Property Standards require that windows and doors in climates with more than 4,500 degree-days in the heating season be protected by double glazed units or storm windows and doors. This standard is reasonable in limiting energy use and in improving comfort as it is affected by radiation losses. Double glazed windows and doors or double doors of other material may reduce heat losses through openings some 40 percent. They do not, however, give optimum economy as these units do not fully recover their amortized cost in the 40-year useful life of a home in most areas of the United States.

For example, if the cost per square foot per year of a storm window, amortized as before, is compared with heating and cooling cost savings in Chicago, the cost of the window is not fully recovered in heat saved over a 40-year period. If a 3- by 5-foot storm window costs $40 and has about 15 square feet of glass area, this comes to $2.67 per square foot for the installation, amortizes to $8.01 at 7 percent, and gives a cost per year of $0.20 per square foot over 40 years. Energy savings for heating and air conditioning, determined by the difference in energy cost between the single window and the double sash, yields only $0.171 per square foot per year (see appendix V). Thus, about 47 years would be required to fully recover the storm window's cost.

It is important to note here, however, that the investment is by no means necessarily a bad one, It will effect a more comfortable interior environment, both in reduced radiant heat losses from the body during extremely cold outside weather and in increased acoustical privacy. It does this at a very small price, since most of the investment is returned in energy cost savings in 40 years, and it represents good energy conservation at the same small price. Also, inflation in energy costs may well greatly exceed inflation in other costs, a contingency that would improve the economy of the units.

Chicago has, of course, a rather severe climate with average heating degree days of 6,600. The example indicates an economic break-even point of some 7,500 degree-days for storm windows, but some north-central locations have as high as 10,000 degree-days, where the storm windows would pay for themselves in less than 40 years at current prices.

Similar cost comparisons can be shown for storm doors. Costs for sealed double glass windows and doors are generally higher than for single units plus storm sash, and the energy savings are about the same. However, the double glass units do offer greater convenience, as there is no interference with the unit's ventilating function and only two surfaces require cleaning. In new construction, particularly, they merit consideration because of these conveniences.,

Reflective glass has been used for some years in air-conditioned commercial buildings to reduce solar heat gain. It can be obtained in single glass or sealed double glass units and deserves consideration in areas of high solar load.

AIR CHANGE AND INFILTRATION

Air leakage may account for very significant energy losses in a home. This usually occurs as infiltration around window and door units or leakage between the frames and wall surfaces and, of course, as doors are opened for entry or egress or windows are opened for ventilation. Other ventilating units, such as air conditioning systems, provide for variable amounts of air change, as do kitchen or bathroom fan ventilators when in use. Cumulatively, these and other miscellaneous sources of leakage provide the air change necessary for health and for combustion of stoves or furnaces, but they usually do so at an unnecessary and excessive rate, wasting energy in the process.

Excessive ventilation by careless use of doors or windows is an obvious source of waste. Cracks around poorly fitted window sash or doors are major causes of unwanted heat loss or gain, particularly in older homes inadequately weatherstripped, or perhaps poorly adjusted or warped.

Permanent, metal or plastic channel weatherstripping of windows and doors is an economical device for reduction of the considerable energy lost through these cracks. It may often be installed by the homeowner and pays for itself in energy cost savings in a few years in most climates. Storm windows and doors reduce crack losses even when weatherstripping is not used, but additional reductions can be made by weatherstripping the inside unit. The storm unit should be less tightly fitted, since some ventilation to the outside is desired to limit condensation between the units. Crack losses can be reduced further if inside windows are kept locked, for the locking devices usually operate to pull sliding sash together or to tighten swinging sash to the frames.

MISCELLANEOUS LOSSES

Energy losses from ducts, pipes, and chimneys can be significant when they are inadequately insulated or sealed.

Hot or cold air ducts and returns which pass through unheated attics or open crawl spaces should be insulated with the equivalent of at least 1 inch of air-cell asbestos. Greater thickness is justified in extreme climates where the inside-outside temperature difference is large, and a 2-inch wrapping of mineral wool is common in northern locations. Steam and hot water pipes should be similarly covered when they pass through unheated spaces. In basements, ducts and pipes are frequently left uninsulated so that they contribute some heat to the basement area, but'insulating cold water pipes to prevent dripping from condensation in the summer is desirable.

When heating ducts or radiant heating pipes or wires are incorporated in concrete slabs on the ground, the entire slab should be insulated from the outside walls and the ground, with moisture-proof insulation. When warm air perimeter ducts are used, it is satisfactory to limit the insulated area to the perimeter of the slab under the ducts, using at least 2 inches of insulation extending from the top of the slab, down the outside wall, and 24 inches under the ducts and slab.

Modern open fireplaces, commonly regarded as heating units, are insidious heat wasters. They are very inefficient, delivering little more than 10 percent of the energy generated to a room while pouring the larger portion of the heat up the chimney. Used in a home heated by other means, they draw much of the heated air from other parts of the house, reducing the effectiveness of the principal heater. They have a necessary function in places where other heating units may not be available and ample supplies of firewood exist, and they can be designed and located to yield a larger portion of their heat to a living area. In mild climates, they may also be a handy, occasional heat source when operation of a central heat source is not needed.

The fireplace today is a sentimental segment of tradition, emanating a cheerful, pleasant warmth to the family circle, while providing visual interest, lively sounds, and a pleasing aroma. These values cannot be measured in economic terms, and reasonable use of the fireplace is an individual choice. Moreover, it can be used as an indoor barbecue and is an excellent ventilator when large numbers of people are present.

Occasional use of the fireplace is least wasteful of heat when the room can be closed off from the rest of the dwelling to avoid drain on the central heater. A window may be opened a crack to provide draft within the room. If the fire is started sometime during the day or late afternoon and can be allowed to burn down early in the evening, it may be completely extinguished so the damper may be closed for the night. The damper should not be closed while any coals remain and very often is allowed to remain open all night to draw heat from the entire house. The fireplace damper should fit tightly, must be properly balanced so that the wind cannot open it, and should be kept closed when the fireplace is not in use. If a persistent draft is evident when the damper is closed, the fireplace opening may be closed off with a piece of plywood or other building board.

Conclusion

In summary, a lifetime cost analysis may be used in estimating insulation requirements in a wood-framed house. A simplified method of doing so for the principal wall and ceiling areas of a conventional home has been presented. This kind of analysis results in the 'best total economy for the homeowner and in maximum practical conservation of the energy used for heating and cooling. Increasing energy costs tend to demand greater amounts of insulation in buildings of all kinds, and all other sources of heat loss must be reexamined in terms of economy and minimum waste.

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APPENDIXES

Appendix I

I. Heat transmission values used for roof-ceiling construction

No insulation:

Construction	R value between rafters	R value at rafters
Outside surface (7.5-mi/h wind)	0.25	0.25
Asphalt shingles	.44	.44
Felt	.06	.06
1/2-inch plywood deck	.63	.63
Attic airspace	.90	.90
1/2-inch gypsum board ceiling	.45	.45
Inside surface (still air)	.61	.61
1-inch wood depth at rafter		1.25
Total R	3.34	4.59
U values = $\frac{1}{R}$ =	0.299	0.217

Rafters 24 inches o.c. (on center) cover 8 percent of ceiling area, and average U value is:

$$\frac{(0.299 \times 92) + (0.217 \times 8)}{100} = 0.292$$

*4-inch-thick insulation (example):

Total R construction	3.34	3.34
Add R 4-inch insulation	14.80	
Add R 5-inch-depth wood		6.25
Total R	18.14	9.59
U values = $\frac{1}{R}$ -	0.055	0.105

$$\text{Average } U = \frac{(0.055 \times 92) + (0.105 \times 8)}{100} = 0.060$$

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*An average K value for mineral wool products of 0.27 (Btu's per hour per square foot per degree Fahrenheit temperature difference) has been assumed. This is equivalent to an R value of 3.70 for each inch thickness of insulation.

Appendix II

11. Heat transmission values used for wall construction

No insulation:

Construction	R value between studs	R value at studs
Outside surface (7.5-mi/h wind)	0.25	0.25
1/2-inch x 8-inch lapped siding	.81	.81
Building paper	.06	.06
1/2-inch plywood sheathing	.67	.67
3-1/2-inch airspace	.97	.97
Vapor barrier	0	0
1/2-inch gypsum board	.45	.45
Inside surface (still air)	.68	.68
1-inch wood depth at stud		1.25
Total R	3.89	5.14
U values = $\frac{1}{R}$ =	0.26	0.20

Studs 16 inches o.c. cover 10 percent of wall area, and average U value is:

$$\frac{(0.26 \times 90) + (0.20 \times 10)}{100} = 0.25$$

*2-inch-thick insulation (example):

Total R construction	3.89	3.89
Add R 2-inch insulation	7.40	
Add R 3-inch-depth wood		3.75
Total R	11.29	7.64
U values = $\frac{1}{R}$ =	0.089	0.131

$$\text{Average } U = \frac{(0.089 \times 90) + (0.131 \times 10)}{100} = 0.093$$

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*An average K value for mineral wool products of 0.27 (Btu's per hour per square foot per degree Fahrenheit temperature difference) has been assumed. This is equivalent to an R value of 3.70 for each inch thickness of insulation.

Appendix III

111. Increased costs for stud depths greater than 3-1/2 inches

Cost increases were estimated using references 3 and 8 for the increased framing cost for 2- by 6-inch and 2- by 8-inch studs, on 24-inch centers, and for 2-inch increments in window and door frame depths, assuming an average amount of fenestration. Increases shown in tables 3 and 4 were:

	2-inch by 6-inch	2-inch by 8-inch
	[Dollars)	
Increased cost of stud framing per 1,000 square feet per year	1.05	8.33
Increased cost of window and door frames per 1,000 square feet per year	4.80	9.60
Total construction increase	5.85	17.93

Appendix IV

IV. Costs for heating and cooling

Cost of heating (natural gas) per year per thousand square feet:

$$\text{cost} = U \times \frac{D \times C_t \times 24 \times 1{,}000}{100{,}000 \times E_g}$$

For No. 2 oil heating:

$$\text{cost} = U \times \frac{D \times C_g \times 24 \times 1{,}000}{140{,}000 \times E_o}$$

For electric cooling:

$$\text{cost} = U \times \frac{CH \times C_k \times \Delta_T \times 1{,}000}{3{,}413 \times E_e}$$

Symbols used above are:

U = coefficient of heat transfer of construction (Btu's per h per ft^2 per degree Fahrenheit temperature difference)

D = winter degree-days per year

CH = summer cooling hours per year

C_t = cost per therm of natural gas (dollars)

C_g = cost per gallon of No. 2 oil (dollars)

C_k = cost per kilowatt-hour of electricity (dollars)

Δ_T = equivalent sol-air temperature difference (degrees Fahrenheit)

E_g = efficiency of gas burner (0.67 assumed)

E_o = efficiency of oil burner (0.67 assumed)

E_e = efficiency of electric cooling unit (2.0 assumed)

Equivalents:

1 therm - 100,000 Btu's
1 gallon oil = 140,000 Btu's
1 kilowatt = 3,413 Btu's

Appendix V

V. Energy cost savings in Chicago from addition of storm windows (for this example, a window facing west is assumed, with roller shade half drawn)

<u>Single window</u>:

Heating cost per square foot per year =

$$U \times \frac{D \times C_t \times 24}{100{,}000\ E_g} = 1.13 \times \frac{6{,}600 \times 0.1123 \times 24}{100{,}000 \times 0.67} = \$0.30$$

Cooling cost per square foot per year =

$$D_s{}^* \times \frac{CH \times C_k}{3{,}413 \times 2.0} = 65 \times \frac{750 \times 0.0199}{3{,}413 \times 2.0} = 0.142$$

Total energy cost per square foot per year =

0.30 + 0.142 = $0.442

<u>Window with storm sash</u>:

Heating cost per square foot per year =

$$0.56 \times \frac{6{,}600 \times 0.1123 \times 24}{100{,}000 \times 0.67} = \$0.149$$

Cooling cost per square foot per year =

$$0.56 \times \frac{750 \times 0.0199}{3{,}413 \times 2.0} = \$0.122$$

Total energy cost per square foot per year =

0.149 + 0.122 = $0.271 .

Energy cost saving per square foot per year =

0.442 - 0.271 = $0.171

Number of years required to amortize cost of storm window = $\frac{8.01}{0.171}$ 47

$^*D_s$ = design solar and conduction heat gain through windows. See "Handbook of Fundamentals" (*I*, chapter 22, table 51).

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