NATIONAL BUREAU OF STANDARDS

BUILDING SCIENCE SERIES 64

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards
in cooperation with
FEDERAL ENERGY ADMINISTRATION/Energy Conservation and Environment

Retrofitting Existing Housing For Energy Conservation: An Economic Analysis

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Foreword

This study is a product of the continuing economic research being sponsored by the Office of Energy Conservation at the National Bureau of Standards in cooperation with the Federal Energy Administration. The study is significant in that it provides a methodology for determining economically optimal levels of investment in energy conservation for reducing energy use in residential space heating and cooling.

Economists, architects, home builders, planners and others will find in the conclusions which are drawn from the model, derived from basic principles of economics, proof that more investment in thermal improvements for both existing and new buildings makes good sense in terms of long term energy <u>and</u> dollar savings.

In view of its technical nature, this study is not intended to be a homeowner's guide to improvements for energy savings. It is the technical foundation for a consumers pamphlet, which is being published in conjunction with this study. The pamphlet is available from the National Bureau of Standards and the Federal Energy Administration.

R.W. Sant, Assistant Administrator Federal Energy Administration	R.W. Roberts, Director National Bureau of Standards

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CONTENTS

FIGURES

TABLES

Cover: The Bowman House, on the National Bureau of Standards' campus at Gaithersburg, MD, is used in the experimental validation of energy savings achieved by retrofitting an existing residence.

EXECUTIVE SUMMARY

Rising real energy prices serve as an incentive for energy consumers to become energy conservers. Energy conservation does not imply a life style of austerity, however, but rather a more effective utilization of energy resources. This is especially true in the case of space heating and cooling operations in residential buildings. Increased resistance to heat transfer in the building envelope, as well as a more efficient heating, ventilating, and air conditioning (HVAC) system, are direct and nearly perfect substitutes for energy consumption.

However, most of the nation's stock of housing units were constructed in a period of relatively low energy costs, lower HVAC requirements, and in a building market where first costs dominated design decisions. As a result, these buildings use considerably more energy than newer buildings designed to reflect higher energy costs and to minimize present-value life-cycle HVAC costs. Still, many energy conservation techniques (ECT's) which increase energy efficiency in new housing can be retrofitted into existing housing with a considerable savings potential in life-cycle HVAC costs. Homeowners in general are aware of many of these techniques, such as insulation, storm windows and doors, and weather stripping. However, opinions differ as to the extent to which these ECT's should be utilized. In general the homeowner is not able to cope with the complex thermal engineering and economic analysis necessary to determine the optimal size or allocation of an energy conservation budget for his own home.

The purpose of this Building Science Series report is to formulate an economic model, with thermal engineering input, to determine systematically that combination of ECT's which will maximize the potential present-value dollar savings in HVAC operations for existing housing, subject to varying climatic conditions, energy costs, and ECT costs. This model is then utilized to demonstrate the effect of climatic conditions and fuel prices on the optimal level of application of certain ECT's given prevailing ECT costs. The actual ECT's to be examined include:

(1) attic insulation,

(2) wall insulation,

(3) floor insulation,

(4) duct insulation in unheated areas,

(5) storm windows,

(6) storm doors, and

(7) weather stripping.

This study goes considerably beyond other economic studies of energy conservation in buildings because

1) no limit to the application of insulation was used where there are no physical constraints;

2) the energy savings potentials per dollar of investment from the various ECT's are compared in order to formulate a balanced energy conservation budget;

3) the model is quite sensitive to fuel prices and to projected rates of fuel price increases, as well as to climatic conditions, ECT costs, and discount rates; and

4) maximization of dollar savings to the homeowner is stressed.

The economic model formulated for use in this study utilizes marginal analysis to determine the optimal combination of the ECT's examined. Marginal analysis is especially useful in determining the efficient allocation of productive resources in order to maximize their output. Here the ECT's are considered to be productive resources, and net dollar savings (savings less costs) is the output to be maximized.

Two basic applications of marginal analysis are discussed: the first determines the optimal size and distribution of an energy conservation budget with no financial constraints; the second distributes a constrained budget among techniques in order to maximize dollar energy savings within the constraint.

Various empirical assumptions are made in order to apply the model to retrofitting existing housing. An allowance for physical constraints is incorporated into the model. A real (adjusted for inflation) discount rate of 1 percent is assumed, based on an after-tax alternative rate of return to the average homeowner. A 1 percent annual rate of real price increase is assumed for heating fuel and electricity. In effect this yields a minimum rate of return on investment equivalent to the rate of fuel price increases over the lifetime of the ECT's. The average rate of return will be considerably higher than this minimum rate of return, however, depending on how well the house was insulated before retrofitting, climate factors, and energy prices. A lifetime expectancy of 20 years is assumed for the ECT's (except for 10 years in the case of storm doors and weather stripping).

Calculations of energy savings are based on ASHRAE recommended procedures. Conductive heat gains and losses are calculated for applications of insulation; conductive and infiltrative heat gains and losses are calculated for storm windows and doors; and infiltrative heat gains and losses are calculated for weather stripping. Marginal energy savings and costs are calculated for each incremental inch of insulation, for various size storm windows, and for prime doors with varying glass content. Calculations are based on average seasonal loads rather than on design (extreme) conditions. The results are applicable to most housing designs if the ECT's considered can be retrofitted without structural modification.

Tabular results of this study show that the optimal level of investment in ECT's increases considerably as climate conditions grow more severe and more expensive heating and cooling energy forms are used. While government and industry recommendations for ceiling insulation currently call for six inches, this appears optimal in most geographical areas only when using low-priced natural gas. Ten to 12 inches of insulation is indicated as optimal for attics in oil-heated houses, except in the mildest climates, and 12 inches or more is indicated for most electrically heated and cooled houses. Insulation blown into existing walls is shown to be economically advantageous in many climates where higher fuel prices prevail (provided that this can be accomplished without damage to the structure). Insulation in floors over crawlspaces, garages, and unheated basements, as well as around exposed heating and cooling ducts, is shown to be economically rewarding in conjunction with attic and wall insulation, and often at considerably higher levels than currently recommended in promotional literature. Weather stripping, when installed by the homeowner, is found to be economical in all climates above 2000 degree days.

The conclusions of this research project contain several important points:

1) Most housing units in the U.S. today, especially older houses and those with added air-conditioning units, are underinsulated with respect to economic efficiency.

2) Homeowner-optimal levels of investment in energy conservation techniques are generally higher than current industry and government recommendations.

3) Energy conservation investment recommendations which reflect the variation in prices for different fuels will be of greater benefit to consumers than recommendations which consider climate variation only.

4) Artificially low or controlled energy prices encourage socially inefficient use (waste) of energy because economic incentives to conserve are reduced.

5) Building codes for energy conservation purposes should not substitute for consistent economic analysis. If such codes are viewed as maximums as well as minimums, they may be responsible for underinvestment in energy conservation.

Several recommendations are made as well:

1) Estimates of energy savings from high levels of insulation should be field validated.

2) More research is needed into suitable materials for retrofitting walls and their long-term effects on moisture transfer.

3) Economic benefits from other ECT's including forced-air ventilation, clock thermostats, and solar shading, should be examined.

4) Most importantly, the information derived from this study must be made available to homeowners in a manner which they can understand and implement. Such information is essential if they are to respond efficiently to increased fuel prices and scarcer energy resources. By doing so they will permanently reduce their demand for energy used in the space heating and cooling of buildings.

1. INTRODUCTION

While the energy "crisis" and spot fuel shortages may be temporary in nature, long range forecasts of rising energy prices[1] over and above the rate of general inflation signal the growing scarcity of energy in relation to other resources. These rising prices, more than any other factor, will convince energy consumers that they must become energy conservers. Energy conservation does not necessarily imply a new life-style of austerity, however. In many cases, rising energy prices will provide a significant incentive to increase the effectiveness of energy utilization with little or no decrease in our present standard of living.

This is especially true for space heating and cooling operations in buildings. More efficient heating, ventilating, and air conditioning (HVAC) equipment and a building envelope[2] with increased resistance to heat loss and gain are direct and nearly perfect substitutes for energy consumption. As the cost of heating fuels and electricity rises, additional investments in such energy conservation techniques (ECT's) will become economically attractive, thereby encouraging a permanent reduction in energy consumption.

However, additional investments in ECT's generate increasingly smaller energy savings, and beyond a certain level such improvements no longer pay for themselves. For this reason it is important that the benefits and costs of the various ECT's considered be identified so as to select only those investments which are potentially profitable. Profitability, of course, is not the only incentive for increasing energy conservation efforts. Comfort factors and a desire to head off another "energy crisis" may also play an important role. But while all of these may provide an initial incentive to undertake such actions, ultimately economic considerations will give the best indicators as to how much to invest and in what priority order among the various ECT's available.

Currently there is little information available, especially for homeowners, regarding economically optimal investment levels of energy conservation techniques available for reducing space heating and cooling costs. And yet decision-making in energy conservation investments can be quite complicated. Among the many variables which must be considered simultaneously are climate factors, comfort requirements, fuel prices, and the costs and energy saving potentials of a wide variety of energy conservation techniques.

It is therefore important that information on the economic aspects of energy conservation, sensitive to localized climates and fuel prices, be developed for transmittal to homeowners. The homeowner who responds to his own best economic interests will, in most cases, increase his energy conservation efforts. In doing so, costly and time-consuming energy conservation legislation and enforcement could be avoided, and the national goal of energy self-sufficiency might be more easily achieved on a voluntary basis.

1.1 Purpose

The purpose of this study is to systematically estimate economically optimal combinations of selected energy conservation techniques for reducing HVAC operation costs in existing residences. Such combinations will be considered optimal in the sense that they maximize potential net dollar savings in space heating and cooling operations over the lifetime of the investment, in this case considered to be a maximum of 20 years. Such combinations will be economically balanced in that no further energy savings can be achieved by trading off one technique for another within the available energy conservation budget.

Improvements in the utilization of energy for residential space heating and cooling operations have a considerable impact potential on national energy demand. There are nearly 70 million existing residences in the U.S.[3] which make up nearly 20% of the annual energy consumption,[4] some 15 quadrillion Btu. Sixty percent of this is used for space heating and cooling alone.[5] Because the majority of these residences were built when energy was relatively inexpensive (and, in many cases, before air conditioning became commonplace), there were few incentives to encourage the conservation of energy. As a result there exists a considerable potential for reducing heating and cooling energy requirements in the major-

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[1]See Nordhouse, William V., "The Allocation of Energy Resources," Brooking Papers on Economic Activity, III, 1973.

[2]For the purpose of this study, "building envelope" refers to those surface areas which allow the transfer of heat into or out of a building, including roof, walls, floor, windows and doors, and heating ducts in unheated areas.

[3]U.S. Department of Commerce, Bureau of Census, Housing Division, 1970 Census of Housing, Table 32.

[4]Seidel, Marquis R.; Steven E. Plotkin; and Robert O. Reck; "Energy Conservation Strategies," Environment Protection Agency, Washington, D.C., July 1973, p. 13.

[5]Ibid., p. 13.

ity of U.S. housing. These potential reductions have been estimated to be as high as 20%[6] across the entire country and as high as 50% for many individual homes and geographical areas.[7] It should be recognized, however, that such potential reductions are largely a function of energy prices. If energy prices increase at a rate greater than that of ECT prices, the potential energy savings due to the reallocation of resources away from energy consumption and toward energy conservation will increase as well.

Rather than emphasizing energy conservation as a national priority, however, this study emphasizes energy conservation from the standpoint of the energy consumer. A concerted effort by government and industry has made most homeowners aware that there are a considerable number of actions that can be taken to reduce residential energy consumption.[8] Some of these require a substantial investment, however, which the homeowner may be hesitant to make if he is unsure of a sufficient return. In addition, failure to understand the economic trade-offs between the various ECT's will most likely lead to investments which do not maximize potential savings in terms of energy or dollars. This study provides economic information which can be used to complement current technical information regarding energy conservation for existing housing. With this economic information, the homeowner will be better able to respond fully and accurately to rising energy prices, reaping considerable economic benefits for himself.

1.2 Scope and Approach

The energy conservation techniques examined in this study are those suitable for retrofitting into existing residences, in many cases by the homeowner himself, which will reduce the heat loss or heat gain through the building envelope.[9] Only those ECT's which offer substantial potential energy savings and require a large initial investment on the part of the homeowner have been considered, however. This in general includes increased levels of insulation, storm windows and doors, and weather-stripping. The potential savings of these ECT's are examined under a wide range of climates and economic assumptions in order to provide as much useful data as possible. Marginal analysis, a well-known microeconomic analytical tool, is used to establish a methodology for systematically determining the optimal (i.e., most profitable) combination of ECT's under any given set of assumptions. Optimal combinations of ECT's are then estimated for different climate factors and energy prices, using ECT costs typical of mid-1974 price levels.

We believe that this study goes considerably beyond most other economic analyses of residential energy conservation opportunities in several ways:

1) It establishes a systematic methodology for determining the most profitable level of energy conservation investments available to the homeowner.

2) It does not limit the application of insulation to commonly accepted levels (except in the case of physical barriers).

3) It considers the profitability of the various ECT's _vis-a-vis_ each other (i.e., in combination) rather than as discrete entities.

4) It is sensitive to current fuel prices, fuel price differentials, and projected fuel price increases for the major sources of energy use in space heating and cooling.

1.3 Organization

The general plan of this study is to briefly describe the ECT's to be considered, formulate an economic model for determining their most profitable combination, and calculate these optimal combinations for a wide variety of economic and climatic conditions. Specifically this study is organized as follows:

Section 2 will outline the ECT's to be considered and give some insight into options available to the homeowner in terms of materials and installation.

Section 3 will present the optimality conditions which must be met if net savings are to be maximized. Economic variables such as discount rates, fuel price rises, and institutional considerations will be discussed.

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[6] _Ibid._, p. 7.

[7] _Ibid._, p. 47.

[8] See for instance "7 Ways to Reduce Fuel Consumption in Household Heating . . . Through Energy Conservation," U.S. Department of Commerce, NBS, December 1972; "11 Ways to Reduce Energy Consumption & Increase Comfort in Household Cooling" (same reference); Technical Options for Energy Conservation in Buildings, NBS Technical Note 789, U.S. Department of Commerce, National Bureau of Standards, July 1973; and the "Builders Guide to Energy Conservation," NAHB, 1974.

[9] Heating and cooling equipment are assumed to be fixed in size for existing houses.

Section 4 will provide the basic approach used in calculating marginal energy savings for both winter heating and summer cooling.

Section 5 will present, in tabular form, the results of this analysis for a wide range of economic and climatic conditions. Some interpretation of the tables will be made in order to facilitate their understanding and make interpolation of the data possible.

Section 6 will include a short summary and some recommendations for further research.

Included in the appendices will be a more detailed discussion of the ECT's considered, ECT costs, climatic factors for various geographic locations, a more detailed methodology for computing marginal heat losses and gains from various envelope sections of a residential building, and a note on the computer programs used for calculating the optimal levels of investments.

2. RETROFITTING EXISTING HOMES

2.1 Why Existing Homes Need Retrofitting

The vast majority of existing buildings in the United States, whether residential, commercial, or public in nature, are wasteful thermal shelters in view of today's energy prices. If the real (i.e., adjusted for general inflation) price of electricity and heating fuels continues to increase during the coming years, as expected, the financial burden of heating and cooling these buildings will grow accordingly unless energy conservation measures are undertaken.

However, construction practices in the past were not necessarily irrational with respect to energy conservation. Until recently energy has always been considered a relatively abundant resource in the U.S., and real energy prices have been accordingly low -- in some cases actually declining. What is now considered to be inefficient energy utilization was not economically inefficient while energy prices reflected this abundance. On the other hand,consumers have been poorly informed about the potential for energy and dollar savings that can be realized from the many ECT's available. Consequently, they have failed to demand many of these features when purchasing a new home. Instead, a "first cost" design philosophy developed which stressed the minimization of construction costs rather than recurring operational costs. As a result, most existing buildings were never built with energy conservation in mind.

Neglect of energy conservation opportunities in existing and new housing cannot continue indefinitely. Homeowners in many parts of the country are receiving monthly fuel bills which are twice that of the previous years. As the cost of heating and cooling the home makes up an increasingly larger percentage of the costs of owning and maintaining a home, present and future homeowners will be forced to curtail their standard of living if they do not take adequate conservation measures. For unlike mortgage payments and investments in ECT's, dollars spent on heating and cooling the home are permanently foregone.

Many existing homes in the U.S., especially those built before 1960, have no more than three inches of insulation in the attic, no insulation in the walls or under floors over unheated areas, no storm windows or double-glazed windows, and no solar shading. FHA Minimum Property Standards (MPS) after 1959 began to require increased insulation in new houses that it insured after 1959,[10] especially in the colder climates, and have been responsible for upgrading much of the new housing stock since that time. However, there still exists a significant economic potential for further improvement in new and existing housing in most areas of this country today.

A recent study sponsored by the Oak Ridge National Laboratory[11] has shown that for most areas in the U.S., 6 inches of attic insulation, 3 1/2 inches of wall insulation, a foil insulator in the floor, and storm windows and doors have the greatest potential dollar return in new housing. Significantly, that study did not consider more than 6 inches of insulation in any application and was completed before the recent energy shortage and accompanying price rises took place. Results of this NBS study show that in many climatic regions even further insulation is easily economically justifiable (barring physical constraints) for existing housing and similar conclusions can be made for new housing as well.

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[10] These 1959 MPS required that the heat loss of a gas or oil heated house be no more than 50 Btuh per square foot of living area (40 Btuh for electrically heated homes). The current MPS have more than halved these allowances.

[11] Moyers, John C., "The Value of Thermal Insulation in Residential Construction: Economics and the Conservation of Energy," Oak Ridge National Laboratory, December, 1971.

2.2 Retrofitting Techniques

a. Selection of Techniques

While there are a large number of potentially profitable energy conservation actions that can be undertaken in the home, only a limited number of them will be examined here. We will not deal with clearly profitable conservation actions such as adjusting the furnace to increase its efficiency, caulking around window and door frames, sealing other cracks and openings which permit infiltration of outside air, and other such steps which have been outlined elsewhere. These usually have small economic costs and considerable economic benefits and should therefore be given the highest priority. Rather, this paper is concerned with investments in energy conservation which may take several years to pay for themselves, therefore requiring more specific knowledge as to potential energy savings which can be realized over their lifetime.

The retrofitting techniques which will be examined in this study are as follows:

1) attic insulation,
2) wall insulation,
3) floor insulation over unheated areas,
4) insulation of ducting in unheated spaces,
5) storm windows,
6) storm doors, and
7) weather stripping.

Most of these techniques might have been incorporated into the house at the time of construction at a lower cost than when retrofitting because walls, ceilings, and floors are more accessible, labor is better allocated, and materials can usually be purchased at a builder's discount during construction. Furthermore, savings due to such improvements would have accrued from the first day of occupancy. Retrofitting these techniques may still be profitable in varying degrees of application, however, as will be shown in the results of this benefit/cost study.

The following guidelines were used in deciding exactly which techniques would be considered. In general these energy conservation modifications will:

1) require a capital investment on the part of the homeowner which may take several years to recover;
2) reduce heat transfer through the envelope of a house; i.e., through the ceiling, walls, floors, windows, and doors;
3) be suitable for retrofitting into existing houses;
4) have resistances to heat transfer which can be reasonably estimated;
5) be acceptable to most homeowners;
6) not significantly alter the appearance of the house or reduce its market value; and
7) be available on the open market.

Other energy conservation techniques which may be considered as worthwhile but are not specifically treated in this study include the clock thermostat; a fan to substitute for air conditioning when the outside temperature falls below the inside temperature; heavy drapes; and solar shading, in the form of awnings, solar screens, or trees and taller shrubs.

b. Variations of Techniques Considered

For most of the ECT's examined in this study there are a wide variety of materials available that will reduce heat gain and loss through the various sections of the building envelope. Depending on actual physical and climatic conditions, some of these will be more suitable than others. Some discussion as to specific options, including variables which are not easily quantifiable, is presented in Appendix A. The actual materials considered in this study are as follows.[12]

1. Attic insulation (no limit to thickness)

    a. glass fiber--loose fill (R-2.2 per inch)
    b. glass fiber--blanket/batt (R-3.1 per inch)
    c. cellulose--loose fill (R-3.7 per inch)

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[12] Resistance (R) values are approximately those claimed by the manufacturers. Thickness limits are due to physical constraints. It is not intended that structural modifications be made to increase physical space for insulation where more is indicated than can be practically installed in any envelope section.

2. Wall insulation (3 1/2" thickness limit)

    a. cellulose--loose fill (R-3.3 per inch)

    b. glass fiber--blanket batt (for open walls only) (R-3.1 per inch)

3. Floor insulation over unheated space (10" thickness limit)

    a. glass fiber blanket/batt (R-3.1 per inch)

4. Ducting insulation in unheated spaces (10" thickness limit)

    a. glass fiber duct wrap (R-4 per inch)

5. Storm windows

    a. triple track metal sash

6. Storm doors

    a. metal sash with screen inserts

7. Weather stripping

    a. doors

    b. windows

c. Prices

The prices used in this study are based on a considerable amount of data gathered from many sources during the spring and summer of 1974. These sources include retail firms which do considerable business in energy conservation materials and services, and the results of a survey run by the U.S. League of Savings Associations which contains price estimates for these ECT's collected from 35 cities in the U.S. Actual prices used are included in Appendix B.

It should be noted that prices for many of these ECT's vary by as much as a factor of two or more, even within the same marketing area. The distribution of prices generally reflects a concentration of rather competitive estimates at the lower end, however, and the actual prices used reflect this concentration. At the same time it should be stressed that the estimates used are for average working conditions (as defined by the contractors themselves) any may vary according to total job size. Homeowners are cautioned to get several estimates and to weigh the reputation of the contracting company carefully when choosing to contract for installation.

3. ECONOMICS OF RETROFITTING

This study is basically a benefit/cost analysis of energy conservation techniques suitable for retrofitting in existing residences. Its goal, however, is to do more than just identify potentially profitable ECT's. Rather it seeks to identify the most profitable combination of techniques available for a particular residential application. The criteria for determining an optimal solution will be discussed in this section, as well as other economic considerations that may play an important role in the analysis.

3.1 Marginal Analysis

Marginal analysis is a particularly useful microeconomic tool for examining potential energy conservation investments because it provides a systematic approach to the solution of profit maximization problems which involve variable-sized investment opportunities. While marginal analysis is often used in benefit/cost analyses, it has not been frequently utilized in energy conservation studies of this type. With its use, however, a considerable amount of useful information can be generated that was previously not available.

The term "marginal", as used in this study, refers to the last increment of some variable; for example, the last inch of insulation in an attic. Marginal savings (MS) are the dollar savings generated by that last increment. Marginal cost (MC) is the cost attributable to that last increment.[13]

Two basic applications of marginal analysis are made here in determining optimal investments in ECT's. The primary application is used to select the optimal combination of ECT's for a given set of climatic, architectural, and economic variables, in the sense that no other combination will generate greater net savings (i.e., total savings less total costs) over the life span considered. The secondary application of marginal analysis is used in selecting economically "balanced" combinations of ECT's for any given investment size, in the sense that no other combination will generate greater dollar energy savings for the same or lesser total cost. While the primary optimality criterion assumes an economically balanced combination of ECT's, it is important to note that this secondary, or alternative, application is significant in its own right. It enables the homeowner to maximize the potential dollar energy savings available from <u>any</u> given energy conservation budget.

a. Optimal Combination of ECT's

As stated above, the primary application of marginal analysis will help us determine that combination of ECT's which maximizes net savings in residential space heating and cooling operations. The basic criterion for the optimal combination is expressed as Condition I, namely, that for each ECT considered,

$$MS = MC, \qquad (3\text{-}1)$$

where MS = marginal savings, or the savings generated by the last increment of an ECT, and

MC = marginal costs, or the cost attributable to that last increment.[14]

This condition simply states that investment in any given ECT should continue up to the point where the last dollar invested generates exactly one dollar in energy savings.[15] When this condition has been met for all techniques, no further investment will be profitable.[16]

Figure 3.1 illustrates an application of the optimal investment criterion for attic insulation. In Figure 3.1, the depth of this insulation is measured on the horizontal axis. Total savings (TS) and total cost (TC) are measured on the vertical axis of the upper part of Figure 3.1. While total costs increase at a constant rate as a function of insulation depth, total savings increase at a decreasing rate, rising considerably above the total cost curve at first, but eventually intersecting this curve at insulation thickness q_2, and thereafter falling below it. At any point on

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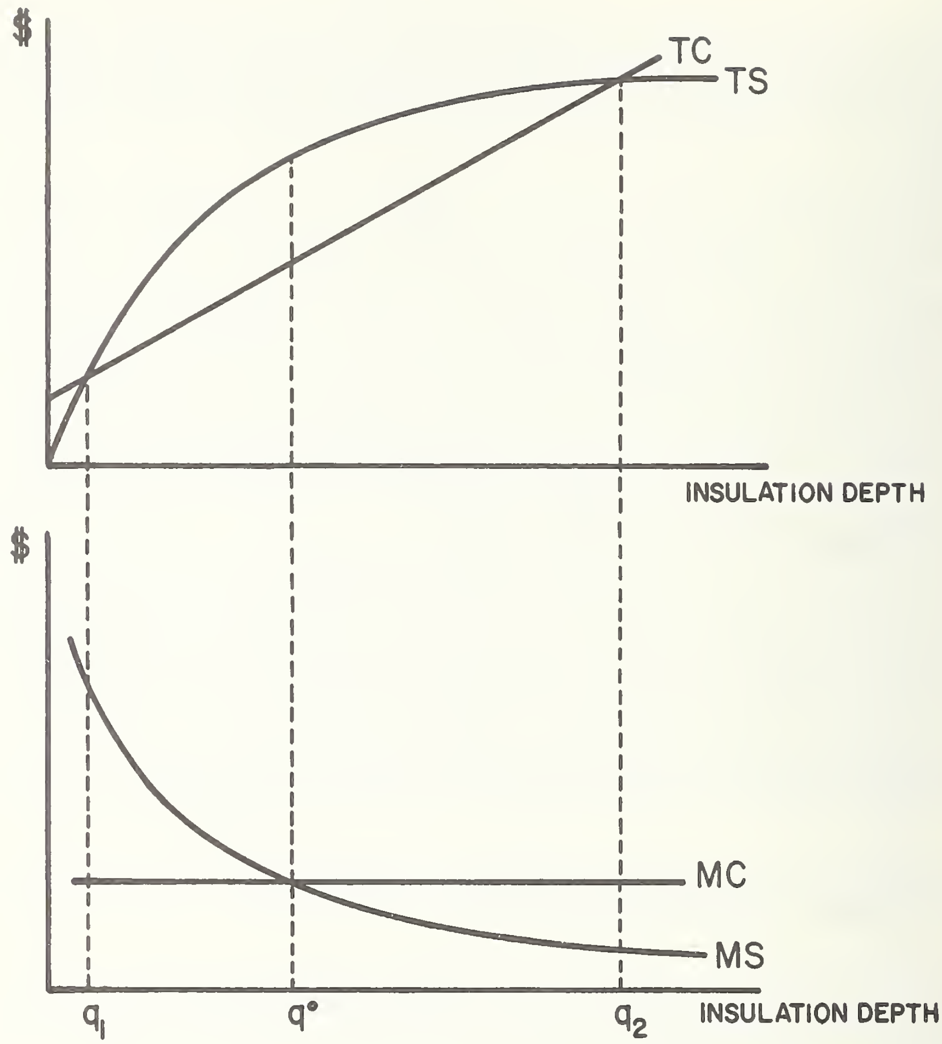
[13] It is important to distinguish between MC and MS and total cost (TC) and total savings (TS). MC and MS represent the rate of change (or first derivative) of the TC and TS functions at each increment; the summation of the MC of each increment (or the definite integral of MC) will result in TC; summation of MS of each increment will result in TS.

[14] Second order conditions require that, locally, MS minus MC be decreasing. Care must be exercised in distinguishing local optimals from global optimals. This will be discussed in Section 3.2.

[15] These dollar savings result from a stream of energy savings generated over the expected lifetime of the ECT's discounted to present value to reflect alternative investment opportunities over this period of time.

[16] In some cases it will not be possible to reach the point where MS = MC because of physical or other constraints. This will be discussed further in Section 3.2.



CONDITION I: MS=MC

OPTIMAL LEVEL OF INVESTMENT

Figure 3.1 Condition I assures maximum net dollar savings generated by investment in a given ECT.

the horizontal axis between q_1 and q_2, total savings are maximized only at that level of insulation where the difference between TS and TC is maximized. This will occur only where the slope of the TS curve is equal to the slope of the TC curve, i.e., at $q°$. Moving to the lower diagram we see that this is precisely the point where the MS curve intersects the marginal cost curve; i.e., where MS = MC.[17]

The reason for requiring MS to equal MC is clear: At any point to the left of $q°$, increases in the level of insulation will generate savings greater than costs so that net savings will be increased. At any point to the right of $q°$, however, the cost of additional insulation is not covered by the incremental savings so that net savings are decreased. This leaves only $q°$ as the profit-maximizing level of insulation.

While the "optimal" combinations of ECT's presented in the tables of Section 5 reflect a wide range of climatic conditions and energy prices, they are all consistent in that they satisfy Condition I.

b. Balanced Combination of ECT's

Marginal analysis is particularly appropriate in the analysis of most ECT's precisely because the potential energy savings generated by any given technique generally decrease as more of that technique is utilized. As these savings decrease, it becomes more profitable to shift further investment into other techniques which generate greater marginal savings (per dollar invested). As we shall see, marginal analysis is quite useful in treating these economic "tradeoffs."

The second application of marginal analysis provides the criterion for selecting an economically balanced combination of ECT's for any given investment size, i.e., that combination which saves more energy dollars than any other for the same or less cost. This requires not only an absolute determination of the profitability of each energy conservation technique at each incremental level of application, but of their relative profitability, in relation to each other, at each incremental level of application as well.

The equilibrium condition for this balanced combination is expressed as Condition II:[18]

$$\frac{MS_1}{MC_1} = \frac{MS_2}{MC_2} = \frac{MS_3}{MC_3} = \ . \ . \ . = \frac{MS_n}{MC_n} \qquad (3\text{-}2)$$

where MS_i = the marginal savings generated by the i^{th} technique,

MC_i = the marginal cost of the i^{th} technique, and

$i = 1, 2, 3, \ldots, n$ techniques.

When Condition II is satisfied, the last dollar spent on each technique will generate the same dollar energy savings. In order to remain within the implied budget constraint, any increase in one technique will require a decrease in one or more of the other techniques.

Condition II is shown graphically in Figure 3.2. Here the curved lines show marginal savings per dollar invested (MS/MC) for each technique. The horizontal axis represents the level of investment for each technique; as more is invested in each technique, MS/MC decreases monotonically. The horizontal line (B) running continuously through all the MS/MC functions is the budget line. It assures by construction that MS/MC will be equal for each technique. The higher B crosses the vertical axis, the higher is MS/MC, and the lower is the total budget. The lower B, the higher the total budget. The quantity of each technique considered is determined by the intersection of B with each MS/MC curve; thus q_1 is the quantity of the first technique obtained, q_2 of the second, etc. The budget, or total investment size (B) is then equivalent to

$$B = q_1AC_1 + q_2AC_2 + q_3AC_3 + \ . \ . \ . + q_nAC_n, \qquad (3\text{-}3)$$

where AC_i = the average cost of the i^{th} technique at level q_i.

[17]This is a straightforward extension of the fact that MS and MC are the first derivatives of the TS and TC functions, respectively.

[18]An important assumption in this criterion is that the savings and cost functions of the various ECT's be independent of each other. This will be discussed further at the end of this Section.

CONDITION II:

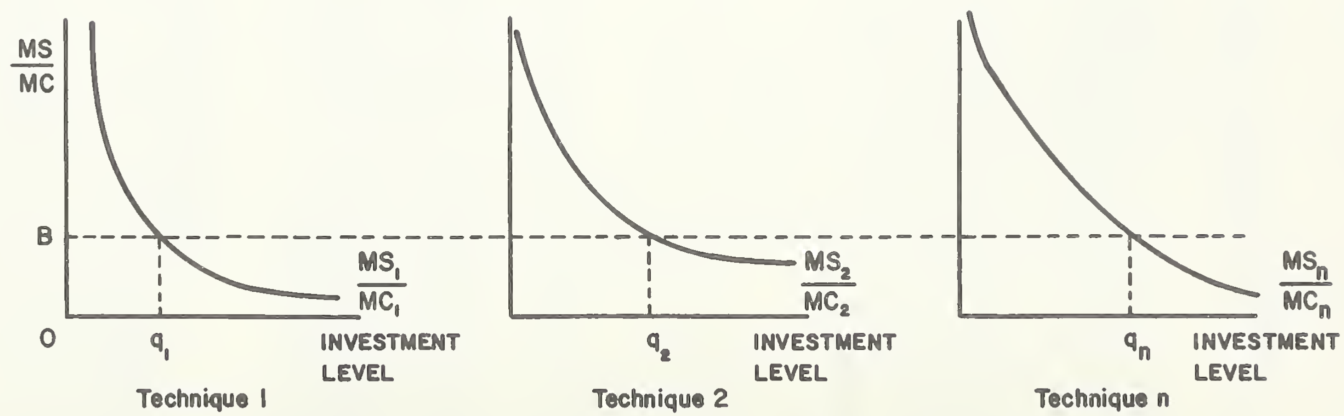
$$\frac{MS_1}{MC_1} = \frac{MS_2}{MC_2} = \frac{MS_3}{MC_3} \quad \cdots \cdots = \frac{MS_n}{MC_n}$$

Where:

MS_i = Marginal Energy Savings (in dollars) of the i^{th} technique.

MC_i = Marginal Cost of the i^{th} technique.

i = 1,2,3,....n number of technique.



OPTIMAL COMBINATION OF INVESTMENTS

Figure 3.2 Condition II assures an optimal distribution of a energy conservation budget among ECT's.

As the budget increases, the budget line moves downwards and additional levels of investment in each ECT are determined.[19]

A graphical demonstration of the desirability of equal dollar savings per dollar of investment at the margin is given in Figure 3.3. Here technique 1 at q_1° and technique 2 at q_2° are generating equal savings per dollar at the margin. Suppose now that we wish to increase the investment level in technique 1 to $\bar{q}_1$. This will require an equivalent decrease in investment for technique 2 in order to remain within the budget constraint. The cross-hatched area for technique 1 shows the increase in savings due to the increased investment and the cross-hatched area for technique 2 shows the concurrent decrease in savings. Note that this increase is not sufficient to offset the decrease. Again, only at that point where MS/MC is equal for each technique will the combination be economically balanced.

As a further example, consider two alternative ECT's, say attic installaion and floor insulation (over an unheated crawlspace) in a given house. Assume that the fixed labor cost of installing insulation in the floor is twice that of the attic (because of poor accessibility) but the materials cost and variable cost of installation for each additional inch is the same in both cases. Furthermore, let us assume that equal dollar energy savings will accrue from equal applications of each technique. How does one distribute a limited budget between these two ECT's?

One might intuitively feel that more attic insulation should be installed than floor insulation since the total cost of the attic insulation (labor plus materials) is less than that of floor insulation for the same level of application. This may at first appear reasonable because the net savings generated by attic insulation in this case are potentially greater than those due to the insulation in the floor. But to satisfy Condition II, equal amounts of both should be installed. Only in this way will MS/MC be equal for both.[20]

A numerical example of this problem is shown in Table 3.1. Marginal costs per square foot for each increment are shown together with the marginal savings generated. If 6 inches are used in both applications, for example, the MS/MC ratio is 2.5 (.05/.02) for both and thus Condition II is satisfied. The total cost of the attic insulation at this point is \$.17 per square foot and the total cost for floor insulation is \$.22. (We assume here that our budget is limited to \$.39 per square foot for the two ECT's together.) Thus for a total budget of \$.39 we save \$4.84 (\$2.42 x 2). But suppose we wish to add 7 inches of insulation to the ceiling and only 5 inches to the floor (in order to remain within the budget constraint). The budget remains at \$.39 (now \$.19 and \$.20), but while the total savings generated by the attic insulation rise to \$2.45, the savings from the floor insulation fall to \$2.37, for a total savings of only \$4.82. Total savings have thus declined by \$.02 per square foot for failure to meet Condition II. Net savings have declined as well, since total costs have remained the same. As more attic insulation is substituted for floor insulation (in this case) the total savings fall quite rapidly, as can be seen by using 9 inches of attic insulation and 3 inches of floor insulation. In this case total savings fall by \$.155 per square foot. Thus the more imbalanced the combination of ECT's, the greater the decline in net savings. It should now be clear why we cannot ignore MS and MC when selecting a combination of ECT's that will maximize savings.

As discussed at the outset of this section, Condition I implies that Condition II has been met. This can be shown quite simply because Condition I can be restated as

$$\frac{MS_1}{MC_1} = \frac{MS_2}{MC_2} = \frac{MS_3}{MC_3} = \ldots = \frac{MS_n}{MC_n} = 1 \qquad (3\text{-}4)$$

We now see that at the margin all ECT's are generating the same MS per dollar invested; in this case the last dollar invested in each technique generates exactly one dollar in savings. Again referring to Table 3.1, we can now determine the optimal level of investment in each technique where there is no budget constraint. Condition I is met only when 8 inches of insulation are installed in each location.

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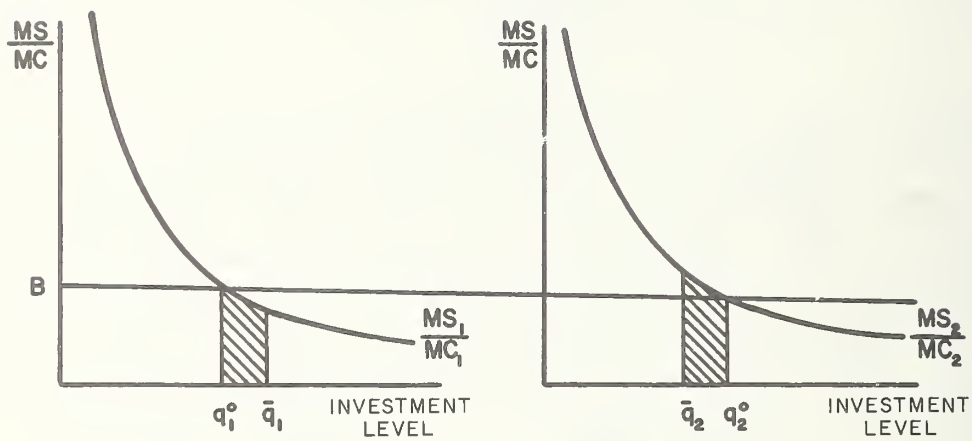
[19] An exception to this will occur if there is some physical or cost constraint for a particular ECT, in which case its MS/MC ratio will remain above those of the other techniques. This will be discussed further in Section 3.2.

[20] Implicit in this assumption is a budget large enough to include first increments of both ECT's. If the budget falls short of this level, the entire budget will be allocated to that technique with the lower fixed cost.



Technique 1 Technique 2

VIOLATION OF CONDITION II
PRODUCES SUBOPTIMAL RESULTS

Figure 3.3 Violation of Condition II produces suboptimal results.

Table 3.1 Hypothetical Costs and Savings Due to Attic and Floor Insulation[1]

	Cost/Ft.^{2}				Savings/Ft.^{2}	
	Attic		Floor		Attic = Floor	
Inch	MC	TC	MC	TC	MS	TS
1	\$.07	\$.07	\$.12	\$.12	\$1.50	\$1.50
2	.02	.09	.02	.14	.50	2.00
3	.02	.11	.02	.16	.20	2.20
4	.02	.13	.02	.18	.10	2.30
5	.02	.15	.02	.20	.07	2.37
6	.02	.17	.02	.22	.05	2.42
7	.02	.19	.02	.24	.03	2.45
8	.02	.21	.02	.26	.02	2.47
9	.02	.23	.02	.28	.015	2.485

[1]Values are hypothetical as they will vary accordingly to climate, construction type, and market area. The marginal savings are the present value of the stream of dollar savings expected from each inch of insulation over its expected lifetime.

An important limiting assumption required of Condition II is that of the independence of the various ECT's included in the analysis. This means that the amount of energy savings generated by one technique cannot be influenced directly or indirectly by other ECT's, whether included in the model or not. (For example, setting back the thermostat will have some effect on the savings potential of all ECT's.) Where the savings generated by two or more techniques are interdependent, the model will give valid results provided that all interdependent techniques but the one to be examined are held constant at some level determined more or less outside the immediate analysis. (This can be done by an iterative approach if warranted.) While this may present some problems in a few instances, especially in building systems with a large number of potential ECT's and variable design parameters, the independence requirement is generally successfully met in the more limited applications found in residential retrofit. The more practical aspects of this assumption are discussed further in the following subsection.

3.2 Further Economic Considerations

A methodology for determining theoretically optimal levels of investment in energy conservation techniques has been presented. We now examine how well the model will perform in practical applications.

a. Discrete versus Continuous Investment Sizes

Up to this point, energy savings have been assumed to be generated by a continuously available range of investment levels for each technique.[22] In reality, no such continuity exists. Instead, energy conservation techniques are generally available in a finite number of sizes only. Furthermore, external constraints may limit the amount of any given technique that can be implemented. But this does not imply that feasible solutions are inefficient.

Insulation batts, as an example, come in a limited number of preformed sizes and shapes and may not conform to the exact amount of insulation specified in a continuous analysis. But in this discrete case the last available increment of insulation whose MS/MC ratio is closest to the optimal MS/MC ratio (without falling below it) provides the optimal "feasible" solution. This feasible solution is indeed optimal for in reality the marginal cost could be quite high for an increment that would exactly meet that level determined in a continuous analysis. This is because production and distribution costs associated with a very large number of sizes would be higher than that of a limited number of sizes.

Similar reasoning can be used in those cases where external constraints limit the use of a technique so that its MS/MC ratio cannot approach the continuously determined optimal level. A good example is insulation in walls. Most walls are limited to 3.5 inches of insulation by construction design, although more might be economically desirable if there were room for it. But the marginal cost of the next increment, given a 3.5" constraint, would be quite high since major redesign and reconstruction would be necessary. Again we have an optimal feasible solution.

b. Independence versus Interdependence of ECT's.

As discussed in subsection 3.1, independence of the various ECT's is required if the model is to be successfully used. It is important that we examine the ECT's considered in this study in order to determine how well they fit this assumption.

1) Reducing the thermostat setting in winter and raising it in summer will have a direct effect on the savings generated by all techniques, since the rate of heat transfer is a function of the inside-outside temperature differential. To the extent that a thermostat is set back in order to conserve energy _per se_, this new setting should be reflected in the calculations of energy savings. This may slightly reduce the optimal level of investment in other ECT's.[23] It should be noted, however, that in a well-insulated house the thermostat level may be reduced somewhat over that of a poorly insulated house, with no loss of comfort, due to draft reduction, a higher mean radiant temperature, and a more even distribution of heat thoughout the house. In this case, the savings due to the decreased thermostat setting should be internalized into the savings function. Since energy savings are the difference between energy use before and after retrofit, the original setting should be used to calculate previous energy use and the lower setting (if known) to calculate energy use after retrofit. (Marginal increments of insulation are unlikely to have any measurable effect on thermostat reduction, however, so that the lower temperature can be used in evaluating this last increment both before and after its use is considered.)

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[22] The methodology for estimating these energy savings will be discussed in Section 4.

[23] The reduction of a thermostat setting to reduce energy consumption in a well-insulated house will save considerably less energy than in a poorly-insulated house. For this reason thermostat setback may not be considered necessary from the standpoint of conservation in a well-insulated house.

2) The heat losses through the ceiling, walls, windows, floors, and doors are assumed independent in that a constant indoor temperature is assumed. While there may be some variation in temperature near these surfaces in a poorly-insulated house, these will approach the average room temperature as the house becomes better insulated, so that the accuracy of the calculations at the margin will be improved.

3) The effects of storm windows and weather stripping on air infiltration are certainly interdependent. However, by examining the effect of one while holding the other constant, the model will perform well. In this case storm windows can be considered as applied to weather stripped or nonweather-stripped windows. And weather stripping can be considered as being added to windows with or without storm windows. This same approach can be used for storm doors and weather stripping as well.

4) Savings generated by insulation around exposed heating and cooling ducts are sensitive to, among other variables, the amount of time which the furnace or air conditioner must operate in order to maintain the desired indoor temperature. As the house is better insulated this operating time will be shortened and therefore potential savings will decrease. For this reason the savings generated by duct insulation must be estimated after the investment levels in other ECT's have been determined and their effects on operation time evaluated. This will be discussed further in the section on duct insulation in Appendix A.

c. Local versus Global Optimal Solutions

Under certain conditions, it is possible that Condition I and Condition II might be met at several different levels as more of a given ECT is considered. This presents a problem in that while each of these levels may define a local optimum, where net savings are optimized in some local range, in general only one will be a global optimum, in that net savings are maximized for the entire range of application. It is important that under such circumstances the global optimum be identified.

Such a problem will not occur under the assumptions made earlier, where marginal savings decrease monotonically (i.e., at no point do marginal savings increase as more of any one technique is added), and at the same time marginal costs are constant or monotonically increasing. Under such conditions only one optimum will be found and it will be both a local and global solution.

While, in general, marginal savings meet this criterion, marginal costs sometimes behave differently. This is especially true of batt (or blanket) insulation. These batts are generally available in sizes from 2 to 6 inches thick, with installation charges being approximately the same for any size within this range. Each additional batt requires additional installation, however, giving rise to a marginal cost function similar to that in Figure 3.4. Under such conditions, Condition I (or II) might be met at several points, as shown in Figure 3.5, at 6 and 12 inches. The marginal cost of inches 7 and 8 rise above marginal savings so that a local optimal exists at the 6th inch. However, marginal costs fall and then rise again so that another local optimal exists at the 12th inch. A criterion is therefore needed for determining the globally optimal level.

We must examine the cumulative marginal costs and marginal savings between the 6th and 12th inches to determine if the sum of these marginal savings is greater than the sum of the marginal costs. Since these savings are indeed greater than costs, i.e., AEFG > ABCD in Figure 3.5, the additional 6 inches should be added and 12 inches is the global optimum. The criterion for determining the global optimum between two local optimum can be stated as follows: If the sum of the marginal savings (ΣMS) generated by the cummulative increments between the two local optima is greater than the sum of their marginal costs (ΣMC), the higher level is the global optimum. If $\Sigma MS < \Sigma MC$, the lower level is the global optimum. If $\Sigma MS = \Sigma MC$, both are equally preferable.

d. Present Value Determination

Since the appropriate investment size is a function of present value energy savings expressed in dollar terms, it is important that this present value be estimated as realistically as possible. But to do so requires knowledge of annual energy savings, energy prices now and in the years to come, discount rates, and the time period over which these dollar savings will accrue. Unfortunately, these are difficult to estimate accurately. Energy prices have risen sharply in the past year and it is estimated that they will continue to rise at rates which will vary from year to year and location to location. Homeowner discount rates, which are bounded on the lower side by the rate of return on alternative investments (opportunity cost) and on the upper side by the cost of borrowing[23], will vary from homeowner to homeowner. And the expected lifetime of the various modifications considered often depend on external conditions that are impossible to predict. Nevertheless, a general model can be formulated for estimating present value if one is willing to assume values for these variables.

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[23] If the rate of return on investment (at the margin) is greater than the rate of interest for borrowing available for such investments, rational economic behavior would opt for borrowing, if funds for such investments were not otherwise available.

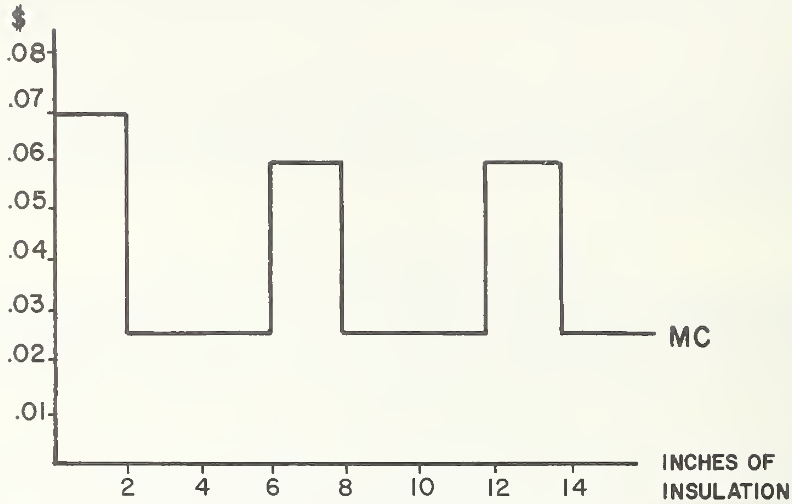

Figure 3.4 Marginal cost of batt insulation will increase when installation costs recur.

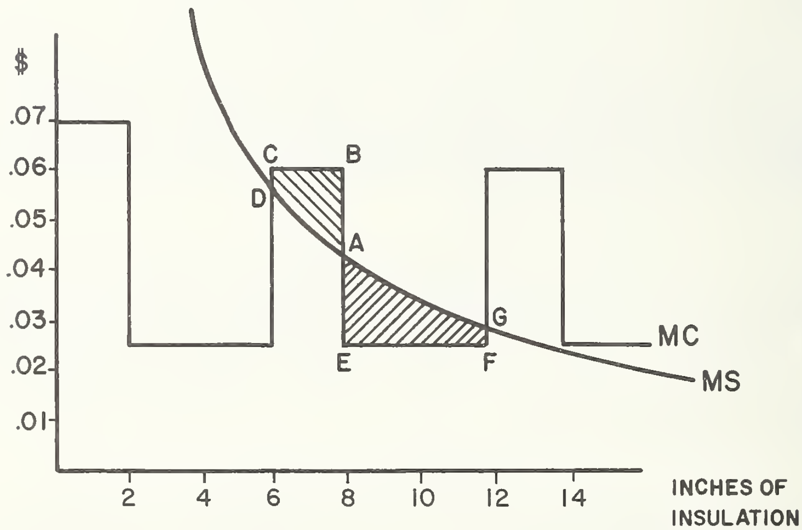

Figure 3.5 Net savings generated by the 9th through 12th inches are greater than net loss generated by the 7th and 8th inches.

Specifically, we are concerned with finding the present value of a stream of annual energy savings valued at (S) at today's energy prices, accruing over the lifetime (L) of the ECT. These energy savings, while constant in Btu terms, are growing in dollar terms because of price rises at some average annual rate (P). But at the same time these savings must be discounted to present value using an appropriate discount rate (D).

Thus present value can be expressed in terms of nominal (actual) price increases and discount rates as

$$P.V. = \sum_{t=1}^{L} \left(\frac{1 + P}{1 + D}\right)^t \cdot S. \qquad (3\text{-}5)$$

However, both price rises and discount rates are a function of two forces: a real rate of change (P' and D')[24] and the rate of inflation (I).[25] Because the I term appears (implicitly) in both the numerator and the denominator of equation (3-5), its effect cancels out,[26] leaving only the real terms to be estimated. This is of considerable value to us because the need to estimate the rate of inflation has been eliminated. Throughout the remainder of this report we will refer only to these real components, P' and D'. Equation 3-5 above then reduces to[27]

$$P.V. = \sum_{t=1}^{L} \left(\frac{1 + P'}{1 + D'}\right)^t \cdot S. \qquad (3\text{-}6)$$

Some discussion as to appropriate values for P', D', and L is now needed:

1) Estimates of projected rates of energy price increases for fossil fuels and electricity are available from several sources. Most of these are based on different sets of assumptions, however, and the estimates vary accordingly. While it is improbable that natural gas, fuel oil, and electricity will all increase in price at the same rate, it is difficult to predict relative changes with any accuracy now. A real rate of increase (over and above the rate of general inflation) of 1% for all energy sources is used in this study, based on the NBS draft proposal for "Design and Evaluation Criteria for Energy Conservation in New Buildings."[28] This may be considered conservative by some because of recent price increases many times this rate in some cases. This rate is meant to be representative of the long run rate of real price increases for the next 20 years, however, and in this respect it reflects price increases determined by long run market forces.

Although some energy prices, particularly those for electricity, have historically declined in real terms up until a few years ago, it is unlikely that such a pattern will continue before the end of the century for several reasons. First, environmental controls are growing stricter; second, more intensive extraction methods are now being used; third, many new oil fields are located in remote areas; and fourth, generating equipment and refining processes have been developed to the point where increasing their scale may no longer lower average cost significantly.

Controls on well-head prices for natural gas may be eased in the future, allowing natural gas prices to rise closer to their free-market level, which is substantially higher than current prices. Therefore, it may be wise to use a somewhat higher base price than currently being experienced when estimating the optimal investment level in energy conservation for natural gas heating.

2) Before estimating an "appropriate" discount rate for the "typical" homeowner, some insight into discount rates is needed.

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[24] Real energy price rises are due to those resources becoming scarcer relative to other resources, not inflation, which raises the nominal price of all resources. Real discount rates here refer to that rate of return required to attract an investment, apart from the need to recover purchasing power lost by inflation.

[25] When discrete (vs. continuous) compounding is used, $P = I + P' + I \cdot P'$ and $D = I + D' + I \cdot D'$

[26] This can be shown as follows:

$$\frac{1 + P}{1 + D} = \frac{1 + I + P' + I \cdot P'}{1 + I + D' + I \cdot D'} = \frac{(1 + P')(1 + I)}{(1 + D')(1 + I)} = \frac{1 + P'}{1 + D'}$$

[27] For ease of computation this can be expressed as

$$P.V. = \frac{1 + P'}{D' - P'} \cdot \left[1 - \left(\frac{1 + P'}{1 + D'}\right)^L\right] \cdot S \qquad D' \neq P' \quad (3\text{-}7a)$$

$$P.V. = L \cdot S \qquad D' = P' \quad (3\text{-}7b)$$

[28] U.S. Department of Commerce, National Bureau of Standards, February 27, 1974.

In order that energy conservation investments be considered in their proper economic priority, they must be compared with the next most profitable alternative investments available to homeowners after adjusting for risk, tax liabilities, and preference for short- over long-term investments. An appropriate discount rate will then reflect an "opportunity cost," i.e., the cost of foregone profit from the next best alternative. In this study the discount rate may also be viewed as the minimum rate of return needed to induce further investment in energy conservation.

It is quite important to note that returns on investment in ECT's are not subject to income taxation for homeowners as they arise from reduced expenditures of after-tax disposable income. (This is not true for enterprises because decreased costs imply increased, taxable, profits.) Therefore, for homeowners, alternative after-tax rates of return should be used in determining an appropriate discount rate for investments in energy conservation.

While such alternative investment opportunities will vary from homeowner to homeowner, the discount rate used in this study reflects rates of return from U.S. Government 3-5 year securities available between 1952 to 1970.[29] These securities represent low-risk investments available to homeowners and their rate of return is generally comparable to interest rates paid by regulated savings institutions. More importantly, the real rate of return over their lifetime (average of 4 years) could be tracked using the Consumer Price Index (CPI)[30] as the basis for the rate of inflation appropriate to the average homeowner[31]. This resulted in an average real rate of return of 1.6% before taxes (standard deviation = .75%) and an after-tax return of only .7% (25% tax on nominal returns). While these may be biased somewhat low because of index problems inherent in the CPI, they are representative of the magnitude of real rate of return on low-risk investments. Apparently these returns are quite small in comparison to nominal rates of return. For this reason a 1% real rate of return on investment may be sufficient to induce further homeowner investment into energy conservation. It might be noted that at the present rate of inflation it is quite difficult for the average homeowner to realize even this low real rate of return after taxes.

However, one must clearly understand that this is the potential rate of return to be realized at the margin, i.e., for the last increment of investment. The average annual rate of return on the total investment will usually be considerably higher, depending on the existing state of the house to be retrofitted. For example, where the addition of six inches of insulation will pay back its cost in three to five years or less, but continues generating savings over its entire lifetime, one can easily see that the actual rate of return on the total investment is quite high.

The marginal investment (that for the last increment) may also be viewed as requiring its full expected lifetime to be repaid (including interest at the discount rate). Each previous increment will take less and less time to be repaid, however, and the first increment may be paid back (in some cases) within a few months of retrofit. The average length of payback will then be considerably shorter than the expected lifetime, as can be seen by examining the tables in Section 5.

Because the marginal investment does require the full expected lifetime to be repaid, this may be considered a relatively long-term and illiquid investment (unless the house is sold before the last increment is completely amortized). For this reason such a marginal investment may not be as attractive to the homeowner as a short-term investment yielding the same rate of return. While the additional rate of return needed to induce such long-term investments may be somewhat higher than for a short-term invest-

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[29] Source: U.S. Department of Commerce, Social Economic Statistics Administration, Bureau of Economic Analysis, Business Statistics, 1972, p. 92.

[30] Ibid., p. 40.

[31] The following formula was used in computing the real after-tax rate of return, R, for each security issue in year t:

$$R_t = \frac{\left[[(1 + r_t)^n - 1]\ (1 - x) - 1 \right]^{\frac{1}{n}}}{\prod_{t=1}^{n} (1 + I_t)} - 1$$

where R_t = real after-tax rate of return on investment for security bought in year t,

r_t = nominal interest rate of security issue purchased in year t,

I_t = inflation rate in year t,

n = lifetime of security, and

x = appropriate income tax bracket (in decimal form).

These real rates of return for the years 1952 to 1970 were then averaged to provide the 1.6% estimate before taxes and .67% after taxes.

ment, this difference is overshadowed by other considerations, especially the effect of high inflation rates on actual investment opportunities and the somewhat conservative estimate used in estimating the rate of fuel price increases.

A further note is required to cover the case of borrowing by the homeowner, where he may not have sufficient investment funds available for energy conservation improvements. In this case, the real discount rate should be no higher than his real cost of borrowing, recognizing that income tax credits from interest payments reduce the actual cost of borrowing and that he will be paying back cheaper dollars because of inflation. If the homeowner can borrow at 10% for home improvements[32] and he is in the 25% tax bracket, his nominal cost of borrowing is only 7.5%. If the rate of inflation is 7-8% over the life of the loan, the real rate of borrowing will actually approach zero, which is less than the real discount rate used here. Again a 1% real discount rate appears to be a reasonable assumption for marginal investments.

3) Since the real rate of fuel price increase has been considered equivalent to the homeowner's discount rate of 1%, the present value of future energy savings is simply the sum of these savings, at current prices, over the life of the specific ECT considered.[30] This, of course, leaves the estimated lifetime as a critical variable in the assessment of marginal savings generated by these various ECT's. For this reason we must now consider the appropriate lifetime over which energy conservation modifications to existing houses might be amortized. This is especially relevant to homeowners or prospective home buyers who do not foresee occupying their house long enough for the marginal investments (i.e., the cost of last increments of the various techniques) to be completely paid back in the form of energy savings.

As discussed in Section 2.1, there have been certain failures in the market for buildings to properly value energy conservation investments. Insufficient consumer information and a "first-cost - minimization philosophy" were cited as probable causes of this problem. As energy costs increase relative to other costs, however, and energy conservation rises in economic priority, these factors will diminish in effect. Energy consumers will become more conscious of the economic desirability of energy conservation and the market value of buildings will better reflect their energy usage (as reflected in fuel bills). In this respect a well-insulated house will be more likely to sell quickly and command a price higher than that of a poorly insulated home, making it considerably easier for a homeowner to recoup the unamortized portion of his investment if he is not intending to occupy the house throughout the lifetime of the ECT's.

Homeowners now have an increased incentive to invest in energy conservation modifications, for these investments can be more readily capitalized than in the past. It is not necessary that such expenditures be completely amortized in the length of time they expect to remain in the house. Investment decisions can more readily reflect the lifetime expectancy of the modifications.

While the expected useful lifetime of some ECT's, such as insulation may extend to the life of the building, any lifetime assumption over 20 years is likely to be unrealistic in view of large-scale uncertainties as to economic conditions beyond that time period, especially for energy prices. For this reason we conservatively chose 20 years as the appropriate time period for use in estimating the present value of future energy savings. When lifetime expectancies are clearly shorter than 20 years, as in the case of storm doors, more conservative lifetime estimates should be used.

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[32] This is approximately the FHA Title I rate available to homeowners for home improvements.

[33] See equation 3-7b in this subsection.

4. CALCULATION OF ENERGY SAVINGS

Estimation of BTU energy savings in this study are based largely on ASHRAE methodologies as found in the Handbook of Fundamentals.[35] While more sophisticated heating and air-conditioning load estimating methodologies are available, such as the NBS Load Determination (NBSLD) Program, the massive computational requirements of these programs, when applied to the large-scale computational requirements of this study, would have exceeded the available resources many times over.

4.1 Basic Assumptions

The general approach used in calculating heating and cooling loads and some important assumptions fundamental to the estimating process are presented in this section. The methodologies actually used in calculating these loads will be outlined in Appendix D.

Consistent with current ASHRAE procedures, degree days[36] below 65°F are used as the basis for heating loads, and summer cooling hours over 80°F are used for air-conditioning load requirements. While the degree day concept has been widely accepted as a useful determinant of annual heating loads, cooling hour estimates are not generally considered to be more than a rough approximation to the total air conditioning load. This latter methodology has been used before in similar studies,[37] however, and is used here because no better approximation, consistent with the large number of calculations required by this study, has been forthcoming.

Unlike much of the ASHRAE procedure, the purpose of these estimates is not to determine the heating and/or cooling load under design conditions for an entire building or for a zone within the structure in order to properly size heating and cooling equipment. Instead, we wish to estimate the net effect on the average yearly heating and cooling energy loads caused by a given change in the thermal resistance of a given envelope section. The most important assumption here is that the reduction of Btu losses or gains in any given envelope section has a corresponding effect on the reduction of the total heating or cooling load.

To the extent that such reductions in heat losses and gains are independent, as in the case of wall and ceiling insulation, the energy savings realized are additive. This is one of the basic assumptions on which the marginal analysis model is formulated. However, with some techniques these reductions are interdependent, as in the case of weather stripping together with storm windows and doors. In such cases one technique must be held constant while the other is varied. This latter approach is used on an ad hoc basis when dealing with such interdependent techniques in this study.

Furthermore, it is assumed that the marginal reduction of heating and cooling loads will have no significant effect on the efficiency of the mechanical heating and cooling system. In most cases overdesigned equipment may not be as efficient as properly-designed equipment. By reducing the Btu load in a residence with a fixed heating and cooling system we are in effect "creating" an overdesigned system. However, heating and cooling systems seldom operate under design (extreme) conditions. As a consequence, seasonal efficiencies for oil and gas fired furances generally range from 50 to 70%.[38] (Electric resistance heating units are considered to be 100% efficient regardless of utilization rate). At the margin there is unlikely to be a significant difference in the seasonal efficiency so that this should have little effect on optimal investment levels. The system efficiency used in the estimating procedure should reflect seasonal, rather than design, considerations.

4.2 Application of Marginal Analysis to Energy Conservation Techniques

Marginal analysis is particularly useful in evaluating energy conservation investments because savings generated by successive increments of most modifications generally decrease in magnitude and thus total savings are not proportional to investment size. This makes it quite difficult to determine optimal levels of investment without analyzing the savings and costs of each increment. As we have seen, marginal analysis gives us a consistent and straightforward approach to this problem.

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[35] ASHRAE, Handbook of Fundamentals, 1972

[36] Degree days are the sum of all average daily temperature differentials below 65°F over a year's time. A good correlation between this parameter and heating loads has been established over a long period of time.

[37] See J. C. Moyers, "The Value of Thermal Insulation in Residential Construction."

[38] See for instance, S. Stricker, "Measurement of Heat Output of Residential Furnaces," ASHRAE Transactions, Volume 76, Part II, 1970.

Decreasing marginal savings are most apparent where varying amounts of insulation are considered. The amount of heat which passes through a given section of insulation varies inversely with its depth. This results in smaller marginal energy savings generated by each additional inch.[39] Other energy conservation techniques may not be directly variable in increments in the same sense that insulation is. Some of these techniques can still benefit from the application of marginal analysis, however. Consider storm windows as an example: They come in a large range of sizes but vary little in cost up to a certain size (usually up to 100 united inches[40]). If each size window is ranked according to its savings/cost ratio, each window can be treated as a marginal investment and only those windows whose MS/MC ratio exceeds or equals the MS/MC ratio of other techniques is economically justifiable. This permits a great deal more flexibility in analyzing such techniques. Often storm windows have been found to be either economical or uneconomical, depending on climatic conditions or fuel costs. Now we may state that storm windows above a given size may be economical in certain areas even where storm windows on all windows may not be. As the climate grows more severe, or fuel prices increase, smaller and smaller windows will become cost effective. This will be demonstrated in the data generated in Section 5.

4.3 Measurement of Marginal Savings

There are three basic mechanisms through which heat transfer contributes to the heating and cooling loads of a building:

1) Conduction, or the flow of heat through mass in the direction of decreasing temperature.
2) Convection, or the flow of heat carried by a dynamic medium such as infiltrating air.
3) Radiation, or electromagnetic energy transmission which is converted to heat at its point of termination or absorption.

The retrofitting techniques considered in this study can effect direct reductions in the first two factors and indirectly reduce loads caused by the third. Solar shading is generally the most effective way to reduce radiation heat gain, especially through windows.

Hourly conductive heat losses and gains can be estimated using the following relationship:

$$H_{ch}/A = U \cdot (t_i - t_o), \tag{4-1}$$

where H_{ch} = hourly conductive Btu heat loss ($t_i > t_o$) or heat gain ($t_o > t_i$);

U = coefficient of conductance (Btu's per hour per square foot per degree Fahrenheit temperature difference (Btuh ft^{-2} F^{-1});

A = area in square feet (ft^2);

t_i = average inside air temperature; and

t_o = average outside air temperature.

As the thermal resistance (R) of an envelope section in increased, the thermal conductance (U) decreases in inverse proportion ($U = 1/R$), reducing the thermal load resulting from that section. The marginal Btu savings (ΔH_{ch}) due to the increase in resistance is then given by

$$\Delta H_{ch}/A = (U_1 - U_2) \cdot (t_i - t_o) \tag{4-2}$$

where U_1 = thermal conductance before R is increased,

U_2 = thermal conductance after R is increased.

Annual heating loads are found by taking the sum of the differences between inside and outside daily average temperatures (where $t_i > t_o$) during an annual heating season. When t_i is equated to 65°F, the degree day methodology for computing annual heating loads is consistent with the methodology outlined above:[41]

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[39] However, energy savings may still be significant. Every time that the total resistance of a thermal barrier is doubled, heat transfer through that barrier is halved.

[40] "United inches" equal height plus width in inches.

[41] Degree days are based on 65°F rather than 70°F as the 5°F temperature differential is considered to be provided by small solar radiation gains and internal heat sources other than direct heating and should therefore not be reflected in direct energy savings. For this reason all energy saving calculations, while reflecting a 70°F inside temperature, are based on 65°F.

$$H_{ca}/A = U \cdot DD \cdot 24, \tag{4-3}$$

where H_{ca} = annual Btu conductive heating load,

DD = annual degree days, and

24 = hours per day.

Annual cooling loads are found by using the average temperature difference between the inside and outside surface of the envelope section during the cooling hours.

$$C_{ca}/A = U \cdot CH \cdot (t_o - t_i), \tag{4-4}$$

where C_{ca} = annual Btu conductive cooling load, and

CH = annual cooling hours over 80°F

t_o = average outside temperature during cooling hours (sol air temperature equivalents used where appropriate.)

Marginal annual heating and cooling savings generated at any given envelope section are simply the difference between the loads before and after the last increment of thermal resistance is added.

Heating and cooling loads due to air infiltration in buildings are primarily a function of the cubic feet of air entering per hour and the temperature difference between the inside and outside air.

Direct reductions in these loads can be produced by installation of storm windows, storm doors and weather stripping. These loads are made up of two components, sensible heat and latent heat. Sensible heat loss (gain) is equivalent to the number of Btu required to heat (cool) the air, which enters by infiltration, to desired room temperature.

$$H_{sh} = 0.24 \cdot Q \cdot \rho \cdot (t_i - t_0), \tag{4-5}$$

where H_{sh} = sensible hourly Btu load,

0.24 = specific heat of air,

Q = volume of infiltrating air in cubic feet per hour,

ρ = density of air at t_o, pounds per cubic foot ($\simeq$ .075),

t_i = inside average air temperature, and

t_o = outside average air temperature.

The latent heat load is the Btu requirement for adding or removing moisture from the air. In winter this load is due chiefly to a humidifier, which is not considered in this study. In the summer this load is a complex function of humidity and internal moisture loads which are removed by the air conditioner. Because of the limited ability of home air conditioners to remove moisture from the air, it is not clear whether or not marginal decreases in infiltration will decrease the actual amount of latent heat removed. This is especially true where smaller equipment or less frequent utilization of equipment results from reduced sensible heat loads. For these reasons latent heat loads will not be considered in this study.

Degree days are utilized in estimating annual infiltration heat loads as well, so that the annual heat load due to infiltration (H_{sa}) is expressed by:

$$H_{sa} = 0.24 \cdot Q \cdot \rho \cdot DD \cdot 24, \tag{4-6}$$

and annual cooling load due to convection (C_{sa}) is expressed by

$$C_{sa} = 0.24 \cdot Q \cdot \rho \cdot CH \cdot (t_o - t_i). \tag{4-7}$$

Marginal heating and cooling loads are calculated using the difference between the infiltration rate before retrofit and after retrofit at any point in the building envelope.

The amount of fuel saved by increasing the thermal resistance or decreasing the rate of infiltration is a function of the load reduction, the Btu content of the fuel, and the efficiency of the mechanical equipment. The following Btu fuel contents were used in this study:

Natural gas = 100,000 Btu per therm,

#2 Heating Oil = 140,000 Btu per gallon, and

Electric Heating = 3,413 Btu per kWh.

Heating system efficiencies are typically between 50 to 70% for natural gas and fuel oil and 100% for electrical resistance heating. Air conditioners generally provide 6000-8000 Btu per kWh, having a coefficient of performance (COP) of approximately 2.

Annual marginal heating fuel savings (ΔF_h) are then estimated using

$$\Delta F_h = \frac{\Delta H_{ca} + \Delta H_{sa}}{B_h \cdot E_h} \tag{4-8}$$

where ΔH_{ca} = marginal annual Btu conductive heating load reduction,

ΔH_{sa} = marginal annual Btu infiltration heating load reduction.

B_h = Btu content per unit of heating fuel, and

E_h = efficiency of heating system.

Annual marginal cooling energy savings (ΔF_c) are estimated using

$$\Delta F_c = \frac{\Delta C_{ca} + \Delta C_{sa}}{3413\ \phi_c} \tag{4-9}$$

where ΔC_{ca} = marginal annual Btu conductive cooling load reduction,

ΔC_{sa} = marginal annual Btu infiltration cooling load reduction,

3414 = Btu per kWh

ϕ_c = Coefficient of performance

Algorithms for evaluating heat losses and heat gains from specific section of the building envelope are treated in Appendix D.

Annual marginal dollar savings (S) are then equivalent to $\Delta F_h \cdot P_1 + \Delta F_c \cdot P_2$, where

P_1 = price per unit of heating energy, and

P_2 = price per unit of cooling energy.

5. DISCUSSION OF RESULTS

5.1 General Observations

Using the general methodology outlined in Section 4 along with specific methodologies for the various techniques considered, as outlined in Appendix D, energy savings in eight different climatic regions were estimated for each inch of insulation up to 30 inches in attics, 10 inches below floors, 3.5 inches in walls, and 10 inches around exposed ducts, as well as for storm doors, storm windows, and weather stripping. These latter cases included savings generated by both loose and average fitting weather-stripped windows and doors.

The estimates generated using this methodology are based on a typical wood-frame residential structure.[1] However, the results are typical of a wide variety of construction types, with the exception of solid brick or masonry walls, slab floors on grade, and ceiling/roof systems with no attic space for additional insulation, in the cases of wall, floor, and attic insulation respectively. Again, insulation estimates are applicable only where no structural modifications are necessary.

Optimal combinations of ECT's have been estimated for five climatic regions ranging from 2,000 degree days to 10,000 degree days with no cooling requirements and for three regions with 500 to 1,500 cooling hours in addition to heating requirements. Although these regions are not typical of all U.S. climates, they represent a broad range of climatic conditions into which most housing requiring significant retrofitting can be interpolated.

In addition, these combinations were estimated for a wide range of current energy prices, enabling the reader to see the effect of these prices on the optimal levels of ECT investments determined as optimal. Note that the energy prices (including efficiency adjustments) used for heating fuels are varied by a factor of ten, i.e., from \$.15 per 100,000 Btu, representative of low-prices natural gas to \$1.50 per 100,000 Btu, representative of relatively high priced electric resistance heating. Cooling energy costs vary only by a factor of two because only electric energy is considered. (In addition, summer kWh costs are assumed to be \$.01 greater than winter kWh costs due to higher peak loading charges.) At the same time climatic conditions are varied by a maximum factor of five (2000 to 10,000 degree days). The paired heating and cooling energy costs shown are meant to be representative of frequently encountered price relationships. In some cases, where cooling requirements are present, the cooling energy costs corresponding to the heating energy costs shown may be substantially different. In this case some judgment will be needed in interpreting the tables or the model will have to be rerun for the actual prices encountered.

ECT costs, on the other hand, were held constant at representative mid-1974 price levels because these costs vary little compared to climate factors and energy prices. The costs actually used are listed in Appendix B. These include an allowance for commercial installation except in the cases of weather stripping and duct insulation (for reasons discussed in Appendix A).

Tables 5.2A through 5.2H contain the tabularized results of this study for the ECT's considered, based on a lifetime expectancy of 20 years for all but storm doors and weather stripping, for which 10 years may be considered more appropriate. This in effect limits the payback period of the last increment of any technique to 20 years (or 10 where appropriate) although the payback period for the total investment may be as low as one year in some cases. Techniques which have an "all or nothing" application, such as blown-in wall insulation, may take up to 20 years to pay back completely in this case. It should be remembered that this payback includes an after-tax-equivalent annual dividend equal to the actual rate of energy price increases so that it is very likely equal to or better than most other low risk investments available to homeowners. After 20 years all savings are free and clear in these extreme cases.

Before examining these tables more closely, several general observations should be made:

1) Each table lists seven combinations of ECT's for a given climatic zone which are economically balanced in the sense that the MS/MC ratio is equal at the margin for each technique within a given combination (except where limited by physical constraints). More importantly, each combination is optimal at the indicated heating and cooling energy prices in the sense that MC = MS. Therefore dollar savings are maximized when the combination chosen reflects the energy prices encountered at the building site. However, any combination within a given climate will maximize dollar savings per dollar invested. This is important because these other combinations can serve as a guide to those who do not wish to invest up to the point where MS = MC but wish to maximize the return on the dollars that they do invest. In essence this implies that significant departure from these combinations will produce suboptimal results given that there are no physical constraints in the relevant range, and structural conditions and costs of retrofitting are similar to those assumed.

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[1] Walls and roof are assumed unshaded; doors assumed shaded.

2) It is important to note that, while fixed costs may vary, relatively similar marginal costs will give rise to these same optimal combinations of techniques. Thus in cases involving insulation, where installation charges are approximately constant over a given rnage of application (say from 2 to 6 inches), leaving marginal costs equal to incremental materials cost within that range, the optimal level of application will be the same whether it is commercially installed or installed by the homeowner himself, provided, of course, that the total cost (installation and materials costs) are not greater than total savings. Payback periods, however, may be considerably shortened if the homeowner installs these ECT's himself.

3) These estimates were derived using an annual discount rate representing a rate of return at the margin equal to the best alternative use of the marginal investment funds available to the average homeowner. The real discount rate used (1% compounded annually) is equivalent to the real assumed rate of energy price increases (1% compounded annually) over the appropriate lifetime (20 years).

4) These optimal investment levels are not based on an assumed building size or configuration.[41] Insulation levels were determined by examining the thermal transfer through a single square foot of the appropriate envelope section. Doors and windows were analyzed as discrete entities. Weather stripping was examined per foot of crack length. Thus these optimal levels, where applicable, are appropriate to any building size or design; however the payback period for the total retrofitting investment will be a weighted average of the payback periods for each ECT used. The weighting factors will be the percent of the total retrofitting investment applied to each ECT. In essence this means that the average payback period will vary from house to house, even in the same climate and fuel price market, because of design differences and the degree to which the various envelope sections require energy conservation modifications.

5) The energy savings on which these optimal combinations of ECT's are based were calculated assuming an average indoor temperature of approximately 70°F during winter heating and 75°F during summer cooling.[42] Higher average temperatures during the winter and lower average temperatures during the summer will result in higher levels of ECT investment; the reverse will lower these levels. The amount of change will vary from region to region, varying as a function of the percent change in the indoor-outdoor temperature differential.

6) Infiltration reductions due to weather stripping and storm windows and doors are subject to considerable variation depending on the actual leakage conditions of the primary windows and doors. Payback period for storm windows include an allowance for reduction of infiltration. Due to the wide variation in potential energy savings from weather stripping as well as the wide variation in costs, no payback periods for weather stripping are presented. Calculations using the ASHRAE crack methodology for estimating infiltration around windows and doors, as outlined in Appendix D, together with costs of materials based on $.15 per linear foot, show this ECT to be economically justified in all cases where a 20-year life is assumed. Where a 10-year life is assumed all but average fitting windows (or windows with existing storm windows) in the mildest climates with low fuel prices ($.15-.30 per therm output) are cost effective. Weather-stripping materials are available at costs considerably below %.15 per linear foot, however, so that this technique is considered cost effective in all climates and for all fuel prices.

7) The appropriate unit energy cost to use with the following tables is that rate, including all taxes and surcharges, at which the last unit saved by retrofitting would have been purchased. For natural gas and electricity, cost per unit often decreases as more is used per month. (Summer rates for electric power increase after a certain level of consumption in many areas now.) For this reason average costs for these fuels may not be representative of the cost per unit saved. Homeowners should request detailed price schedules from their utility companies which list the prices actually charged by "block" of fuel use, making sure that this includes all relevant taxes and surcharges, in order to determine the proper unit energy prices to use with these tables.

The cost per unit of fuel can be converted to cost per 100,000 Btu output (i.e., after efficiency considerations are made) using Table 5.1. Fuel costs equivalents are shown for a range of utilization efficiencies for gas and oil furnaces and electric resistance heating as well as for typical seasonal equivalent coefficients of performance (COP) for heat pumps and air conditioners. Cost per 100,000 Btu output is calculated for gas, oil, and electric resistance heating as follows:

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[41] Attic, crawlspace, and basement temperatures were calculated using a fixed-size house. Such temperatures are meant to be an average, however, and as such, representative of all such unheated areas.

[42] These temperatures were selected because the best data available for thermal load calculations are based on them. This study in no way suggests that they are appropriate thermostat settings for the homeowner.

$$\text{Cost/100,000 Btu} = \frac{100{,}000 \text{ Btu}}{(\text{Btu content/unit}) \times \text{efficiency}} \times \$/\text{unit.}$$

For heat pumps and electric air conditioners use:

$$\text{Cost/100,000 Btu} = \frac{100{,}000 \text{ Btu}}{3413 \text{ Btu/kWh} \times \text{COP}} \times \$/\text{KWH}$$

8) The effects of differential ECT marginal costs on optimal investment levels can be simulated by changing energy costs for any or all techniques. Because marginal/savings (MS) are directly proportional to energy prices, any percentage change in energy price will result in a corresponding percentage change in MS.

Since

$$\frac{MS/a}{MC} = \frac{MS}{aMC} = 1, \qquad \text{(Condition I met for new MC)}$$

where a = the adjustment factor for marginal cost, such adjustments can be simulated by dividing the appropriate energy price by this adjustment factor. This adjusted energy price can be used as a "reference" energy price for finding the optimal level of investment in the ECT under examination.[43]

As an example, consider the case of insulation used for winter heating savings (no cooling load) with a fuel priced at $.45/100,000 Btu delivered (efficiency considerations accounted for). Suppose that the variable costs of such insulation were raised by 10% (an adjustment factor of 1.1) over the costs shown in Appendix B. In this case a reference energy price of $.41 (.45/1.1) will simulate the effect of the cost differential. Note that relatively small changes in ECT costs (<20%) will have small practical effects on the optimal levels of investment.

5.2 Tabular Results

Tables 5.2A through 5.2H present the estimates of optimal energy conservation combinations for a variety of climates and a wide range of energy prices. In the case of attic and wall insulation, several insulating materials are examined: loose fill glass fiber (R-2.2 per inch), glass fiber batt/blanket (R-3.1 per inch), and loose fill cellulose (R-3.7 per inch in attics and R-3.3 per inch in walls). Insulation in ceiling and floors is examined in the case of no existing insulation and for an existing R-11 base (equivalent to 3.5 inches of glass fiber batt/blanket). Walls are assumed uninsulated; if any insulation exists, blown-in insulation is not practical and unlikely to be cost effective. Duct wrap for insulating heating and cooling ducts in unheated areas is examined. Insulation should be raised to the level shown. (Duct connections should be retaped first, if necessary). Data shown are for ducts in attic spaces. For crawlspaces, garages or unheated basements, the duct estimates for winter degree days only will provide a better guide than those tables showing both heating and cooling requirements.

Minimum storm window sizes that appear cost effective are shown in the tables; sizes 2' x 2' through 4' x 6' were examined for both loose and average fitting, weather-stripped, double-hung, wood-frame prime windows. Results do not appear to vary significantly for these two types of windows once weather stripped. Savings from storm windows over casement windows and fixed (non-openable) windows may be similar as well.

Payback periods are shown for a 3' x 5' window in order to give some indication of the payback period for average size windows. Both winter heating and summer cooling savings are considered.

Storm doors, on the other hand, are considered for winter heating savings only (screen inserts are generally more useful for natural ventilation during the non-heating months.) Energy savings due to the use of storm doors are based on an assumed wooden, weather-stripped prime door, 1.5" thick, size 3' x 6'8", with glass composition ranging from 0 to 50%. Again both loose and average fitting units were examined and found to be similar in savings potential. Results shown are for average fitting prime doors. Prime doors with window sections lose more heat than solid doors under similar thermal loading conditions so that energy savings generated by storm doors increase as the percentage of glass in the prime door increases. In some cases the application of storm doors to prime doors with glass components will be cost effective even while application to solid doors is not. (In Tables 5.2A-H, applications of storm doors which appear to be economical are marked with an x followed by the minimum percentage of glass in the prime door that makes their use justifiable from an economic standpoint.)

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[43] This will not provide exact solutions in those tables (5.2 F-H) which involve both heating and cooling loads because the two sets of energy prices used are not strictly proportional. Note that only changes in variable costs need be adjusted for; changes in fixed costs will have no effect on optimal levels unless they are so high as to eliminate all net savings.

Table 5.1

FUEL COSTS NORMALIZED TO 100,000 Btu OUTPUT

A. HEATING

Cost per 100,000 Btu delivered	$0.15	$0.30	$0.45	$0.60	$0.90	$1.20	$1.50
1. Natural gas (100,000 Btu/therm)							
$/therm a. 50% efficiency	.075	.15	.23	.30	.45	----	----
$/therm b. 70% efficiency	.105	.21	.32	.42	.63	----	----
2. #2 fuel oil (140,000 Btu/gallon)							
$/gallon a. 50% efficiency	.105	.21	.32	.42	.63	----	----
$/gallon b. 70% efficiency	.15	.30	.44	.59	.89	----	----
3. Electric Resistance (3413 Btu/kWh)							
$/kWh 100% efficiency	.005	.01	.015	.02	.03	.04	.05
4. Electric Heat Pump (6826 Btu/kWh)							
$/kWh seasonal COP=2 (EER=6.826)	.01	.02	.03	.04	.06	.08	.10

B. Cooling

Cost per 100,000 Btu removed	$0.45	$0.45	$0.45	$0.45	$0.60	$0.75	$0.90
1. Air Conditioner (6826 Btu/kWh)							
$/kWh COP=2 (EER=6.826)	.03	.03	.03	.03	.04	.05	.06

Table 5.2A

OPTIMAL ENERGY CONSERVATION COMBINATIONS

2000 Degree Days ; 0 Cooling Hours, (– Avg. t_0); 20 Year Life

ELEMENT	ATTIC						WALL		FLOOR Over Unheated Area 1.		EXPOSED DUCTS Equipment Operational Time for Average Loading Conditions			ENERGY PRICES Dollar Cost per 100,000 Btu's Delivered/Removed		ELEMENT	STORM WINDOWS 2. (Triple Track)	STORM DOORS 3.
											20%	30%	40%					
Existing Insulation	None			R-11*			None		None	R-11*	None							
Material Used	A	B	C	A	B	C	B	C	B		D	D	D	Heating	Cooling			
Additional Inches	3"	4"	2"	0	0	0	3"	0	0	0	2"	2"	3"	$.15	$.45		0	0
Years to Pay Back	(19)	(15)	(18)	(0)	(0)	(0)	(11)	(0)	(0)	(0)	(3)	(2)	(2)			Years to Pay Back	(0)	(0)
Additional Inches	4"	4"	3"	0	0	0	3"	0	0	0	3"	4"	4"	$.30	$.45		4' x 5'	0
Years to Pay Back	(10)	(8)	(10)	(0)	(0)	(0)	(6)	(0)	(0)	(0)	(2)	(2)	(2)			Years to Pay Back	(23)	(0)
Additional Inches	6"	6"	4"	0	0	0	3.5"	3.5"	0	0	4"	4"	5"	$.45	$.45		3' x 4'	0
Years to Pay Back	(8)	(7)	(8)	(0)	(0)	(0)	(4)	(17)	(0)	(0)	(2)	(1)	(1)			Years to Pay Back	(15)	(0)
Additional Inches	7"	6"	4"	0	4"	0	3.5"	3.5"	0	0	4"	5"	6"	$.60	$.45		3' x 3'	0
Years to Pay Back	(7)	(5)	(6)	(0)	(17)	(0)	(3)	(13)	(0)	(0)	(2)	(1)	(1)			Years to Pay Back	(12)	(0)
Additional Inches	9"	10"	6"	4"	4"	3"	3.5"	3.5"	4"	0	5"	6"	7"	$.90	$.60		2' x 3'	0
Years to Pay Back	(5)	(5)	(5)	(16)	(10)	(15)	(2)	(9)	(16)	(0)	(1)	(1)	(1)			Years to Pay Back	(8)	0
Additional Inches	11"	10"	7"	6"	6"	4"	3.5"	3.5"	4"	0	6"	7"	9"	$1.20	$.75		2' x 3'	0
Years to Pay Back	(5)	(4)	(5)	(13)	(10)	(13)	(2)	(7)	(12)	(0)	(1)	(1)	(1)			Years to Pay Back	(6)	(0)
Additional Inches	12"	10"	8"	7"	6"	5"	3.5"	3.5"	6"	0	7"	8"	10"	$1.50	$.90		2' x 2'	0
Years to Pay Back	(4)	(3)	(4)	(11)	(8)	(11)	(2)	(5)	(11)	(0)	(1)	(1)	(1)			Years to Pay Back	(5)	(0)

*Equivalent to 3½" of Glass Fiber Batt/Blanket Insulation

A – Loose Fill Glass Fiber (R-2.2 per inch)

B – Glass Fiber Batt/Blanket (R-3.1 per inch) (not applicable to finished walls)

C – Loose Fill Cellulose Fiber (R-3.7 per inch in attic/R-3.3 per inch in walls)

D – Glass Fiber Duct Wrap (R-4 per inch)

1. Floor Over Unheated Basement, Crawlspace, or Garage
2. Minimum Economical Size; Payback for 3'x5' Storm Window
3. Refers to Minimum Glass Composition of Primary Door That Makes Storm Door Economical (10 year life)

Table 5.2B

OPTIMAL ENERGY CONSERVATION COMBINATIONS

4000 Degree Days ; 0 Cooling Hours, (– Avg. t_0); 20 Year Life

ELEMENT	ATTIC						WALL		FLOOR Over Unheated Area[1]		EXPOSED DUCTS Equipment Operational Time for Average Loading Conditions			ENERGY PRICES Dollar Cost per 100,000 Btu's Delivered/Removed		ELEMENT	STORM WINDOWS[2] (Triple Track)	STORM DOORS[3]
											20%	30%	40%					
Existing Insulation	None			R-11*			None		None	R-11*	None							
Material Used	A	B	C	A	B	C	B	C	B	B	D	D	D	Heating	Cooling			
Additional Inches	5"	4"	3"	0	0	0	3"	0"	4"	0	2"	3"	3"	$.15	$.45		4' x 5'	0
Years to Pay Back	(8)	(6)	(8)	(0)	(0)	(0)	(6)	(0)	(14)	(0)	(3)	(2)	(2)			Years to Pay Back	(23)	(0)
Additional Inches	7"	6"	5"	0"	4"	0"	3.5"	3.5"	4"	0	3"	4"	5"	$.30	$.45		3' x 3'	0
Years to Pay Back	(5)	(4)	(5)	(0)	(17)	(0)	(3)	(13)	(7)	(0)	(2)	(2)	(1)			Years to Pay Back	(12)	(0)
Additional Inches	9"	10"	6"	4"	4"	3"	3.5"	3.5"	6"	4"	4"	5"	6"	$.45	$.45		2' x 3'	0
Years to Pay Back	(4)	(4)	(4)	(15)	(10)	(15)	(2)	(9)	(6)	(20)	(2)	(1)	(1)			Years to Pay Back	(8)	(0)
Additional Inches	11"	10"	7"	6"	6"	4"	3.5"	3.5"	6"	4"	5"	6"	7"	$.60	$.45		2' x 3'	0
Years to Pay Back	(4)	(3)	(4)	(13)	(10)	(12)	(2)	(7)	(4)	(15)	(1)	(1)	(1)			Years to Pay Back	(6)	(0)
Additional Inches	13"	12"	9"	9"	10"	6"	3.5"	3.5"	10"	6"	6"	7"	8"	$.90	$.60		2' x 2'	0
Years to Pay Back	(3)	(2)	(3)	(10)	(8)	(10)	(1)	(5)	(4)	(11)	(1)	(1)	(1)			Years to Pay Back	(4)	(0)
Additional Inches	16"	16"	10"	11"	12"	7"	3.5"	3.5"	10"	6"	7"	8"	10"	$1.20	$.75		2' x 2'	x/40%
Years to Pay Back	(3)	(2)	(2)	(9)	(7)	(8)	(1)	(4)	(3)	(8)	(1)	(1)	(1)			Years to Pay Back	(3)	(10)
Additional Inches	18"	16"	11"	13"	12"	8"	3.5"	3.5"	10"	6"	8"	9"	10"	$1.50	$.90		2' x 2'	x/20%
Years to Pay Back	(2)	(2)	(2)	(8)	(6)	(7)	(1)	(3)	(3)	(7)	(1)	(1)	(1)			Years to Pay Back	(3)	(10)

*Equivalent to 3½" of Glass Fiber Batt/Blanket Insulation
A – Loose Fill Glass Fiber (R-2.2 per inch)
B – Glass Fiber Batt/Blanket (R-3.1 per inch) (not applicable to finished walls)
C – Loose Fill Cellulose Fiber (R-3.7 per inch in attic/R-3.3 per inch in walls)
D – Glass Fiber Duct Wrap (R-4 per inch)

1. Floor Over Unheated Basement, Crawlspace, or Garage
2. Minimum Economical Size; Payback for 3'x5' Storm Window
3. Refers to Minimum Glass Composition of Primary Door That Makes Storm Door Economical (10 year life)

Table 5.2C

OPTIMAL ENERGY CONSERVATION COMBINATIONS

6000 Degree Days ; 0 Cooling Hours, (- Avg. t_0); 20 Year Life

ELEMENT	ATTIC						WALL		FLOOR Over Unheated Area[1]		EXPOSED DUCTS Equipment Operational Time for Average Loading Conditions			ENERGY PRICES Dollar Cost per 100,000 Btu's Delivered/Removed		ELEMENT	STORM WINDOWS[2] (Triple Track)	STORM DOORS[3]
											20%	30%	40%					
Existing Insulation	None			R-11*			None		None	R-11*	None							
Material Used	A	B	C	A	B	C	B	C	B	B	D	D	D	Heating	Cooling			
Additional Inches	6"	6"	4"	0	0	0	3.5"	3.5"	4"	0	3"	3"	4"	$.15	$.45		3' x 4'	0
Years to Pay Back	(6)	(5)	(6)	(0)	(0)	(0)	(4)	(17)	(8)	(0)	(3)	(2)	(2)			Years to Pay Back	(15)	(0)
Additional Inches	9"	10"	6"	4"	4"	3"	3.5"	3.5"	6"	4"	4"	5"	5"	$.30	$.45		2' x 3'	0
Years to Pay Back	(4)	(4)	(4)	(15)	(10)	(15)	(2)	(9)	(5)	(10)	(2)	(2)	(1)			Years to Pay Back	(8)	(0)
Additional Inches	11"	10"	7"	7"	6"	4"	3.5"	3.5"	10"	4"	5"	6"	7"	$.45	$.45		2' x 2'	0
Years to Pay Back	(3)	(2)	(3)	(12)	(8)	(11)	(2)	(6)	(5)	(12)	(2)	(1)	(1)			Years to Pay Back	(5)	(0)
Additional Inches	14"	12"	9"	9"	10"	6"	3.5"	3.5"	10"	6"	6"	7"	8"	$.60	$.45		2' x 2'	0
Years to Pay Back	(3)	(2)	(3)	(10)	(8)	(10)	(1)	(5)	(4)	(10)	(1)	(1)	(1)			Years to Pay Back	(4)	(0)
Additional Inches	17"	16"	11"	12"	12"	8"	3.5"	3.5"	10"	6"	7"	8"	9"	$.90	$.60		2' x 2'	x/30%
Years to Pay Back	(2)	(2)	(2)	(8)	(6)	(8)	(1)	(3)	(3)	(7)	(1)	(1)	(1)			Years to Pay Back	(3)	(10)
Additional Inches	20"	18"	12"	15"	16"	10"	3.5"	3.5"	10"	6"	8"	9"	10"	$1.20	$.75		2' x 2'	x/10%
Years to Pay Back	(2)	(2)	(2)	(7)	(6)	(7)	(1)	(2)	(2)	(5)	(1)	(1)	(1)			Years to Pay Back	(2)	(10)
Additional Inches	22"	18"	14"	18"	18"	11"	3.5"	3.5"	10"	6"	8"	10"	10"	$1.50	$.90		2' x 2'	x/0%
Years to Pay Back	(2)	(2)	(2)	(6)	(5)	(6)	(1)	(2)	(2)	(4)	(1)	(1)	(1)			Years to Pay Back	(2)	(10)

*Equivalent to 3½" of Glass Fiber Batt/Blanket Insulation
A – Loose Fill Glass Fiber (R-2.2 per inch)
B – Glass Fiber Batt/Blanket (R-3.1 per inch) (not applicable to finished walls)
C – Loose Fill Cellulose Fiber (R-3.7 per inch in attic/R-3.3 per inch in walls)
D – Glass Fiber Duct Wrap (R-4 per inch)

1. Floor Over Unheated Basement, Crawlspace, or Garage
2. Minimum Economical Size; Payback for 3'x5' Storm Window
3. Refers to Minimum Glass Composition of Primary Door That Makes Storm Door Economical (10 year life)

Table 5.2D

OPTIMAL ENERGY CONSERVATION COMBINATIONS

8000 Degree Days ; 0 Cooling Hours, (- Avg. t_0); 20 Year Life

ELEMENT	ATTIC						WALL		FLOOR Over Unheated Area[1]		EXPOSED DUCTS Equipment Operational Time for Average Loading Conditions 20% 30% 40%			ENERGY PRICES Dollar Cost per 100,000 Btu's Delivered/Removed		ELEMENT	STORM WINDOWS[2] (Triple Track)	STORM DOORS[3]
Existing Insulation	None			R-11*			None		None	R-11*	None							
Material Used	A	B	C	A	B	C	B	C	B	B	D	D	D	Heating	Cooling			
Additional Inches	7"	6"	5"	0"	4"	2"	3.5"	3.5"	6"	0"	3"	3"	4"	$.15	$.45		3' x 3'	0
Years to Pay Back	(5)	(3)	(5)	(0)	(16)	(20)	(3)	(13)	(7)	(0)	(2)	(2)	(2)			Years to Pay Back	(12)	(0)
Additional Inches	11"	10"	7"	6"	6"	4"	3.5"	3.5"	10"	4"	4"	5"	6"	$.30	$.45		2' x 3'	0
Years to Pay Back	(3)	(3)	(3)	(13)	(9)	(12)	(2)	(7)	(5)	(12)	(2)	(1)	(1)			Years to Pay Back	(6)	(0)
Additional Inches	14"	12"	9"	9"	10"	6"	3.5"	3.5"	10"	6"	5"	6"	7"	$.45	$.45		2' x 2'	0
Years to Pay Back	(3)	(2)	(3)	(10)	(8)	(10)	(1)	(5)	(3)	(10)	(1)	(1)	(1)			Years to Pay Back	(4)	(0)
Additional Inches	16"	16"	10"	11"	12"	7"	3.5"	3.5"	10"	6"	6"	7"	8"	$.60	$.45		2' x 2'	x/40%
Years to Pay Back	(2)	(2)	(2)	(9)	(7)	(8)	(1)	(4)	(3)	(7)	(1)	(1)	(1)			Years to Pay Back	(3)	(10)
Additional Inches	20"	18"	13"	15"	16"	10"	3.5"	3.5"	10"	6"	7"	9"	10"	$.90	$.60		2' x 2'	x/10%
Years to Pay Back	(2)	(2)	(2)	(7)	(6)	(7)	(1)	(2)	(2)	(5)	(1)	(1)	(1)			Years to Pay Back	(3)	(10)
Additional Inches	23"	22"	15"	18"	18"	12"	3.5"	3.5"	10"	6"	8"	10"	10"	$1.20	$.75		2' x 2'	x/0%
Years to Pay Back	(2)	(2)	(2)	(6)	(5)	(6)	(1)	(2)	(2)	(4)	(1)	(1)	(1)			Years to Pay Back	(2)	(9)
Additional Inches	26"	24"	16"	21"	18"	14"	3.5"	3.5"	10"	6"	9"	10"	10"	$1.50	$.90		2' x 2'	x/0%
Years to Pay Back	(2)	(1)	(1)	(5)	(4)	(5)	(1)	(2)	(1)	(3)	(1)	(1)	(1)			Years to Pay Back	(1)	(7)

*Equivalent to 3½" of Glass Fiber Batt/Blanket Insulation
A – Loose Fill Glass Fiber (R-2.2 per inch)
B – Glass Fiber Batt/Blanket (R-3.1 per inch) (not applicable to finished walls)
C – Loose Fill Cellulose Fiber (R-3.7 per inch in attic/R-3.3 per inch in walls)
D – Glass Fiber Duct Wrap (R-4 per inch)

1. Floor Over Unheated Basement, Crawlspace, or Garage
2. Minimum Economical Size; Payback for 3'x5' Storm Window
3. Refers to Minimum Glass Composition of Primary Door That Makes Storm Door Economical (10 year life)

Table 5.2E

OPTIMAL ENERGY CONSERVATION COMBINATIONS

10,000 Degree Days; 0 Cooling Hours, (- Avg. t_0); 20 Year Life

ELEMENT	ATTIC						WALL		FLOOR Over Unheated Area[1]		EXPOSED DUCTS Equipment Operational Time for Average Loading Conditions			ENERGY PRICES Dollar Cost per 100,000 Btu's Delivered/Removed		ELEMENT	STORM WINDOWS[2] (Triple Track)	STORM DOORS[3]
											20%	30%	40%					
Existing Insulation	None			R-11*			None		None	R-11*	None							
Material Used	A	B	C	A	B	C	B	C	B	B	D	D	D	Heating	Cooling			
Additional Inches	8"	6"	5"	3"	4"	2"	3.5"	3.5"	6"	4"	3"	4"	4"	$.15	$.45		2' x 3'	0
Years to Pay Back	(4)	(3)	(4)	(17)	(13)	(16)	(3)	(10)	(5)	(20)	(2)	(2)	(2)			Years to Pay Back	(10)	(0)
Additional Inches	12"	12"	8"	7"	6"	5"	3.5"	3.5"	10"	6"	4"	5"	6"	$.30	$.45		2' x 2'	0
Years to Pay Back	(3)	(2)	(3)	(11)	(8)	(10)	(2)	(5)	(4)	(11)	(2)	(1)	(1)			Years to Pay Back	(5)	(0)
Additional Inches	15"	12"	10"	11"	10"	7"	3.5"	3.5"	10"	6"	5"	7"	8"	$.45	$.45		2' x 2'	x/50%
Years to Pay Back	(2)	(2)	(2)	(9)	(6)	(8)	(1)	(4)	(3)	(7)	(1)	(1)	(1)			Years to Pay Back	(4)	(10)
Additional Inches	18"	16"	11"	13"	12"	9"	3.5"	3.5"	10"	6"	6"	8"	9"	$.60	$.45		2' x 2'	x/20%
Years to Pay Back	(2)	(2)	(2)	(7)	(6)	(7)	(1)	(3)	(2)	(6)	(1)	(1)	(1)			Years to Pay Back	(3)	(10)
Additional Inches	22"	18"	14"	18"	18"	11"	3.5"	3.5"	10"	6"	8"	9"	10"	$.90	$.60		2' x 2'	x/10%
Years to Pay Back	(2)	(1)	(2)	(6)	(5)	(6)	(1)	(2)	(2)	(4)	(1)	(1)	(1)			Years to Pay Back	(2)	(10)
Additional Inches	26"	24"	16"	21"	18"	14"	3.5"	3.5"	10"	6"	9"	10"	10"	$1.20	$.75		2' x 2'	x/0%
Years to Pay Back	(2)	(1)	(1)	(5)	(4)	(5)	(1)	(2)	(1)	(3)	(1)	(1)	(1)			Years to Pay Back	(2)	(7)
Additional Inches	29"	24"	18"	25"	25"	16"	3.5"	3.5"	10"	6"	10"	10"	10"	$1.50	$.90		2' x 2'	x/0%
Years to Pay Back	(2)	(1)	(1)	(5)	(4)	(5)	(1)	(2)	(1)	(2)	(1)	(1)	(1)			Years to Pay Back	(1)	(6)

*Equivalent to 3½" of Glass Fiber Batt/Blanket Insulation
A – Loose Fill Glass Fiber (R-2.2 per inch)
B – Glass Fiber Batt/Blanket (R-3.1 per inch) (not applicable to finished walls)
C – Loose Fill Cellulose Fiber (R-3.7 per inch in attic/R-3.3 per inch in walls)
D – Glass Fiber Duct Wrap (R-4 per inch)

1. Floor Over Unheated Basement, Crawlspace, or Garage
2. Minimum Economical Size; Payback for 3'x5' Storm Window
3. Refers to Minimum Glass Composition of Primary Door That Makes Storm Door Economical (10 year life)

Table 5.2F

OPTIMAL ENERGY CONSERVATION COMBINATIONS

2000 Degree Days ; 1500 Cooling Hours, (95° Avg. t_0); 20 Year Life

ELEMENT	ATTIC						WALL		FLOOR Over Unheated Area[1]		EXPOSED DUCTS Equipment Operational Time for Average Loading Conditions			ENERGY PRICES Dollar Cost per 100,000 Btu's Delivered/Removed		ELEMENT	STORM WINDOWS[2] (Triple Track)	STORM DOORS[3]
											20%	30%	40%					
Existing Insulation	None			R-11*			None		None	R-11*	None							
Material Used	A	B	C	A	B	C	B	C	B		D	D	D	Heating	Cooling			
Additional Inches	8"	6"	5"	3"	4"	2"	3.5"	3.5"	0	0	3"	3"	4"	$.15	$.45		3' x 5'	0
Years to Pay Back	(5)	(3)	(5)	(20)	(15)	(18)	(4)	(16)	(0)	(0)	(3)	(2)	(2)			Years to Pay Back	(15)	(0)
Additional Inches	9"	10"	5"	4"	4"	3"	3.5"	3.5"	0	0	3"	4"	5"	$.30	$.45		3' x 3'	0
Years to Pay Back	(5)	(4)	(4)	(17)	(11)	(16)	(3)	(12)	(0)	(0)	(2)	(2)	(1)			Years to Pay Back	(11)	(0)
Additional Inches	9"	10"	6"	5"	6"	3"	3.5"	3.5"	0	0	4"	5"	6"	$.45	$.45		3' x 3'	0
Years to Pay Back	(4)	(4)	(4)	(15)	(12)	(14)	(3)	(10)	(0)	(0)	(2)	(1)	(1)			Years to Pay Back	(5)	(0)
Additional Inches	10"	10"	7"	5"	6"	4"	3.5"	3.5"	0	0	5"	6"	7"	$.60	$.45		2' x 3'	0
Years to Pay Back	(4)	(3)	(4)	(13)	(10)	(13)	(2)	(8)	(0)	(0)	(2)	(1)	(1)			Years to Pay Back	(7)	(0)
Additional Inches	13"	12"	8"	8"	10"	5"	3.5"	3.5"	4"	0"	6"	7"	8"	$.90	$.60		2' x 2'	0
Years to Pay Back	(3)	(3)	(3)	(11)	(10)	(10)	(2)	(6)	(16)	(0)	(1)	(1)	(1)			Years to Pay Back	(5)	(0)
Additional Inches	15"	12"	9"	10"	10"	6"	3.5"	3.5"	4"	0"	6"	8"	9"	$1.20	$.75		2' x 2'	0
Years to Pay Back	(3)	(2)	(3)	(9)	(7)	(9)	(1)	(5)	(12)	(0)	(1)	(1)	(1)			Years to Pay Back	(4)	(0)
Additional Inches	16"	16"	10"	12"	12"	8"	3.5"	3.5"	6"	0"	7"	9"	10"	$1.50	$.90		2' x 2'	0
Years to Pay Back	(3)	(2)	(3)	(9)	(7)	(8)	(1)	(4)	(11)	(0)	(1)	(1)	(1)			Years to Pay Back	(3)	(0)

*Equivalent to 3½" of Glass Fiber Batt/Blanket Insulation

A – Loose Fill Glass Fiber (R-2.2 per inch)

B – Glass Fiber Batt/Blanket (R-3.1 per inch) (not applicable to finished walls)

C – Loose Fill Cellulose Fiber (R-3.7 per inch in attic/R-3.3 per inch in walls)

D – Glass Fiber Duct Wrap (R-4 per inch)

1. Floor Over Unheated Basement, Crawlspace, or Garage
2. Minimum Economical Size; Payback for 3'x5' Storm Window
3. Refers to Minimum Glass Composition of Primary Door That Makes Storm Door Economical (10 year life)

Table 5.2G

OPTIMAL ENERGY CONSERVATION COMBINATIONS

4000 Degree Days ; 1000 Cooling Hours, (90° Avg. t_o); 20 Year Life

ELEMENT	ATTIC						WALL		FLOOR Over Unheated Area[1]		EXPOSED DUCTS Equipment Operational Time for Average Loading Conditions 20%	30%	40%	ENERGY PRICES Dollar Cost per 100,000 Btu's Delivered/Removed		ELEMENT	STORM WINDOWS[2] (Triple Track)	STORM DOORS[3]
Existing Insulation	None			R-11*			None		None	R-11*	None							
Material Used	A	B	C	A	B	C	B	C	B	B	D	D	D	Heating	Cooling			
Additional Inches	7"	6"	5"	0"	4"	2"	3.5"	3.5"	4"	0"	3"	3"	4"	$.15	$.45		3' x 4'	0
Years to Pay Back	(5)	(4)	(5)	(0)	(16)	(20)	(4)	(16)	(14)	(0)	(3)	(2)	(2)			Years to Pay Back	(16)	(0)
Additional Inches	9"	10"	6"	4"	4"	3"	3.5"	3.5"	4"	0"	4"	4"	5"	$.30	$.45		3' x 3'	0
Years to Pay Back	(4)	(4)	(4)	(15)	(10)	(15)	(3)	(10)	(7)	(0)	(2)	(1)	(1)			Years to Pay Back	(10)	(0)
Additional Inches	11"	10"	7"	6"	6"	4"	3.5"	3.5"	6"	4"	4"	5"	6"	$.45	$.45		2' x 3'	0
Years to Pay Back	(4)	(3)	(3)	(13)	(9)	(12)	(2)	(7)	(6)	(20)	(1)	(1)	(1)			Years to Pay Back	(7)	(0)
Additional Inches	12"	12"	8"	7"	6"	5"	3.5"	3.5"	6"	4"	5"	6"	7"	$.60	$.45		2' x 2"	0
Years to Pay Back	(3)	(3)	(3)	(11)	(8)	(11)	(2)	(6)	(4)	(15)	(1)	(1)	(1)			Years to Pay Back	(5)	(0)
Additional Inches	15"	12"	10"	10"	10"	7"	3.5"	3.5"	10"	6"	6"	8"	9"	$.90	$.60		2' x 2'	0
Years to Pay Back	(3)	(2)	(3)	(9)	(6)	(9)	(1)	(4)	(4)	(11)	(1)	(1)	(1)			Years to Pay Back	(3)	(0)
Additional Inches	18"	16"	11"	13"	12"	8"	3.5"	3.5"	10"	6"	7"	9"	10"	$1.20	$.75		2' x 2'	x/40%
Years to Pay Back	(2)	(2)	(2)	(8)	(6)	(7)	(1)	(3)	(3)	(8)	(1)	(1)	(1)			Years to Pay Back	(3)	(10)
Additional Inches	20"	18"	12"	15"	16"	10"	3.5"	3.5"	10"	6"	8"	10"	10"	$1.50	$.90		2' x 2'	x/20%
Years to Pay Back	(2)	(2)	(2)	(7)	(6)	(7)	(1)	(3)	(3)	(7)	(1)	(1)	(1)			Years to Pay Back	(2)	(10)

*Equivalent to 3½" of Glass Fiber Batt/Blanket Insulation
A – Loose Fill Glass Fiber (R-2.2 per inch)
B – Glass Fiber Batt/Blanket (R-3.1 per inch) (not applicable to finished walls)
C – Loose Fill Cellulose Fiber (R-3.7 per inch in attic/R-3.3 per inch in walls)
D – Glass Fiber Duct Wrap (R-4 per inch)

1. Floor Over Unheated Basement, Crawlspace, or Garage
2. Minimum Economical Size; Payback for 3'x5' Storm Window
3. Refers to Minimum Glass Composition of Primary Door That Makes Storm Door Economical (10 year life)

Table 5.2H

OPTIMAL ENERGY CONSERVATION COMBINATIONS

6000 Degree Days; 500 Cooling Hours, (90° Avg. t_0); 20 Year Life

ELEMENT	ATTIC						WALL		FLOOR Over Unheated Area[1]		EXPOSED DUCTS Equipment Operational Time for Average Loading Conditions			ENERGY PRICES Dollar Cost per 100,000 Btu's Delivered/Removed		ELEMENT	STORM WINDOWS[2] (Triple Track)	STORM DOORS[3]
											20%	30%	40%					
Existing Insulation	None			R-11*			None		None	R-11*	None							
Material Used	A	B	C	A	B	C	B	C	B	B	D	D	D	Heating	Cooling			
Additional Inches	7"	6"	5"	0"	4"	2"	3.5"	3.5"	4"	0"	3"	3"	4"	$.15	$.45		3' x 4'	0
Years to Pay Back	(5)	(4)	(5)	(0)	(16)	(20)	(4)	(15)	(8)	(0)	(3)	(2)	(2)			Years to Pay Back	(13)	(0)
Additional Inches	10"	10"	6"	5"	6"	3"	3.5"	3.5"	6"	4"	4"	5"	5"	$.30	$.45		2' x 3'	0
Years to Pay Back	(4)	(3)	(3)	(14)	(11)	(13)	(2)	(8)	(5)	(18)	(2)	(2)	(1)			Years to Pay Back	(7)	(0)
Additional Inches	12"	12"	8"	7"	6"	5"	3.5"	3.5"	10"	4"	5"	6"	7"	$.45	$.45		2' x 2'	0
Years to Pay Back	(3)	(3)	(3)	(11)	(8)	(11)	(2)	(6)	(5)	(12)	(2)	(1)	(1)			Years to Pay Back	(5)	(0)
Additional Inches	14"	12"	9"	9"	10"	6"	3.5"	3.5"	10"	6"	6"	7"	8"	$.60	$.45		2' x 2'	0
Years to Pay Back	(3)	(2)	(3)	(9)	(8)	(9)	(1)	(5)	(4)	(10)	(1)	(1)	(1)			Years to Pay Back	(4)	(0)
Additional Inches	18"	16"	11"	13"	12"	8"	3.5"	3.5"	10"	6"	7"	8"	7"	$.90	$.60		2' x 2'	x/30%
Years to Pay Back	(2)	(2)	(2)	(8)	(6)	(7)	(1)	(3)	(3)	(7)	(1)	(1)	(1)			Years to Pay Back	(3)	(10)
Additional Inches	20"	18"	13"	16"	16"	10"	3.5"	3.5"	10"	6"	8"	9"	10"	$1.20	$.75		2' x 2'	x/10%
Years to Pay Back	(2)	(2)	(2)	(7)	(5)	(6)	(1)	(2)	(2)	(5)	(1)	(1)	(1)			Years to Pay Back	(2)	(10)
Additional Inches	23"	22"	15"	18"	18"	12"	3.5"	3.5"	10"	6"	9"	10"	10"	$1.50	$.90		2' x 2'	x/0%
Years to Pay Back	(2)	(2)	(2)	(6)	(5)	(6)	(1)	(2)	(2)	(4)	(1)	(1)	(1)			Years to Pay Back	(2)	(10)

*Equivalent to 3½" of Glass Fiber Batt/Blanket Insulation
A – Loose Fill Glass Fiber (R-2.2 per inch)
B – Glass Fiber Batt/Blanket (R-3.1 per inch) (not applicable to finished walls)
C – Loose Fill Cellulose Fiber (R-3.7 per inch in attic/R-3.3 per inch in walls)
D – Glass Fiber Duct Wrap (R-4 per inch)

1. Floor Over Unheated Basement, Crawlspace, or Garage
2. Minimum Economical Size; Payback for 3'x5' Storm Window
3. Refers to Minimum Glass Composition of Primary Door That Makes Storm Door Economical (10 year life)

A close look at the tables will reveal a rather consistent increase in the optimal levels of variable techniques as fuel prices per Btu increase and as weather conditions become more severe. This will allow the reader to interpolate rather easily when using different energy rates, different climates (above 2,000 degree days) and different marginal costs for the techniques analyzed.

An example from the tables will be instructive in their use. Let us examine an optimal combination of energy conservation techniques for an existing wood-frame house with 3 1/2 inches of glass fiber batting (R-11) in the attic, but no wall insulation, no insulation over a vented crawlspace, and no storm windows or doors. This house is located in the Washington, D.C. area, which has approximately 4,200 degree days and 1,000 cooling hours, We will assume that it is oil heated and electrically cooled, and that current rates (including taxes, etc.) are approximately 32¢ per gallon for #2 fuel oil (50% efficiency) and 3¢ per kWh for air conditioning (COP = 2). What is the indicated optimal combination of energy conservation techniques?

Table 5.2G with 4000 degree days and 1,000 cooling hours best represents the Washington climate. We refer to the 3rd row of this table which is based on heating at $.45 per 100,000 Btu delivered and air conditioning at $.45 per 100,000 Btu removed, equivalent to our example. (See Table 5.1)

Depending on the availability of materials, the accessability of the attic, and the homeowners preference for one material over another, the optimal amount of insulation to add to the attic is either 6 inches of blown-in glass fiber, a 6 inch glass fiber batt, or 4 inches of cellulose. The payback period for each of these options is included in parenthesis. If the homeowner is able and willing to install one of these alternatives himself, the payback period may be considerably shortened.

Adding blown-in insulation to open wall spaces appears to be economically attractive as well. At 50¢ per square ft., loose-fill cellulose will pay off in about 7 years, at the same time returning an annual dividend equal to the rate of fuel price increases during this period. After checking with several reputable commercial insulation firms to get estimates on both price and the suitability of the walls for blown-in insulation, the homeowner may decide that the exterior walls should be insulated.

Six inches of insulation are indicated as optimal for installation under the floor in the crawlspace. This same amount would be appropriate in floors between heated areas and an unheated basement or garage as well.

All windows and doors should be weather stripped by the owner. Storm windows are indicated for all windows equal to or larger than 2' x 3'. A storm door is not considered economical as there is an existing screen door in place, making its replacement with a storm door difficult to justify.

After calculating the Btu's per hour needed to keep the indoor temperature at approximately 70°F when the outdoor temperature is at its winter average (45°F for Washington), the homeowner determines that the furnace must run 20% of the time to maintain that indoor temperature level after these other retrofitting techniques have been installed. (Alternatively, he can actually time this on a 45° day.) Four inches of insulation are then indicated for wrapping exposed heating ducts in the attic and in an unheated basement, crawlspace, or garage.

5.3 Further Interpretation of Results

The tabular data presented in this section provide additional information of interest to homeowners and others concerned with energy conservation in buildings. The following information on the economic aspects of energy conservation in buildings has been derived from tables 5.2A-H and from the thermodynamic and economic considerations that went into their making.

(1) Closer examination of the tables show that, as expected, optimal investment levels increase as energy prices rise and climate factors grow more severe. (The actual investment level, of course, is dependent on the size of the specific areas to be insulated, the number of windows and doors to be covered with storm sash, etc.) As one moves from price level to price level within a given climate zone, more of each variable ECT is indicated as profitable. Because these combinations are economically balanced (Condition II) at each price level, the marginal increments of each ECT (those newly-profitable increments) are all approximately equivalent in value in that they return approximately the same savings per dollar invested. Each is somewhat less profitable than the marginal investments immediately preceding and somewhat more profitable than those immediately following. Thus one can quite easily determine, for example, whether the fifth or sixth inch (over no existing insulation) of attic insulation is more profitable than a 4' x 5' storm window in a 4000 degree day climate zone. Examination of Table 5.2B with 4000 degree days and 0 cooling hours shows that at $.15 per therm only 4" of insulation is optimal, while at $.30 per therm. 6" is optimal. However, at $.15 per therm. 4' x 5' storm windows are indicated as optimal so that these must return more savings per dollar than the fifth and sixth inches of insulation. (Adjustment of these tables for different ECT costs, or different initial levels of insulation could change these relationships.) Moving further down to $.45 per therm we see that the seventh through tenth inches of attic insulation return approximately the same savings per dollar as the fifth and sixth inches of floor insulation, the fourth inch of duct insulation (at 20% operational time), and the storm windows between 2' x 3' and 3' x 3'.

With a limited retrofit budget the homeowner should use the highest cost combination of ECT's that is consistent with his budget in the appropriate climatic zone. This will assure an economically balanced allocation of his retrofit budget (Condition II) and consequently generate the greatest dollar savings to the homeowner for his limited budget.

An example of such a procedure is shown in Table 5.3. An energy conservation budget of $731 would be needed to invest in the optimal level of ECT's. The homeowner does not wish to invest more than $500, however. In this case he will add those levels of ECT's shown as optimal for the $.15 heating, $.45 cooling energy costs (cost = $461) plus as much as possible of the levels shown for $.30 heating, $.45 cooling energy costs. Here he will add one additional storm window on a 3' x 3' window (the optimal insulation levels have not changed for these higher energy prices). Of the $500 budget the homeowner will spend $486 ($461 + $25). Since these investment levels are economically balanced, the savings generated by this limited investment will be maximized.

(2) Optimal levels of energy conservation investments are as sensitive to fuel prices as they are to climate factors, i.e., doubling of fuel prices is similar in effect to a doubling of climatic factors.[44] As an example, the doubling of #2 fuel oil prices in the winter of 1973-74 had an effect on homeowner pocketbooks similar to that of physically moving their homes from Washington, D.C., to northern Minnesota.

(3) While the optimal level of investment in ECT's varies as a function of climate factors, fuel prices, and ECT costs, note that small variations (i.e., less than 20%) in any one of these have little effect on optimal investment levels. The optimal levels listed in tables 5.2A-H are meant to be guidelines and not to be followed to the exact inch where this is not practical. However, any costly modifications needed to incorporate these ECT's require further analysis.

(4) When determining optimal levels of ECT's, winter heating and summer cooling energy loads should be summed in dollar terms (heating and cooling energy costs are likely to be substantially different). Design criteria which specify insulation levels (or coefficients of conductance) for new buildings or existing buildings should reflect these combined loads rather than the greater of the two, as is common procedure.

(5) When shopping for insulation, the homeowner should consider the cost per resistance unit (R) rather than cost per inch. Loose-fill glass fiber insulation has an R value of approximately 2.2 per inch while glass fiber batts have an R value of approximately 3.1 per inch. Thus even at a 40% greater price per inch, batts would be a better investment than loose fill. Where batts are impractical, loose fill may still be a good buy, however.

(6) Storm windows can be shown to be economical even over existing double-glazed windows in some cases. The additional window will reduce conductive heat loss and heat gain by 33%, as well as reducing air infiltration. Where 3' x 5' storm windows are shown in tables 5.2A through H to pay off (including interest) in less than 7 years, storm windows added to existing double-pane windows of that size or larger will be economical (20 year life, $25.00 cost assumed).

(7) Insulation blown into existing walls with no previous insulation appears to be economical in many climates and for the higher fuel prices. Benefits such as reduced infiltration through walls, a higher mean radiant temperature, and increased occupant comfort make this even more attractive than shown. However, this technique must be considered carefully because of possible moisture problems. More information on this technique can be found in Appendix A.

(8) Much of this study is applicable to new housing design as well. In some cases it may be shown that increasing exterior wall thickness in new homes to accommodate further insulation is economically desirable. The marginal analysis model may not be practical for use in making design decisions about siting, exposure, window size versus wall size, and other design decisions because of the many interdependencies involved. However, once these design decisions are made, the model may be very useful in decision making regarding further energy conservation investments.

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[44] A doubling of degree days will have a slightly greater effect than a doubling of energy prices on the optimal level of insulation for attics and floors over unheated areas because the average temperature in these areas does not vary in constant propotion to the average outside temperature.

Table 5.3

Optimal Allocation of a Limited Energy
Conservation Budget -- Example

Assume $500 Budget

- Wood frame house in Washington, D.C. -- approximately 4000 degree days and 1000 cooling hours (Use Table 5.2G)
- 1200 square feet (single-story)
- Existing R-11 insulation in walls and attic
- Existing weather stripping
- No insulation in floor over crawlspace
- No ductwork in unheated areas
- No storm windows or storm doors
- 11 windows (5 -- 3' x 5', 3 -- 3' x 3', 3 -- 3' x 2')
- No storm doors
- Oil heated ($.45 per 100,000 Btu delivered)
- Electrically cooled ($.45 per 100,000 Btu removed)

Heating/ Cooling Costs		Attic	Floor	Windows	Total
$.15/$.45	Add Cost[1]	4" (1200 x $.135) $162	4" (1200 x $.145) $174	3' x 5' (5 x 25) $125	$461
$.30/.45	Add Cost	4" (1200 x $.135) $162	4" (1200 x $.145) $174	3' x 5', 3' x 3' (8 x 25) $200	$536
$.45/.45	Add Cost	6" (1200 x $.185) $222	6" (1200 x $.195) $234	3' x 5', 3' x 3', 3' x 2' (11 x $25) $275	$731

[1] Costs from Appendix B.

6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

An economic optimization model has been applied to a selected group of energy conservation techniques in order to determine the optimal combination of such techniques in terms of maximizing net dollar savings in space heating and cooling operations for existing residential buildings. Results of this analysis have shown that optimal investment levels in the various techniques are quite sensitive both to climate factors and to energy prices, and that in many cases these levels are considerably higher than those currently recommended by government and industry. These lower recommendations may be due in large part to the failure of these institutions and the general public to adequately consider the impact of recent fuel price increases on the economically optimal levels of energy conservation investments for various climates and fuel types.

It should be noted that these combinations of ECT's are economically optimal for the energy consumer in that they reflect his own expectations of energy and ECT costs. To the extent that such costs may diverge from competitive (free market) prices due to regulation, price controls, or rationing, or to the extent that actual costs may not include externalities, e.g. air pollution from electric power generation, these consumer optimal combinations may not be socially optimal levels. Artificially low fuel prices due to price controls have not only stimulated increased demand for these controlled fuels in comparison to other fuels but have encouraged their socially inefficient use (i.e., waste) by inducing lower levels of consumer-optimal energy conservation investments than those that would be determined by higher free-market prices.

Still, it is essential that an economic analysis of energy conservation requirements be included in strategies for retrofitting existing buildings and in the design of new buildings if there is to be an efficient allocation of resources between energy use and energy conservation. This is especially true in the wake of energy conservation building codes and standards being developed today for adoption by state and local building code authorities. Many of these codes specify (explicitly or implicitly) levels of energy conservation techniques which show little regard for economic optimality, either in terms of maximizing net savings or in terms of an economically balanced combination of energy conservation investments. While it is recognized that these are minimum specifications, the very fact that they are included as an integral part of an "energy conservation" standard may endorse their use as maximums by builders and homeowners. While they may increase energy conservation levels over past efforts, they should in no way be considered as optimal. If treated as such they may be responsible for inefficient energy use and eventually lead to considerable cost burdens on homeowners.

It is hoped that the relatively high levels of insulation determined as optimal in this study will encourage further research, both economic and thermal, into energy conservation techniques for all building types, new and old. Verification data for fuel savings is needed for a wide range of climatic and structural conditions. Current energy conservation research at the National Bureau of Standards includes precise measurements of heat loss and heat gain in new and existing buildings. Fuel usage is being measured in an existing residence on the NBS site before and after retrofitting the ECT's examined in this study. Preliminary results of this testing will be available in 1975.

In addition, more research and development into wall insulation for retrofitting applications are needed. Current techniques are not acceptable to many homeowners because of uncertain results. In general, blown-in insulation has been shown in this study to be cost effective in many climatic regions. More data is needed on the long term durability and effect of such insulation, however.

This research could be further expanded to include new residential buildings and new and existing commercial buildings. Because of difficulties in handling interdependent ECT's simultaneously, the economic model outlined in this study will need to be expanded if it is to handle more complex design decisions in new buildings. The results of such research should be well worth the effort, however.

Further stimulation of homeowner investments in energy conservation might be achieved by increasing the visibility of low cost FHA Title I home improvement loans. It has been shown in this study that it will often pay the homeowner to borrow at Title I loan rates (near 10%) if he invests this in the energy conservation projects outlined. Tax credits for investment in energy conservation would also increase the economic incentives to invest in these projects.

Most importantly, however, this information must be placed in the hands of homeowners and homebuyers if it is to contribute toward any substantial measure of energy conservation. Homeowners must be aware of the economic implications of higher levels of energy conservation investments before they can be expected to respond in an efficient manner to supply and demand conditions in the energy market. Even today, in a period of rapidly rising energy prices, most homeowners have little feeling for the potential economic return from the energy conservation techniques examined in this paper. And yet, in the end, it is up to the homeowners and potential homeowners to demand more energy conservative housing if it is to appear in the housing market.

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SI Conversion Units

In view of the present accepted practice in this country for building technology, common U.S. units of measurement have been used throughout this publication. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the metric SI system of units in 1960, appropriate conversion factors have been provided in the table below. The reader interested in making further use of the coherent system of SI units is referred to:

NBS SP330, 1972 Edition, "The International System of Units"

E380-72 ASTM Metric Practice Guide (American National Standard Z210.1)

Table of Conversion Factors to Metric (S.I.) Units

Physical Quantity (and symbol used in paper)		To convert from	to	multiply by
Length	x	inch	meter	$2.54^{*} \times 10^{-2}$
		foot	m	$3.048^{*} \times 10^{-1}$
Area		inch^2	m^2	$6.4516^{*} \times 10^{-4}$
		foot^2	m^2	9.290×10^{-2}
Volume		inch^3	m^3	1.639×10^{-5}
		foot^3	m^3	2.832×10^{-2}
Temperature		Fahrenheit	Celsius	$t_C = (t_F - 32)/1.8$
Temperature difference		Fahrenheit	Kelvin	$K = (\Delta t_F)/1.8$
Pressure		inch Hg (60F)	newton/m^2	3.377×10^3
Mass		lbm	kg	4.536×10^{-1}
Mass/unit area	M	lbm/ft^2	kg/m^2	4.882
Moisture content rate		lbm/ft^2 week	$\text{kg}/m^2 s$	8.073×10^{-6}
Density	ρ	lbm/ft^3	kg/m^3	1.602×10^1
Thermal conductivity	k	Btu/hr ft^2 (F/inch)	$\frac{W}{mK}$	1.442×10^{-1}
U-value	U	Btu/hr ft^2 F	$\frac{W}{m^2 K}$	5.678
Thermal resistance	R	F/(Btu/hr ft^2)	$K/(W/m^2)$	1.761×10^{-1}
Heat flow		Btu/hr ft^2	W/m^2	3.155
Water vapor:				
permeability	μ	$\frac{\text{grain}}{\text{hr ft}^2\text{(in.Hg/in.)}}$	kgm/Ns	1.457×10^{-12}
permeance	p,P	$\frac{\text{grain}}{\text{hr ft}^2\text{(in.Hg)}}$ (perm)	kg/Ns	5.738×10^{-11}

*Exact value; others are rounded to fourth place.

Appendix A

ENERGY CONSERVATION TECHNIQUES - SOME OPTIONS

The purpose of this appendix is to explore briefly some of the options available to homeowners who may wish to retrofit their residence with the energy conservation techniques outlined above. There is often considerable flexibility in choosing materials and procedures for accomplishing a given conservation goal. What is best in one situation may not be best in another, however, so that some judgment must be made as to which options are economically or structurally more attractive in any given application.

Whichever materials are used, it is of utmost importance that they be properly installed so that the full potential savings, on which the estimates in the study are based, will be realized. This is especially true for the "do-it-yourself" homeowner, but it should not be overlooked by those who may contract for such work, in order to assure that the installation has been properly accomplished.

In general the manufacturers of energy conservation materials will supply complete installation instructions at no charge. Further information may be useful, however, especially for insulation applications. One such source is the Insulation Manual - Homes/Apartments. 44/ Other sources may often be found at the local library under household repair.

a. Insulation in Attic Spaces

Insulation of heated rooms from unheated attic spaces directly above is usually accomplished by the placing of insulating materials between the ceiling joists in the attic area. This is the most likely location in an existing house to have some existing level of insulation; it may be desirable to upgrade this, however.

There are two basic forms of attic insulation available, both of which are acceptable if properly installed. The first of these is preformed glass or mineral fiber blankets or batts; the second is loose fill materials, generally made of cellulose (recycled waste paper) or glass fiber. The following R values [45/] are approximately correct for proper installation;

Glass fiber batts: R = 3.1 per inch [46/]

Cellulose loose fill (2 1/2 lbs. per cubic foot): R = 3.7 per inch

Glass fiber loose fill (0.7 lbs. per cubic foot): R = 2.2 per inch [47/]

Preformed insulation blankets or batts may be more economically attractive than loose fill materials in an unobstructed attic area with no flooring, especially for the do-it-yourself homeowner. These blankets or batts can be rolled out quickly and minimize the raising of fibers into the air which create an uncomfortable working environment.

If no previous insulation exists, foil-faced vapor barrier batts should be used, with the foil facing downward. This is to retard moisture, rising from the room below, from penetrating into the insulation. When adding batts over existing insulation, it is preferable to install unfaced batts. These are generally cheaper, and prevent moisture from condensing in the existing insulation. If unfaced batts are not available or cannot be purchased for less than faced batts, faced batts can be used if the facing is stripped off or slashed at frequent intervals to allow free passage to moisture.

[44/] National Association of Home Builders Research Foundation, Inc., 627 Southlawn Lane, P.O. Box 1627, Rockville, Md. 20850.

[45/] The R value, or coefficient of resistance, is the reciprocal of U, the coefficient of conductance, which in turn is defined as the time-rate of heat flow through a thermal barrier (Btu per hour per square foot per degree Fahrenheit temperature difference between the air on either side).

[46/] ASHRAE Handbook of Fundamentals, 1972, p. 361.

[47/] Based on recent manufacturers report (downgraded from ASHRAE value).

Loose fill insulation may be preferred when the attic is difficult to access or flooring is present. If flooring is present some strips may be pulled up or holes can be drilled in the floor at intervals between the joists. This insulation is usually pneumatically pumped or blown into the attic through flexible tubing by a small machine which puffs up the insulation as it pushes it through. This may cause some settling after the insulation is in place so that some margin of safety should be allowed in measuring depth. For this reason the densities recommended by the manufacturer for different desired R values should be carefully adhered to.

There is no reason to restrict the depth of attic insulation to the height of the ceiling joists, in areas not needed for storage, if more insulation is warranted. However, insulation should not come in contact with the roof above at any point. When installing blankets or batts above the joists it may be useful to run the batts perpendicular to the joists in order to cover the attic more thoroughly.

It is essential that a well insulated attic be well ventilated. This will minimize the chance of condensation during the heating months which can cause temporary or permanent damage to the insulation and increase the heat flow. More on this can be found in the Insulation Manual - Homes/Apartments mentioned above or from manufacturers of ventilating equipment.

b. Insulation in Exterior Walls

The potential energy savings from insulating exterior walls of wood frame and brick veneer residences is certainly significant, both in terms of BTU savings per square foot and in sheer wall area. On the other hand the problems that arise in assessing the benefits and costs of retrofitting exterior walls with insulation make this the most difficult of all the energy conservation techniques considered in this study. Where the addition of insulation appears to be economically advantageous to the homeowner, he should undertake such a project only after securing the best technical advice available. Equally important is the careful selection of a firm to do the work. Only a reliable firm with considerable experience should be chosen, for it is nearly impossible to check on the quality of work done inside the wall, and doing the job right takes a good deal of skill and time.

The basic feature of an exterior wall which lends itself to thermal insulation is the airspace, usually 3 1/2" to 4" deep, between the exterior and the interior wall. Three and one-half inches of insulation properly placed in the airspace can reduce the heat loss and heat gain through the walls by as much as two-thirds. The proper time to install insulation in the airspace is during construction, just before the inside wall is attached. Many older houses and even some new houses outside of extremely cold climates were not insulated at this time, however, for reasons discussed elsewhere in this study. As a result, retrofitting insulation into exterior walls requires that access to the airspace be gained through the outside or inside wall. This immediately presents several problems.

1. It is relatively costly.

2. It is difficult to monitor the quality of work done, both at the time of installation and at periodic intervals later in time.

3. A vapor barrier cannot be placed between the interior wall and the insulation so that possible water damage from condensation can result. This cannot be detected until it begins to show through the wall.

4. It may be difficult to restore the wall through which access was made to its original condition.

Despite these problems, there has been a growing demand for insulation added to existing walls. The most commonly used materials are cellulose and urea-formaldehyde foam. These are generally adaptable to pneumatic "blowing" or "pumping" through small holes drilled between the studs into the airspace.

Loose-fill glass or mineral fiber is not considered to be adequate for such applications because of its low density and its tendency to hang up in the wall, making its even dispersion in the wallspace difficult. Cellular plastics, such as polyurethane and polystyrene, are no longer being used in residential applications because of potential fire and gas hazards. Polyurethane also expands with greater pressure than other foams which can cause some problems with bursting walls.

Cellulose in walls has a resistance value (R) per inch of approximately 3.3. [48] The urea-formaldehyde resistance value is closer to 5 per inch.[49] The most common procedure for insulating existing

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48/ Based on report of Cellulose Insulation Manufacturers Association (CIMA) at density of 3.5 lbs/ft^3 in walls.

49/ ASHRAE Handbook of Fundamentals (1972) p. 361.

walls is to remove a strip of exterior siding from around the top of the house, drill a hole 1 inch in diameter through the sheathing, and pump the insulation from a mixing machine through a flexible hose into the airspace until it is filled. The siding is then replaced over the sheathing. If there is a firestop between the studs halfway up the wall, this whole procedure must be repeated below the firestop. Alternatively, holes may be drilled right through the exterior wall and later plugged up. This procedure is occasionally applied from the inside of the exterior walls as well. In brick veneer homes, bricks may be removed in order to reach the sheathing and replaced when finished.

While there are substantial benefits available in retrofitting existing walls, there are also considerable problems that may arise, and these should be carefully considered.

The most important of these is the moisture accumulation problem. It is extremely important that water vapor generated from within the home be either stopped at the interior wall surface or allowed to pass entirely through the wall to the outside. Several coats of a good grade, low permeability paint should be used on the interior walls while the outside wall covering should have a permeable surface. Water vapor that is allowed to pass through the interior wall on a cold day will condense and turn to moisture or ice if it comes into contact with a cold surface that it cannot permeate. Unfortunately, it is difficult to monitor the build-up of moisture in a wall and it may not be noticed until the paint begins to peel away from the wall. Generally the problem can be avoided if the proper precautions are taken. Trouble spots that may require extra care are bathrooms and kitchens, both of which produce a significant amount of water vapor. High humidifier settings should also be avoided. In fact, in a well insulated home with storm windows and weather stripping, a humidifier may not be needed.

Another problem which may occur within the wall is settling or shrinkage of the insulation materials over time; and like the moisture problem, it is difficult to detect. While many insulation installers will guarantee that there will be no settling, in general there will be some, and its effect may be significant. As the settling occurs no insulation is protecting the top of the wall, and heat transfer through this area resumes its pre-insulation rate. A 10 percent allowance for settling and unfilled cavities was made in calculating the conductive heat savings due to wall insulation. Over a period of many years the settling of some types of insulating materials may amount to more than this, however. With urea-formaldehyde foam some shrinkage occurs rather than settling -- this is claimed by the manufacturer to be about 2 percent. The R value of approximately 5 per inch reflects this shrinkage. However, improper installation and curing can cause shrinkage to be considerably higher.

A potential means of monitoring settling at the time of installation and at periodic intervals is through thermographic imagery. An infra-red "picture" of the wall taken from the outside on a cold day will show "hot spots" which are most likely uninsulated areas. Unfortunately, such systems are quite expensive and limited in use at present.

In addition to the conductive heat savings due to the addition of insulation, there may also be some savings in convective heat transfer, i.e., infiltration through the wall may be slowed. While infiltration through walls may be negligible for well-constructed homes, it may be significant in older homes or in walls which were not well sealed. One suggested way to detect the relative amount of infiltration entering through a wall is to remove a switch plate cover from the inside of an exterior wall on a windy day and hold a burning match close to the opening. If it flickers wildly or blows out, there may be significant air infiltration leaking into the house. Filling the wall with insulation will stop much of this air leakage, but it is difficult to assess the savings available under the wide variety of conditions that may exist.

Cost estimates for insulation blown into existing walls vary considerably from house to house and firm to firm. Much of the work involves removing and replacing siding or bricks to gain access to the walls. Where holes are drilled directly into the wall, costs are somewhat less, but the results are not as acceptable. In general the removal of bricks is somewhat more expensive than wood or aluminum siding or asbestos-cement shingles. At present the cost of such work ranges from about \$.25 to \$1 per square foot with the median value around \$.40 per square foot for cellulose insulation and somewhat higher for urea-formaldehyde. Repainting the interior and other incidental charges would probably make \$.50 per square foot a more reasonable estimate for cellulose insulation and this is the figure that is used in evaluating the benefit-cost ratio in the study.

c. Insulation Under Floors

Insulation of heated rooms from unheated areas directly below, usually a crawlspace, garage, or unheated basement, is generally accomplished by installing preformed glass fiber blankets or batts in the floor joists directly below the floor. Such insulation is often overlooked because many homeowners feel that heat flow downward is not a problem. This is not correct, of course; heat flows to cold in any direction. Where the basement is heated, no insulation in the floor is warranted. Where heat escaping from the furnace or hot water heater raises the temperature of an otherwise heat basement, the optimal level of insulation may be somewhat less than that level indicated on Table 5.2A-H.

The insulation batts can be held in place by a number of methods. Where the depth of the insulation is less than the depth of the joists it may be secured by using wire bows which spring into place between the joists. If the insulation is approximately the same depth as the joists, it can be secured by stringing wire in a criss-cross fashion over small nails in the joists. In basements and garages it is not recommended that the insulation extend below the joists where it may be exposed to damage. In crawlspaces, however, it is possible to extend the depth of the insulation several inches, where warranted, by the use of long nails with heads, around which a wire harness can be strung. Analysis of floor insulation was limited to ten inches in this study due to impracticality of extending the depth further. In extreme climates where fuel is expensive, this may be considered, however. When insulating floors over vented crawlspaces it may be necessary to insulate water pipes as well to keep them from freezing in the more severe climates.

As in the case of attic insulation, when adding preformed batts to existing insulation, it is preferable to use unfaced blankets or batts. If batts with facing are found to be less expensive or the only type available, the facing should be stripped off or slashed.

d. Insulation of Exposed Ducting

Heating and cooling ducts which run through unconditioned spaces (especially attics, garages and crawlspaces) can be a major source of heat loss (or gain) if not properly taped and insulated.[50/] Even where a sufficient amount of insulation exists it may be worthwhile removing this temporarily to check on the condition of the ducts: escaping air indicates the need for retaping the joints. This is especially important if the warm air in the duct is humid, as condensation inside the moisture barrier surrounding the insulation will result.

Most homes have no more than one or two inches of insulation wrapped around the exposed ducting. However, it will be seen that considerably more than this may be economically desirable in colder climates, especially for electrically heated homes.

Duct wrap insulation is available in a wide variety of widths; it is generally not available in thicknesses greater than two inches, however. Where more than two inches are indicated, several layers of duct wrap should be used. Unfaced wrap should be installed beneath the outer layer. A heavy foil face is usually used on the outer layer as a vapor barrier during space cooling operations. Alternatively, regular unfaced batts can be wrapped around the ducts and covered with a vinyl wrapping sealed to form an adequate vapor barrier. In either case it is important to avoid crushing the insulation or binding it too tightly in order to maximize its resistance to heat flow.

The R value of duct wrap may vary considerably according to its density. Estimates of optimal thickness are based on glass fiber with a resistance value of 4 per inch. A 50 percent materials allowance was made over the basic duct perimeter measurement to allow for the wider perimeter at the outside of the insulation pack and for some crushing of the insulation. Labor charges are not included in these estimates, unlike the analysis for other energy conservation techniques. Such charges are to a great extent dependent on total job size rather than on a per square foot basis. To the extent that installation charges are independent of the depth installed, this should have no effect on the optimal level of insulation when there is no existing base. The addition of insulation to an existing base will probably not be cost-effective, however, unless the homeowner undertakes this himself or the ductwork is obviously leaking and the insulation in bad shape.

Ducting insulation requirements are not directly proportional to exterior climatic conditions but rather are a function of the climate, the general insulation level of the building envelope, and heat/cooling system efficiency. In a well-insulated home, other things held equal, the heating/cooling system will be used less and the heat loss and gain through the duct work will be lower. For this reason, insulation requirements for exposed ducting are not independent of other insulation levels and thus must be estimated as a function of other energy conservation modifications. In this study the percent of time the heating/cooling system operates to maintain the desired indoor temperature when the outdoor temperature is at its average level[51/] is used as the basis for determining insulation requirements in any given climate. This should be estimated for the thermal load that is expected after all energy conservation modifications have been incorporated.

50/ Insulation is not generally needed on ducting within a heated basement or walls of a single-family house as the heat loss and gain is retained within the building.

51/ For winter this is defined as (65^{o}-degree days/heating days); for summer this is the average temperature in the duct-occupied space during cooling hours.

e. Storm Windows and Doors

Storm windows and doors vary widely in basic design, durability, and cost. Storm windows range from single glass panels that must be put in place each fall and removed each spring to triple track assemblies which include sliding upper and lower windows and a screen. These latter windows are recommended for double-hung windows and sliding casement windows because they can be left in place permanently, thereby encouraging their use during winter heating and summer cooling, while allowing windows to be left open for natural ventilation during the mild weather seasons. This also minimizes wear and tear on the windows and the chance of breakage. Other types of storm windows, especially those for use on basement windows or hinged casement windows are often somewhat less expensive than triple track windows. Therefore the data in Tables 5.2A-H should be adjusted to reflect these lower costs.

Storm doors with interchangeable glass and screen inserts are recommended because such doors can be used for ventilation during the non-heating months when needed. Because such inserts are not conveniently and quickly interchangeable it is suggested that the screen be left in place during the non-heating months. For this reason no summer cooling savings are included. Storm doors over primary doors with substantial window area are more likely to be cost-effective than those over solid doors.

Both storm windows and storm doors can be effective in slowing infiltration as well as conductive heat transfer. In combination with weather stripping a great deal of infiltration may be eliminated. In this case, however, the marginal effect due to either one when the other is in place will be considerably smaller than when it is used singlely. In this study weather stripping will be assumed to be in place. Therefore infiltration through the cracks directly around windows and doors will be assumed to be reduced by 30 percent in loose fitting and 10 percent in average to tight-fitting windows and doors.[52/] Such savings are based on tight fitting storm windows. In order to assure a tight fit, these windows should be sealed to the outer window frame with caulking compound or other sealing solutions.

Storm windows from a particular manufacturer generally vary little in cost up to 100 united inches.[53/] After this a cost per united inch is usually included. A considerable savings on such windows can be realized if stock sizes, available at many department and hardware stores, are used. Custom made windows cost considerably more. A cost of $25 per window has been assumed for storm windows up to 100 united inches plus $.50 per inch over 100". This is for a basic triple track window without colored trim. While considerably more may be spent, muct of this will be for convenience or aesthetic value and not directly for energy conservation purposes.

Storm doors costs vary widely as well. Again stock sizes may be less expensive than custom made doors. Costs here are based on $75 per door.

f. Weather Stripping

When properly installed, weather stripping can be quite effective in reducing the rate of infiltration through cracks around windows and doors, especially that of the loose fitting variety. (In conjunction with storm windows or doors, however, its effect is generally halved.) Weather stripping is available in a wide selection of materials and shapes, some of these being more durable than others and likely to be more effective at the same time. Good weather stripping will not only cut heat loss (or gain) but reduces uncomfortable drafts as well.

52/ This does not include infiltration around the outside of window and door frames, which should be sealed by caulking.

53/ United inches is the sum of the height and width of the storm window, in inches. One hundred united inches is approximately 3' x 5'.

Prices Used for Energy Conservation Techniques

1. Attic Insulation (dollars per square foot)

   a. R-2.2 blown-in glass fiber
   Materials and installation
   First inch = $.06
   Each additional inch = $.03

   b. R-3.1 glass fiber batting

   Materials:

Inch	1	2	3	4	5	6
Foil Faced	.035	.025	.02	.02	.025	.025
Kraft Faced/ Unfaced	.025	.025	.02	.02	.025	.025

   Installation: $.035 first batt.
   .025 each additional batt

   c. R-3.7 cellulose
   Materials and installation
   First inch = $.075
   Each additional inch = $.045

2. Wall Insulation (dollars per square foot)

   a. Blown-in cellulose:[54]

   Materials and installation: 3 1/2 inches = $.50

   b. R-3.1 glass fiber batts (in open walls)
   Materials (see Attic insulation)
   Installation=$.025

3. Floors (dollars per square foot)

   a. R-3.1 glass fiber batt
   Materials (see attic insulation)
   Installation:
   (a) Floors over garage or basement:
   First batt = $.025
   Each additional batt = $.025
   (b) Floors over crawlspaces:
   First batt = $.045
   Each additional batt = $.025

[54] 10 percent assumed settling not included.

4. Duct Insulation (dollars per square foot of duct surface)
   R-4 glass fiber duct wrap[55/]
   Materials Only
   - Foil faced: $.20 per two inches
   - Unfaced: $.15 per two inches

5. Storm Windows
   Triple track plain aluminum (with screen) $25.00 up to 100 united inches
   + $.50 per additional united inch.

6. Storm Doors
   Plain Aluminum (with screen inserts) $75.00

7. Weather Stripping
   Materials Only: Maximum of $.15 per linear foot.
   (Installation prices run as high as $20.00 per window or door.)

55/ Does not include 50 percent allowance for greater perimeter at outside of insulation pack and compression of insulation.

APPENDIX C: CLIMATE FACTORS FOR SELECTED CITIES

Climate factors that may be used for quick reference are presented in this appendix. However, it is recommended that climatic data more specific to a given geographic area be obtained for use with this study when referenced for actual retrofitting purposes. Such data can often be obtained from the local weather bureau. More data is also available from the sources which were used as the basis of the following data.

The degree day chart (chart C-1) and the average winter temperature chart (chart C-2) are taken from the Handbook of Air Conditioning, Heating and Ventilating, Strock and Koral, The Industrial Press, 1965. Cooling hours over 80°F (rounded to the nearest 50 hours) are taken from Air Force publication AFM88-8, Chapter 6, "Engineering Weather Data." Similar data can also be found in the NAHB Insulation Manual - Homes/Apartments.

Alabama, Birmingham	1500
Alaska	n/a
Arizona, Flagstaff	200
Phoenix	2750
Arkansas, Little Rock	2000
California, Los Angeles	550
Sacramento	1000
San Francisco	< 50
Colorado, Denver	650
Connecticut, Hartford	500
Delaware, Wilmington	600
District of Columbia, Washington	1000
Florida, Miami	2400
Jacksonville	1800
Georgia, Atlanta	1000
Hawaii, Honolulu	1350
Idaho, Boise	700
Illinois, Chicago	750
Indiana, Indianapolis	750
Iowa, Des Moines	600
Kansas, Topeka	1150
Kentucky, Louisville	1050
Louisiana, New Orleans	1750
Maine, Bangor	200
Maryland, Baltimore	850
Massachusetts, Boston	400
Michigan, Detroit	500
Minnesota, Minneapolis	500
Mississippi, Jackson	1600
Missouri, St. Louis	1150
Montana, Helena	250
Nebraska, Lincoln	1000
Nevada, Las Vegas	2350
Reno	650
New Hampshire, Concord	400
New Jersey, Trenton	450
New Mexico, Albuquerque	1150
New York, New York City	650
North Carolina, Raleigh	1050
North Dakota, Bismarck	450
Ohio, Columbus	600
Oklahoma, Oklahoma City	1450
Oregon, Salem	300
Pennsylvania, Philadelphia	700
Rhode Island, Providence	700
South Carolina, Columbia	1350
South Dakota, Rapid City	550
Tennessee, Nashville	1300
Texas, San Antonio	2000
Utah, Salt Lake City	900
Vermont, Montpelier	300
Virginia, Richmond	1000
Washington, Seattle	100
West Virginia, Charleston	800
Wisconsin, Madison	500
Wyoming, Casper	550

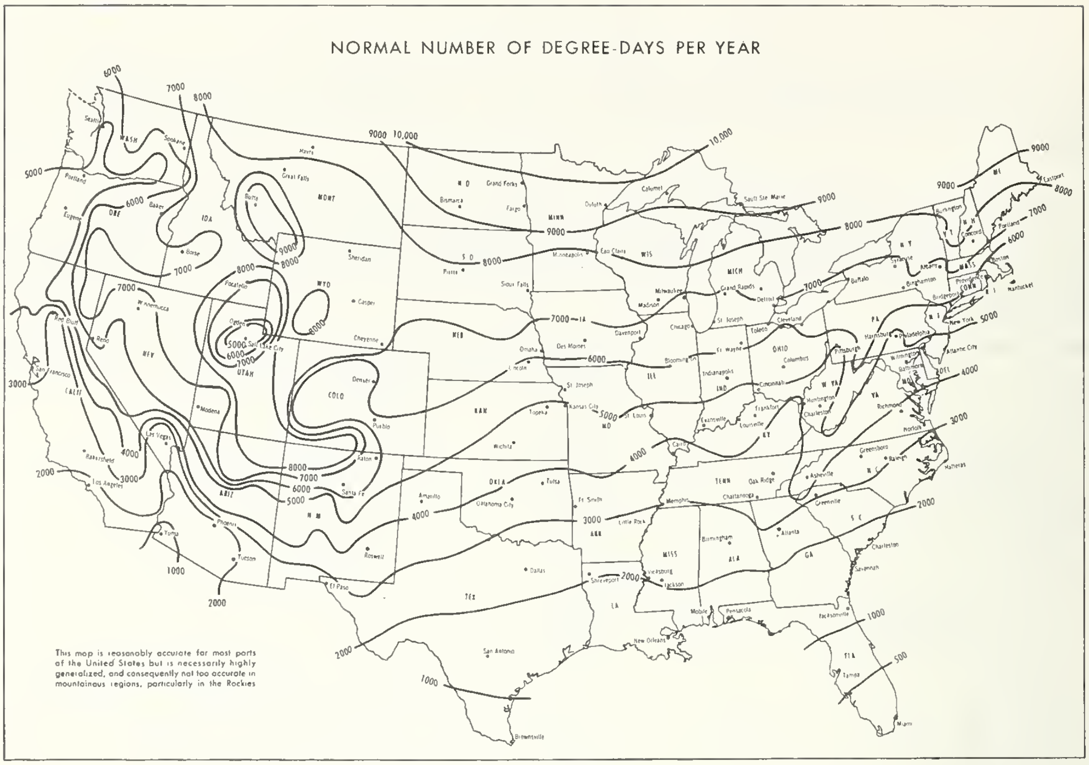

Chart C-1. Normal number of degree-days per year for the continental U.S.

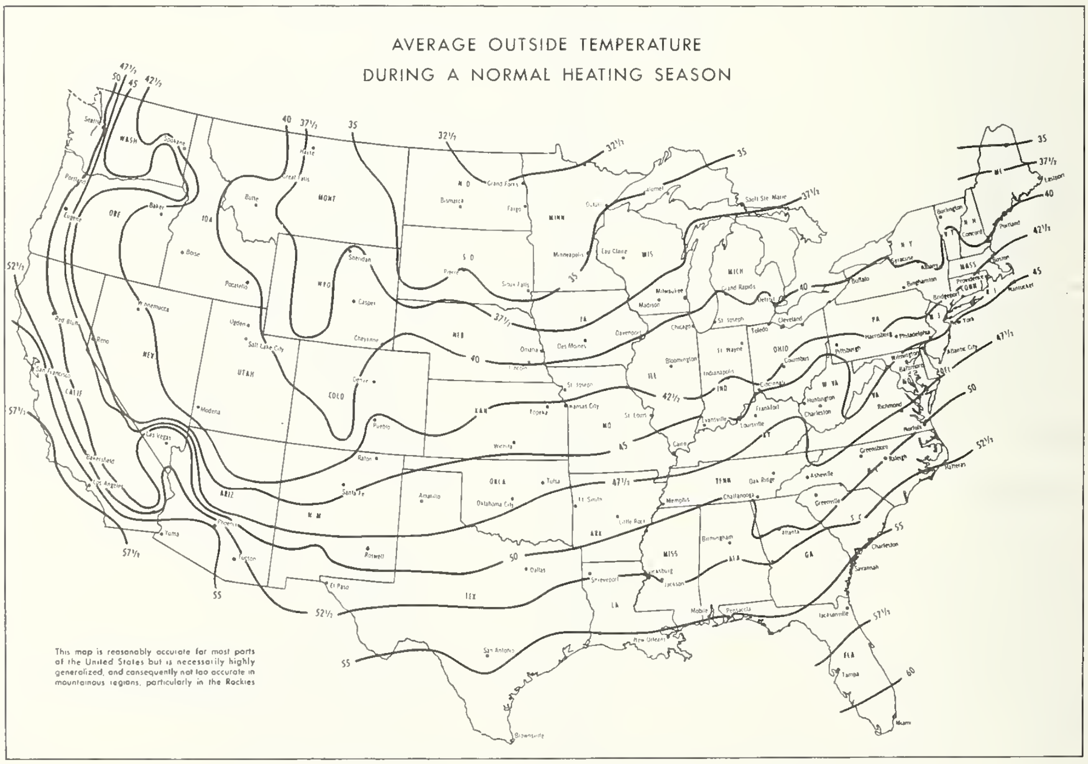

Chart C-2. Average outside temperature during a normal heating season in the continental U.S.

APPENDIX D

Methodology for Calculation of Marginal Heat Losses and Heat Gains

The following methodologies were used in calculating annual heat losses and heat gains for specific envelope sections of residential structures. These heat losses and heat gains are the basis of the marginal savings attributed to the various energy conservation techniques considered in this study.

Notation is meant to be consistent throughout. Basic notation is as follows:

U = thermal conductance

R = thermal resistance

A = area

V = ventilation rate

V_w = wind velocity (M.P.H.)

t = temperature

DD = degree days

HD = heating days

ATTIC INSULATION: WINTER (All calculations per square foot of attic floor area.)

(1) Compute ceiling U:

$U_c = .875/(1/U_p + a \cdot R_t) + .125/(1/U_p + S)$

where U_c = equivalent thermal conductance of ceiling

U_p = thermal conductance of ceiling without insulation or joist adjustment

a = insulation thickness, inches

R_t = thermal resistance per inch of insulation

S = thermal resistance of ceiling joists

.875 and .125 are weights for non-joist and joist areas of attic floor respectively.

(2) Compute attic temperature:

$$t_a = \frac{A_c U_c t_i + t_o (A_r U_r + A_w U_w + 1.08\ A_c V)}{A_c U_c + A_r U_r + A_w U_w + 1.08\ A_c V}$$

where t_a = attic temperature

t_i = inside air temperature (near ceiling)

t_o = outside air temperature

V = ventilation rate of attic in CFM/sq. ft. of ceiling

1.08 = specific heat of air x density of air x minutes per hour = $.24 \cdot .075 \cdot 60$

and subscripts

c = ceiling

r = roof

w = end walls of attic

t_a is computed at average t_o where average $t_o = 65° - \frac{DD}{HD}$

t_a is recomputed for each additional increment of insulation.

(3) Compute hourly heat loss into attic (H_L):

$H_L = U_c(t_i - t_a)$

(4) Compute annual heat loss (H_{AL}):

$H_{AL} = H_L \cdot HD \cdot 24$

(5) Compute annual heat loss reductions due to the i^{th} increment of insulation (ΔH_{AL_i})

$\Delta H_{AL_i} = H_{AL_{(i-1)}} - H_{AL_{(i)}}$

Parameters Used:

U_p = .60

U_w = .31

U_r = .44

A_c = 1000

A_w = 150

A_r = 1120

V = .1 CFM/sq. ft.

S = 6.88 (5.5 inches thick)

ATTIC INSULATION: SUMMER (All calculations per square foot of attic floor area.)

(1) Compute ceiling U:

(See Attic Insulation: Winter)

(2) Compute attic temperature

$$t_a = \frac{A_c U_c t_i + A_r U_r t_{sr} + A_w U_w t_{sw} + 1.08\, A_c V t_o}{A_c U_c + A_r U_r + A_w U_w + 1.08\, A_c V}$$

Where t_{sr} = sol air temperature equivalent of roof

t_{sw} = sol air temperature equivalent of walls

t_o = outside dry bulb temperature

t_a is computed for <u>average</u> outdoor dry bulb temperature during cooling hours above 80° using sol air temperature equivalent appropriate for such conditions[1] (design temperature is not used).

t_a is recomputed for each additional increment of insulation.

(3) Compute hourly heat gain from attic (H_G):

$H_G = U_c\ (t_i - t_a)$

(4) Compute annual heat gain (H_{AG}):

$H_{AG} = H_G \cdot CH$

(5) Compute annual heat gain reduction due to the i^{th} increment of insulation (ΔH_{AGi}):

$\Delta H_{AG_i} = H_{AG_{(i-1)}} - H_{AG_{(i)}}$

Factors used:

U_p = .43 (adjusted for heat flow downward: R increased by 2 x (.92 - .61))

U_w = .31

U_r = .44

A_c = 1000

A_w = 150

A_r = 1120

V = .1 CFM/sq. ft.

---

[1]Sol air temperature equivalents for this study were based on "Design Equivalent Temperature Differences" (ASHRAE Handbook of Fundamentals, 1972, p. 441, Table 50) plus 75°, on which these estimates are based. Medium daily temperature ranges were used. Results compare favorably with available measured data.

WALL INSULATION (All calculations per square foot of wall area)

(1) Compute wall U:

$$U_w = .875/(R_p + R_a + a \cdot R_t) + .125/(R_p + S)$$

where .857 and .125 are weights for non-studded and studded areas of wall, respectively.

R_p = thermal resistance of basic wall (less air space and studding)

R_a = thermal resistance of air space

R_t = thermal resistance per inch of insulation

a = thickness of insulation in inches

S = thermal resistance of studding

Note: When $a = 3.5$, $R_a = 0$

(2) Compute hourly heat loss (gain) (H_L, H_G):

$$H_L = U_w \cdot (t_i - t_o)$$

$$H_G = U_w \cdot \Delta t$$

where Δt = temperature difference between outside sol air temperature equivalent[1] and inside air temperature.

(3) Compute annual heat loss (gain) (H_{AL}, H_{AG}):

$$H_{AL} = U_w \cdot DD \cdot 24$$

$$H_{AG} = U_w \cdot \Delta t \cdot CH$$

(4) Compute annual heat loss (gain) reduction due to the i^{th} increment of insulation (ΔH_{AL_i}, ΔH_{AG_i}):

$$\Delta H_{AL_i} = H_{AL_{(i-1)}} - H_{AL_{(i)}}$$

$$\Delta H_{AG_i} = H_{AG_{(i-1)}} - H_{AG_{(i)}}$$

Factors used:

R_p = 4.76 (Winter, wind speed = 10 mph.)

R_p = 4.80 (Summer, wind speed = 7.5 mph.)

R_a = 1 (Winter); R_a = .84 (Summer)

S = 4.35 (3.5 inches thick)

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[1] See footnote for Attic Insulation: Summer.

FLOOR OVER UNHEATED BASEMENT (WINTER ONLY) (All calculations per square foot of floor area)

(1) Compute floor U Value (U_f):

$U = .875/(R_p + a \cdot R_t) + .125/(R_p + S)$

where .875 and .125 are weighing factors for non-joist and joist areas of floor.

a = thickness of insulation in inches

R_p = thermal conductance of floor without insulation or joists

S = thermal resistance of studs

R_t = thermal resistance per inch of insulation

(2) Compute basement temperature (t_b):[1]

$$t_b = \frac{A_f U_f t_i + t_o(A_G U_G + A_{w1} U_{w1}) + t_g(A_b U_b + A_{w2} U_{w2})}{A_f U_f + A_g U_g + A_{w1} U_{w1} + A_b U_b + A_{w2} U_{w2}}$$

with subscripts:

f = floor over basement

G = window

w1 = wall above grade

w2 = wall below grade

b = basement floor

t_g = ground water temperature

Note: t_b is recomputed for each additional increment of insulation.

t_b is computed at average $t_o = 65° - \frac{DD}{HD}$

(3) Compute hourly heat loss through floor (H_L):

$H_L = A_f \cdot U_f \cdot (t_i - t_b)$

(4) Compute yearly heat loss (H_{AL}):

$H_{AL} = H_L \cdot HD \cdot 24$

(5) Compute annual heat loss reduction due to the i^{th} increment of insulation (ΔH_{AL_i}):

$\Delta H_{AL_i} = H_{AL_{(i-1)}} - H_{AL_{(i)}}$

Factors used:

A_f, A_b = 500 sq. ft.

A_{w1} = 180 sq. ft. (1/4 basement wall above grade)

---

[1]Heat losses to basement from furnace and hot water heater are not accounted for. If these are substantial, little or no insulation may be needed.

A_{w2} = 540 sq. ft. (3/4 basement wall below grade)

A_G = 10 sq. ft.

U_f = .36

U_b = .1

U_{w1} = .5

U_{w2} = .2

U_G = 1.0

Ground water temperatures used:

2000 DD - 65°

4000 DD - 55°

6000 DD - 50°

8000 DD - 45°

10000 DD - 40°

FLOOR OVER VENTED CRAWLSPACE (WINTER ONLY) (All calculations per square foot of floor area)

(1) Compute floor U value (U_f):

(See: Floor Over Unheated Basement)

(2) Compute crawlspace temperature (t_c):

$$t_c = \frac{A_f U_f t_i + t_o\ (A_w U_w + 1.08\ A_f V) + A_g U_g t_g}{A_f U_f + A_w U_w + 1.08\ A_f V + A_g U_g}$$

with subscripts:

f = floor

w = walls

g = ground

V = ventilation rate in CFM/ft.^{2} of floor

t_c is computed at average t_o, where average $t_o = 65 - \frac{DD}{HD}$.

t_c is recomputed for each additional increment of insulation.

(3) Compute hourly heat loss (H_L):

$$H_L = U_f \cdot (t_i - t_c)$$

(4) Compute yearly heat loss (H_{AL})

$$H_{AL} = U_f \cdot DD \cdot 24$$

(5) Compute annual heat loss reduction due to the i^{th} increment of insulation (ΔH_{AL_i}):

$$\Delta H_{AL_i} = H_{AL_{(i-1)}} - H_{AL_{(i)}}$$

Factors used:

$A_f = A_g = 1000$ ft.^{2}

$A_w = 380$ ft.^{2}

$U_f = .36$

$U_g = .33$ (1 foot of earth assumed as thermal barrier)

$U_w = .35$

$V = .1$ CFM/ft.^{2} of floor area

See: "Floors Over Unheated Basement" for t_g used.

EXPOSED DUCTING INSULATION (IN ATTIC) (All calculations per square foot of duct surface)

(1) Compute ductwork R and U (R_d, U_d):

$R_d = 1/U_p + a \cdot R_t$

where U_p = thermal conductance of duct wall (without insulation)

a = thickness of insulation around duct in inches

R_t = R value per inch of insulation

$U_d = 1/R_d$

Computation of U_p:

$$U_p = \frac{1}{.72 + .01 + .26} \simeq 1.0$$

where $.72 = \dfrac{.61 + .68 + .68 + .92}{4}$ (Average R for 4 directions of heat loss from duct)

.01 = R for sheet metal

.26 = R value for inside air surface (air velocity ≅ 600 FPM, ASHRAE recommended)

(2) Compute hourly heat loss (gain) (H_L, H_G) when in operation:

$H_L = U_d \cdot (t_i - t_a)$ $(t_i > t_a)$

$H_G = U_d \cdot (t_a - t_i)$ $(t_a > t_i)$

where t_i = average temperature inside duct

t_a = average temperature in attic

(3) Compute yearly heat loss (gain) (H_{AL}, H_{AG})

$H_{AL} = U_d \cdot (t_i - t_a) \cdot HD \cdot 24 \cdot X_w$

$H_{AG} = U_d \cdot (t_a - t_i) \cdot CH \cdot X_s$

where X_w = % of time furnace system operates when outdoor temperature is at average winter temperature (decimal form).

X_s = % of time air conditioner operates when outdoor temperature is at average cooling hour temperature (decimal form)

[No heat loss (gain) assumed when HVAC system is not operating -- conservative estimate.]

Note: During winter attic temperature is assumed = t_o in well-insulated attic. During summer attic temperature is calculated as outlined in "Attic Insulation: Summer" (see values used below)

(4) Calculate annual heat loss (gain) reduction due to the i^{th} increment of insulation (ΔH_{AL_i}, ΔH_{AG_i}):

$$\Delta H_{AL_i} = H_{AL_{(i-1)}} - H_{AL_{(i)}}$$

$$\Delta H_{AG_i} = H_{AG_{(i-1)}} - H_{AG_{(i)}}$$

Factors used:

t_i (winter) = 140°

t_i (summer) = 55°

Average Cooling t_o	Corresponding t_a used
90°	105°
95°	110°

WINDOWS -- STORM WINDOWS OVER WOODEN DOUBLE-HUNG PRIMARY

(1) Conductive heat loss (gain)

(a) Compute U Value of Window:

(i) Compute outside surface air boundary (R_o):

$$R_o = \frac{1}{2 + .2667 \cdot W}$$

where W = wind velocity in mph.

(This is derived from Table I, section A, ASHRAE Handbook of Fundamentals, 1972, p. 357)

(ii) Inside air surface air resistance $R_I = .68$

(iii) Compute window R_w and U_w:

$$R_w = \frac{1}{2 + .2667 \cdot w} + .68$$ (thermal resistance of window pane negligible)

$$U_w = 1/R_w$$

(iv) Adjust U for wood sash-factor:.9 for 80% glass:

$$U_{w_a} = U_w \cdot .9$$

(v) Conductance reduction due to storm windows (ΔU_s):

Storm windows reduce conductive heat loss (gain) by 50%

$$\Delta U_s = .5U_{w_a}$$

(Based on ASHRAE handbook of Fundamentals, 1972, p. 370.)

(b) Compute hourly heat loss (gain) reduction (H_L, H_G):

$H_L = \Delta U_s \cdot A \cdot (t_i - t_o)$ where $t_i > t_o$

$H_G = \Delta U_s \cdot A \cdot (t_o - t_i)$ where $t_o > t_i$

(c) Compute yearly conductive heat loss (gain) (H^c_{AL}, H^c_{AG}):

$H^c_{AL} = U_s \cdot A \cdot DD \cdot 24$

$H^c_{AL} = U_s \cdot A \cdot CH \cdot (t_o - t_i)$

where t_o = average t_o during cooling hours

(2) Air infiltration heat loss (gains)

Crack method is used rather than air change method. Only wind pressure is used in estimating infiltration rates per area of crack. Stack pressure is ignored because of its difficulty to estimate in the abstract.

(a) Compute wind pressure difference:

(i) $P_v = .000482\ V_w^2$

where P_v = velocity head, inches water

V_w = wind velocity, mph.

(ii) Effective pressure difference requires a factor of .64 to account for build up of pressure inside a building.

$$P = .64\ P_v$$

(b) Compute air leakage per foot of crack around double-hung windows as a function of P:

Establish functions for different window types, derived from Table 2, p. 337, ASHRAE Handbook of Fundamentals, 1972.

Types:

(1) Loose fit w/o weather strip

(2.a) Average fit w/o weather strip

(2.b) Loose fit with weather strip

(3) Average fit with weather strip

Infiltration functions:

(1) $I = 40 + 370\ P$

(2) $I = 14 + 132.5\ P$

(3) $I = 7 + 70\ P$

where I = CFH per foot of crack

(c) Compute crack length:

$$L = 2 \cdot H + 3 \cdot w$$

where L = crack length in feet

H = window height

W = window width

(d) Compute effect of storm windows over primary windows in reducing infiltration:

Methodology:

ASHRAE Handbook of Fundamentals states that tight fitting storm windows reduce air infiltration by 50% for loose windows (type 1) and by 30% for equally tight primary windows (2a, 2b). This has been extrapolated to 10% reduction for type 3 windows.

(e) Compute CFH reduced by storm window (ΔQ):

$$\Delta Q = L \cdot I \cdot F$$

where F is the infiltration reduction factor for storm windows

(f) Reduce ΔQ by one half to account for exiting air:

$$\Delta Q = .5 \Delta Q$$

(g) Compute hourly heat loss (gain) reduction due to decreased infiltration (H_L, H_G):

$H_L = .240 \cdot \Delta Q \cdot \rho \cdot (t_i - t_o)$

$H_G = .240 \cdot \Delta Q \cdot \rho \cdot (t_o - t_i)$

where .240 = specific heat of air

ρ = density of air = .075

(h) Compute annual air infiltration heat loss (gain) reduction (H^i_{AL}, H^i_{AG}):

$H^i_{AL} = .240 \cdot \Delta Q \cdot \rho \cdot DD \cdot 24$

$H^i_{AG} = .240 \cdot \Delta Q \cdot \rho \cdot CH \cdot (t_o - t_i)$

Factors used:

Winter wind velocity = 10 mph.

Summer wind velocity = 7.5 mph.

t_i (winter) = 65°F (degree day base)

t_i (summer) = 75°F

(3) Add annual conductive heat loss (gain) reduction to annual air infiltration heat loss (gain) reductions to find total annual heat loss (gain) reduction due to storm window (H_{AL}, H_{AG}):

$H_{AL} = H^c_{AL} + H^i_{AL}$

$H_{AG} = H^c_{AG} + H^i_{AG}$

STORM DOOR

(1) Conductive heat loss

(No summer cooling help attributed because it is better to remove glass and replace with screens for ventilation during non-cooling hours.)

(a) Compute U for primary door:

(i) Compute outside surface R (R_o):

$$R_o = \frac{1}{2 + .2667 \cdot V_w} \qquad \text{(see windows)}$$

(ii) Calculate door R (R_d):

$$R_d = t \cdot R_t$$

where t = thickness (inches) of door, and

R_t = thermal resistance per inch.

(iii) Inside surface $R_i = .68$.

$$U_d = \frac{1}{R_o + R_d + R_i}$$

(b) Compute U for glass in door (if any):

(i) Compute outside surface R, R_o (as above).

(ii) Inside surface R, $R_i = .68$.

$$U_g = \frac{1}{R_o + R_i} \qquad \text{(thermal resistance of glass is negligible)}$$

(c) Compute reduction in thermal conductance due to storm door (ΔU):

(i) Airspace $R_a = 1.0$.

(ii) $$U_{d,s} = \frac{1}{R_o + R_d + R_i + R_a}\ ;\ U_{g,s} = \frac{1}{R_o + R_i + R_a}.$$

(iii) Effective reduction in thermal conductance due to storm door (ΔU):

$$\Delta U = (U_d - U_{d,s}) \cdot \%\ \text{wood} \cdot 10^{-2} + (U_g - U_{g,s}) \cdot \%\ \text{glass} \cdot 10^{-2}$$

(d) Compute area of door (A):

$$A = H \cdot W$$

(e) Compute effective hourly heat loss reduction (H):

$$H = A \cdot \Delta U \cdot (t_i - t_o)$$

(f) Compute annual heat loss reduction (H_{AL}):

$$H_{AL} = A \cdot \Delta U \cdot DD \cdot 24$$

(2) Infiltrative heat loss (again only wind pressure is considered significant):

(a) Compute effective wind pressure differential (P):

$P = .64 \cdot .000482 \cdot V_w^2$

where V_w = wind velocity

(See windows for rationale)

(b) Compute air leakage per foot of crack around door (average):

ASHRAE recommends using two times the window crack rate

(i) Well-fitted door, $I = 2 \cdot (14 + 132.5P)$

(ii) Average/poor-fitted door, $I = 2 \cdot (40 + 370\ P)$

(Based on values for poorly fitted double hung window)

where I = CFH per foot of crack

(c) Compute crack length (L):

$L = 2 \cdot H + 2 \cdot W$

(d) Compute hourly CF of infiltration (Q):

$Q = L \cdot I$

(e) Compute effect of storm door on reducing air infiltration (ΔQ) --

Factors Derived from Data on Windows:

Type (i): Weather stripping reduces infiltration by 50%
Storm door reduces infiltration by 30%
Combination WS and SD reduces infiltration by 55%

Type (ii): Weather stripping reduces infiltration by 50%
Storm door reduces infiltration by 50%
Combination WS and SD reduces infiltration by 65%

(f) Reduce ΔQ by one-half to account for exiting air:

$\Delta Q = .5\ \Delta Q$

(g) Compute hourly heat loss reduction due to storm door (H):

$H = .24 \cdot \Delta Q \cdot \rho \cdot (t_i - t_o)$

(h) Compute yearly heat loss reduction due to storm door (H_{AL}):

$H_{AL} = .24 \cdot \Delta Q \cdot \rho \cdot DD \cdot 24$

Factors used in calculations:

$R_d = t\ R_t = 1\ 1/2'' \cdot .91 = 1.36$

V_w = 10 mph.

Glass in door computed at 0%, 10%, 20%, 30%, 40%, 50%.

Door size = 3' x 6 2/3" = 20 ft.^{2}

Perimeter = 19 1/3'

APPENDIX E

A NOTE ON THE COMPUTER PROGRAMS USED IN THIS STUDY

The computer programs needed to solve for the economically optimal levels of investment in each ECT were written in BASIC (Beginners All-purpose Symbolic Instruction Code) language. One program was written for each ECT, using the methodology outlined in Appendix D. These programs compute annual marginal energy savings for both heating and cooling operations as a function of degree days, cooling hours, inside temperatures, existing coefficients of conductance, the resistance per unit of the ECT materials, and other relevant variables. Marginal savings are computed for each inch of insulation, for decreasing storm window sizes, and for storm doors over prime doors with decreasing glass content. Energy savings due to weather stripping are calculated for loose and average fitting doors and windows with or without existing storm sash.

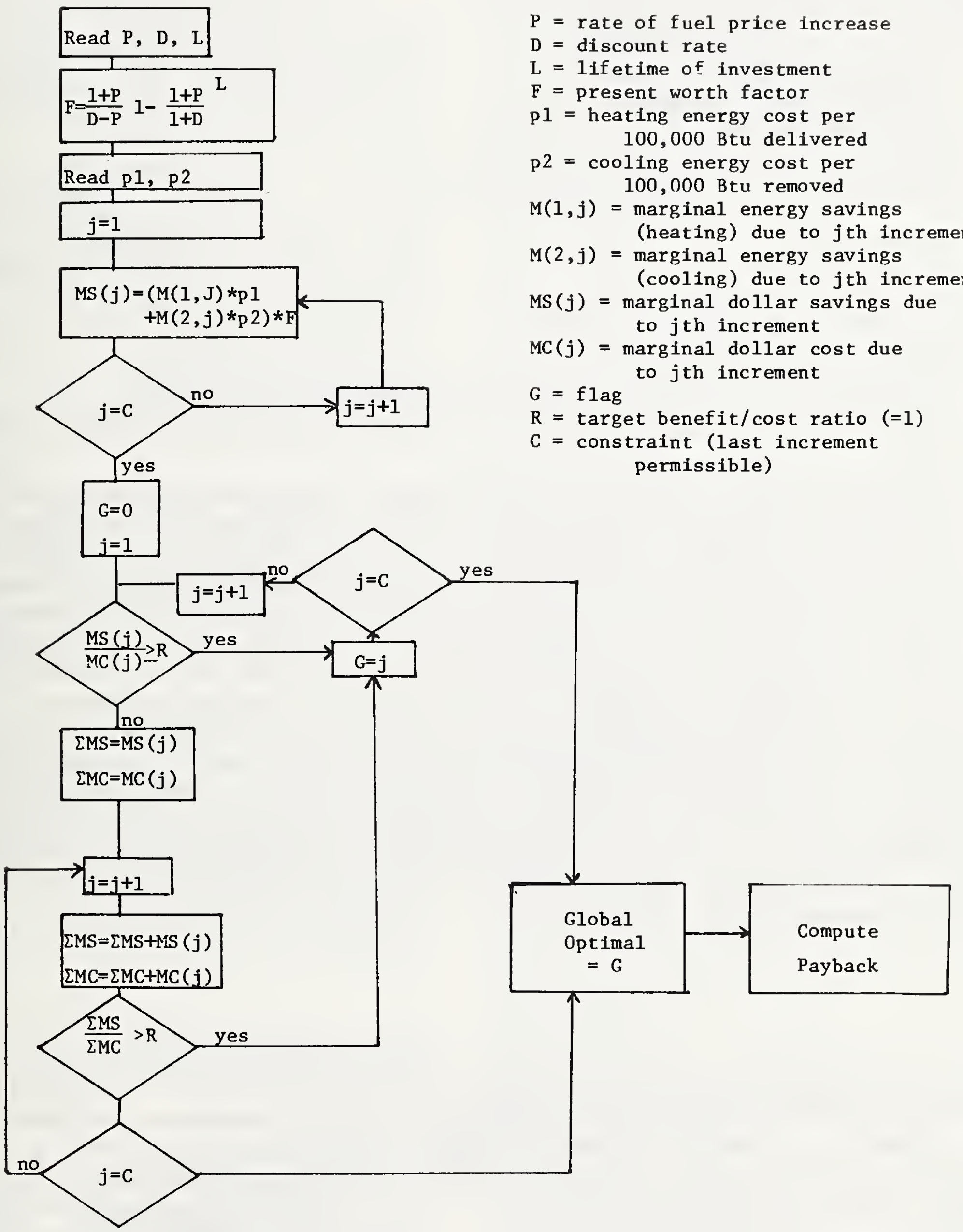
The marginal energy savings generated by variable-usage techniques (insulation, storm windows and storm doors) and then read into a general purpose benefit-cost analysis program (BENCØ). This program calculates the present value marginal savings in dollars corresponding to annual marginal energy savings, calls out appropriate marginal costs from a supporting cost file, and then searches for the globally optimal investment level (satisfaction of condition I and II) for the specified energy prices, using a search procedure similar to that outlined in Figure E-1.

Satisfaction of Condition II only cannot be solved for directly because specific parametric information (building dimensions, number and size of windows and doors, etc.) for a given building is needed in order to calculate the optimal level of investment in each technique which meets the specific budget constraint for that building. However, the model can be used with MS/MC ratios other than 1 in order to find lower or higher levels of investment which are economically balanced in the sense of Condition II. Given a fixed-sized investment budget and specific parametric information, the allocation of a constrained budget among alternative techniques can then be estimated using an iterative approach. (See Section 5.3 for more details on this approach.)

It should be noted that BENCØ is structured to reflect the particular cost and savings functions typical of insulation, i.e., marginal costs (MC) may rise and fall while marginal savings (MS) decline monotonically. In addition, the use of the i^{th} increment assumes the use of the $(i - 1)^{th}$ increment. Because there may be more than one local optimal, this program searches for the global optimal, i.e., that level of investment which maximizes net savings for the entire range of application. Rather than directly identifying those investment levels where MS = MC (Condition I), the program instead examines each successive increment of insulation to insure that total cost does not exceed total savings at the global optimum. This may require more computer time and information on fixed costs than the direct approach but it is manageable in cases where there are a limited number of increments under consideration such as are encountered in this study.

In order that BENCØ finds the minimum economic configuration of storm windows and doors, these configurations must be entered in order of decreasing MS/MC ratios. In general the use of any given size window or door configuration is physically independent of the use of other windows or doors. In ordering such ECT's by decreasing MS/MC ratios, the search routine will select only those units which generate savings greater than or equal to cost.

Payback periods are computed for the total investment (average payback period) for the techniques involving insulation. For storm windows, payback is computed for a 3' x 5' (average size) window as actual average payback is a function of the number and size distribution of windows in an actual house. Payback periods for storm doors are evaluated for the least profitable configuration which has a benefit-cost ratio greater than or equal to one.



P = rate of fuel price increase
D = discount rate
L = lifetime of investment
F = present worth factor
p1 = heating energy cost per 100,000 Btu delivered
p2 = cooling energy cost per 100,000 Btu removed
M(1,j) = marginal energy savings (heating) due to jth increment
M(2,j) = marginal energy savings (cooling) due to jth increment
MS(j) = marginal dollar savings due to jth increment
MC(j) = marginal dollar cost due to jth increment
G = flag
R = target benefit/cost ratio (=1)
C = constraint (last increment permissible)

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

This study examines the economic aspects of energy conservation techniques suitable for retrofitting into existing housing, including insulation, storm windows and doors, and weather stripping. The objective of this study is to determine that combination of techniques which will maximize net dollar savings in life-cycle operating costs for heating and cooling operations in existing homes, subject to specific climate conditions, fuel costs, and retrofitting costs. Using micro-economic marginal analysis we find that such a combination must be economically balanced (i.e., the ratio of savings to cost must be equal at the margin for each technique) and that each technique should be utilized up to the point where the present value of the life-cycle savings generated by the last increment will just cover the costs of that last increment. Thermal engineering data is combined with the economic analysis in a computer-assisted model which estimates such optimal combinations for a wide range of climatic conditions and fuel costs. These combinations include levels of application considerably higher than what has been previously recognized as "economical."

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Benefit-cost analysis; building economics; building envelope; economic analysis; economic efficiency; energy conservation; engineering economics; insulation; life-cycle costs; marginal analysis; thermal efficiency

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