Optimizing thermal insulation and ground levels in residential wall construction : an economic analysis
by Clifford Walter Nixon

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE
in Applied Economics
Montana State University
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Abstract:
The purpose of the study was to identify cost minimizing thermal wall designs in residential buildings by the two fold approach of determining optimal insulation levels and utilizing the effectiveness of the ground as a thermal barrier. To approach the problem cost and savings functions were defined to simulate the experimental wall's structural and thermal characteristics. Insulated wall structures up to 20 inches thick were examined so costs resulting from each change in insulation level within the wall reflected any additional expenditures necessitated by thickened wall designs. The savings generated by each additional level of insulation were estimated by engineering procedures recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers. When net savings from insulation and wall grounding were optimized together, a provision was made in the mathematical model to place the walls deeper in the ground in steps of 10 percent of the total wall height. Such an approach defined a systematic manner of examining the use of the ground as a thermal barrier. Fuel savings resulting from applications of wall insulation were distinguished from those attributable to the placement of the wall in relation to the ground level in the following way: Reductions in heat flow across any section of the model home's thermal envelope which resulted as successive insulation levels were applied to that portion of the wall, were attributed to the thermal insulation. In contrast, savings related to the ground level were calculated from the change in the overall heat flow through the optimally insulated walls of the model home which resulted when the walls were placed deeper in the ground.

The results showed that insulation levels and the savings generated by them were sensitive to changes in fuel price with higher levels being frequently recommended at greater fuel costs. When the thermal characteristics of the soil were included in the analysis, the net savings generated by insulated wall designs declined $1400 to $6700 as the walls were placed deeper within the ground. Fuel consumption for these grounded designs was generally shown to increase over their above-ground, i.e. conventional, counterparts. The net savings generated by fiberglass insulation was greater than comparable savings from urethane in above-ground wall structures. Conventional and grounded designs using fiberglass usually had lower fuel consumption than comparable, walls insulated with urethane. Urethane designs, on the other hand, generated greater net savings in most grounded situations.

The study concludes that the cost minimizing wall design for residential buildings over a broad cross section of the nation is the above-ground structure framed with 2 x 4's 16 inches on center and insulated with R-13 fiberglass.

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OPTIMIZING THERMAL INSULATION AND GROUND LEVELS IN RESIDENTIAL WALL CONSTRUCTION: AN ECONOMIC ANALYSIS

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

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ABSTRACT

The purpose of the study was to identify cost minimizing thermal wall designs in residential buildings by the two fold approach of determining optimal insulation levels and utilizing the effectiveness of the ground as a thermal barrier. To approach the problem cost and savings functions were defined to simulate the experimental wall's structural and thermal characteristics. Insulated wall structures up to 20 inches thick were examined so costs resulting from each change in insulation level within the wall reflected any additional expenditures necessitated by thickened wall designs. The savings generated by each additional level of insulation were estimated by engineering procedures recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers. When net savings from insulation and wall grounding were optimized together, a provision was made in the mathematical model to place the walls deeper in the ground in steps of 10 percent of the total wall height. Such an approach defined a systematic manner of examining the use of the ground as a thermal barrier. Fuel savings resulting from applications of wall insulation were distinguished from those attributable to the placement of the wall in relation to the ground level in the following way: Reductions in heat flow across any section of the model home's thermal envelope which resulted as successive insulation levels were applied to that portion of the wall, were attributed to the thermal insulation. In contrast, savings related to the ground level were calculated from the change in the overall heat flow through the optimally insulated walls of the model home which resulted when the walls were placed deeper in the ground.

The results showed that insulation levels and the savings generated by them were sensitive to changes in fuel price with higher levels being frequently recommended at greater fuel costs. When the thermal characteristics of the soil were included in the analysis, the net savings generated by insulated wall designs declined $1400 to $6700 as the walls were placed deeper within the ground. Fuel consumption for these grounded designs was generally shown to increase over their above-ground, i.e. conventional, counterparts. The net savings generated by fiberglass insulation was greater than comparable savings from urethane in above-ground wall structures. Conventional and grounded designs using fiberglass usually had lower fuel consumption than comparable walls insulated with urethane. Urethane designs, on the other hand, generated greater net savings in most grounded situations.

The study concludes that the cost minimizing wall design for residential buildings over a broad cross section of the nation is the above-ground structure framed with 2 x 4's 16 inches on center and insulated with R-13 fiberglass.

Chapter 1

INTRODUCTION

As finite energy reserves become depleted, increasingly higher cost sources of energy must be utilized. Such conditions may cause the price of fuels to rise with respect to the general price level. In this decade, the rise in energy costs has outstripped the general rate of inflation which indicates that fuels are becoming increasingly scarce in relation to other resources. The housing sector is one portion of the economy which has experienced this shift in relative prices. Consequently forces have appeared in this sector to shift resources away from energy consumption and towards energy conservation.

Rising energy prices provide incentives for homeowners to build more thermally efficient homes. Some new designs will, to be sure, embody energy concepts quite different from those currently used -- perhaps different enough to alter the appearance of the building and the utility derived from it. The homeowner's reaction to such structural changes in the building envelope are an important consideration determining the optimal allocation of resources. This can be easily demonstrated by considering two men's responses to energy conserving structures. The first man will not build a house whose walls are partially buried in the ground even if he understood that the design would yield the highest return on investment of all possible

structures he could erect in his climate and terrain, but would build a house having 2 x 6 studding and R-19 insulation in the walls if it were more "conventional" in appearance. The second man rejects the more heavily insulated design which was acceptable to the first man on the grounds that the thicker walls require additional floor area.[1/] His choice might have 2 x 4 walls with R-13 insulation. These examples show that when preferences of the consumer are considered, increasing thermal insulation can be used as a substitute for fuel consumption.

STATEMENT OF THE PROBLEM

The problem is to define an economic model which will allocate energy related resources in the housing sector in an efficient manner. Such an undertaking requires that all savings resulting from and all costs incurred by each energy conserving modification to a residence, be clearly defined and representative of actual market conditions. The criterion by which decisions in this model will be made is cost minimization to the homeowner, ie. consumer, so costs involving his

---

[1/] If a wall which adjoins the floor of a residence is made thicker inward, floor space available for occupancy is reduced but the external dimensions of the building are not changed. If the broadening of the wall is outward, additional floor space is required to underlay the expanded dimensions of the building. For additional information see footnote No. 8 on page 35.

preferences must also be accounted for, if the affected resources are to be optimally allocated.[2/]

OBJECTIVES

The objective of the economic model is to identify energy conserving modifications to a residential wall structure which will minimize costs to the homeowner. One goal of the study is the determination of optimal insulation levels within walls in a manner which is dependent on the local climate, specified homeowner tastes and preferences, alternative energy costs, and financial conditions. A second goal is the specification of the soil level height in "buried" wall designs. From these two results, net savings, which are defined as total savings minus total cost, will be calculated.

METHODOLOGY

To approach the problem, certain constraints are assigned:

1. The structural modifications are limited to current technology and built from commonly manufactured materials.

[2/] No potential savings from lowering the interior temperature of the dwelling during periods of heating and raising it during periods of cooling will be considered, as such conservation measures may alter homeowner costs related to comfort.

2. Consumer valuation of the changes which alter the physical appearance of the walls are assigned on a dollar basis so they can be appraised along with the materials and labor costs of the modifications. Through this approach, the expenses of living below ground and of thick walls which were faced by the two men in the example above, can be acknowledged as building costs. Penalty functions are used to convert consumer preferences into dollar costs. These functions are explicitly included in the standardized nomenclature used in this study. For more information see page 54.
3. All decisions are assumed to be made from the standpoint of the homeowner who will respond to the relative price of energy and of energy conserving modifications, as well as to his own personal preferences. Therefore, the cost functions used in the analysis are formulated as statements about homeowner choices as well as construction prices.

The economic model developed calculates the maximum present value dollar savings possible from energy conserving modifications in residential walls given assumptions about consumer preferences, fuel prices, financial conditions, and the local climate. Thermal engineering calculations are used to simulate the wall's performance. Provision is made to examine two concepts of wall design. They are the above

ground wall and the partially buried wall which utilizes soil as a thermal barrier. In each case, the cost minimizing level of insulation is determined through marginal analysis. Optimal soil level heights are calculated through a cost minimizing procedure. The wall modeling and economic analysis are done by computer.

The results, which are listed in Chapter 4, are for the Bozeman, Montana area, but their application to other regions which have different climate and construction costs is described in the summary for the same chapter. By making the appropriate changes in the weather, fuel, and construction cost variables, results can be obtained for any region in the country.

DEFINITIONS

Wall thermal response and structure are described in the following special terms. The costs and savings functions used to define the characteristics of each design are also listed. All definitions are placed alphabetically, with the exception of the first five terms which are used in many of the subsequent definitions.

1. Living wall refers to that portion of the total solid wall area of a residence which is a part of the building envelope. Attic and unfinished basement walls are not of this type since they do not have the thermal characteristics or interior finish which is

suitable for human habitation.

2. Component 1 is the above ground frame portion of a living wall.

3. Component 2 is the above ground concrete portion of a living wall.

4. Component 3 is the below ground portion of a living wall. (Components 1, 2, and 3 form the basic building blocks of all wall designs. See Figure 1.1.)

5. Ground ratio (GR) is the percentage of the total living wall height which is component 1. Ground ratios are illustrated in Figure 4.5.

6. Berm wall refers to a living wall which is partly or wholly composed of components 2 and 3.

7. Component 1 wall costs = (insulation costs) + (thick wall costs) + (framing costs) + (interior and exterior wallboard costs).

8. Component 2 and 3 wall costs = (insulation costs) + (thick wall costs) + (concrete costs) + (framing or furring costs) + (interior wallboard costs) + (perimeter insulation costs).

9. Configuration refers to a particular living wall unit whose component areas are defined by the ground ratio.

10. Conventional wall refers to a living wall which is composed entirely of component 1.

11. Cooling hours are all hours when the outdoor drybulb temperature is 80°F or higher.

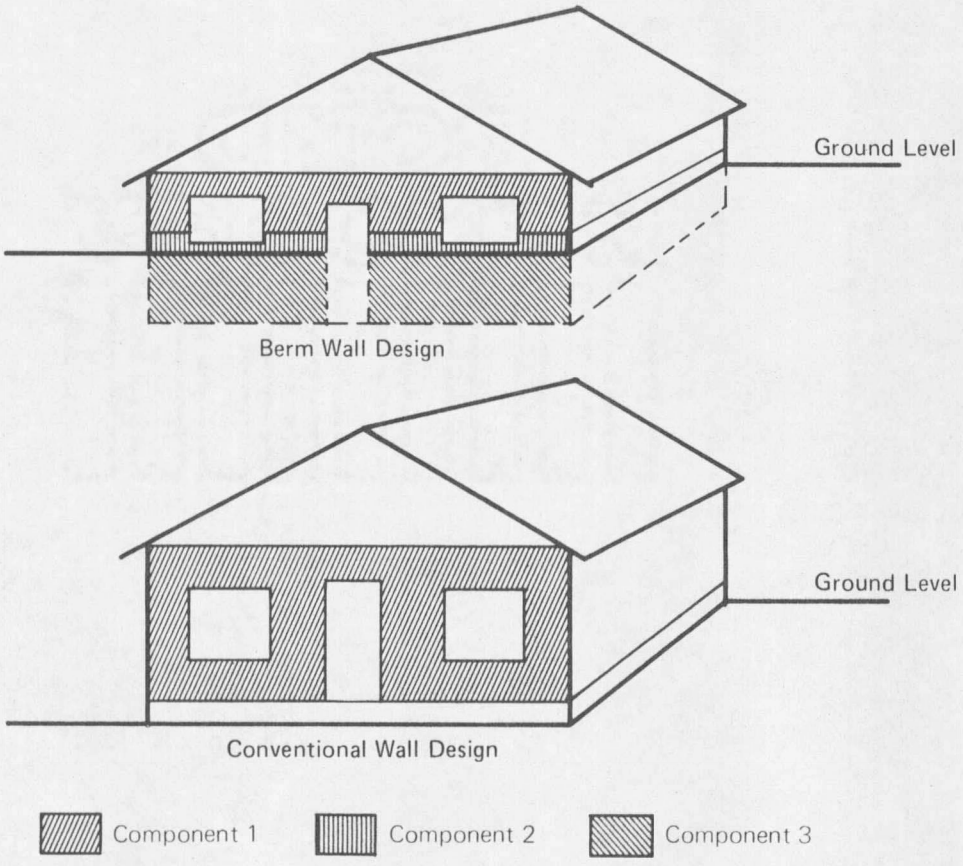

Figure 1.1 The Component Areas of a Living Wall

12. Degree days are a measure of the severity of a local climate. They are the sum of the mean daily temperature differences below 65°F for a year's period of time. (°F days)

13. Entrance costs are the expenditures required for the construction of stairways and landings at the entryway and back door of the dwelling. Net entrance costs for a particular ground ratio = (entrance costs for the configuration in question) - (entrance costs for the conventional design).

14. Entrance cost ratios (ENR) show the preference or aversion of the consumer to using the entryways to his house at a multiple of the net construction cost of the entryways. See page 56.

15. Equivalent temperature differences correspond to the temperature drop across any section of the building envelope which would give the same rate of heat entry as results from the combined effects of the outside drybulb temperature, the incident solar radiation, and the various radiant energy exchanges between the outside surface of the building and the sky and other surroundings.

16. Excavation costs (and backfill costs) are the total expenditures for the dirtwork. They include the costs for floor excavation; for digging the footings; and for backfilling, including the spreading of topsoil. Net excavation costs for a particular ground ratio = (excavation costs for the configuration in question) - (excavation costs for the conventional design).

17. Excavation cost ratios (EXR) show the preference or aversion of the consumer to owning and living in a residence whose ground ratio is less than 100, at a multiple of the net excavation and backfill expenditures involved in the construction of such a residence. See page 57.

18. Glazing fraction = (total glass area)/(total wall area including windows and doors).

19. Ground ratio costs are the structural costs resulting when the ground ratio is shifted down from 100. For a ground ratio of 70 they are defined as the GR = 70 wall cost minus the conventional wall cost. The mathematical expression for ground ratio costs is given on page 48.

20. Ground ratio savings are the sum of the present value savings to all component areas of the living wall which arise when these component areas and their insulation levels are changed from the conventional design due to a downward shift of the ground ratio. (In other words, they are the savings accruing from the change in the overall fuel cost load which results when the wall configuration is changed.) If the ground ratio is 60 these savings are generated in part from the reduction in heat flow through the component 1 wall area which results as the component 1 wall is reduced to 60 percent of its height in the conventional design. Additional savings or losses will be realized for the remaining

component 1 wall area in the GR = 60 configuration if the optimal insulation level for this section of the wall is higher or lower, respectively, than it was in the conventional design. A conventional wall contains no component 2 or 3 areas so as the ground ratio is reduced, the creation of these areas means the creation of additional heat loads on the total wall structure. These component 2 and 3 losses resulting from the downward shift of the ground ratio to 60 are added to the component 1 savings to arrive at the total ground ratio savings for the GR = 60 configuration. The mathematical expression for ground ratio savings is given on page 46.

21. I is the insulation increment number. I = 0 symbolizes no insulation, I = n is representative of the n^{th} increment.

22. Net savings (from insulation and the ground ratio) = (ground ratio savings) - (ground ratio costs) - (net excavation costs times the excavation cost ratio) - (net entrance costs times the entrance cost ratio) + (net savings from insulation).

23. Perimeter insulation cost = (total labor and material cost for the perimeter insulation)/(total component 2 and 3 wall area of the residence less the area of this wall which is taken by windows and doors).

24. R (Thermal resistance) refers to the ability of a material to retard heat flow. It is the reciprocal of transmittance. (°F

hr ft^2/BTU).

25. Thick wall costs for component 1 (when the ground ratio is 100) = (loss of floor area cost due to the thick component 1 wall + thick sill costs + thick jam costs)/(total square footage of the component 1 wall less the area taken by windows and doors).

26. Thick wall costs for component 1 (when the ground ratio is less than 100) = (thick sill costs + thick jam costs)/(total square footage of component 1 wall less the area of this wall which is taken by windows and doors).

27. Thick wall costs for components 2 and 3 = (loss of floor area cost due to the thick component 2 and 3 wall + thick sill costs + thick jam costs)/(total square footage of the component 2 and 3 wall less the area of this wall which is taken by windows and doors).

28. Transmittance and thermal conductance refer to the same unit of heat transfer, namely the rate of BTU flow in an hour's time through a one square foot area of material when the temperature difference across the two surfaces is 1°F. (BTU/hr°F ft^2).

29. Type 1 refers to a component 1 wall having a single row of studs. Depending on the thickness of the wall, these studs may be 4 to 12 inches thick. Figure 1.2 shows a plan of a type 1 wall.

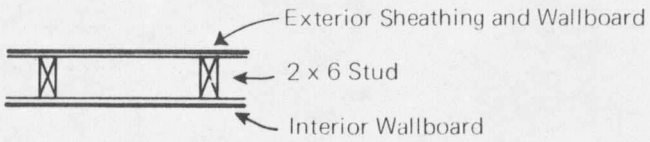

Figure 1.2 Plan of a 6" Type 1 Wall

30. Type 2 refers to a component 1 wall having a double row of 2 x 4 studs. The spacing between the rows of the studs determines the thickness of the wall. Figure 1.3 illustrates this type of design.

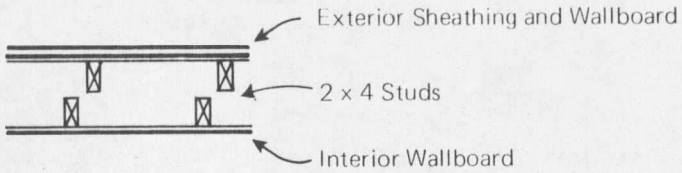

Figure 1.3 Plan of a Type 2 Wall

31. Type 3 refers to a component 2 or 3 wall. Its structure varies depending on how it is insulated. Figure 1.4 shows some variations in type 3 wall construction.

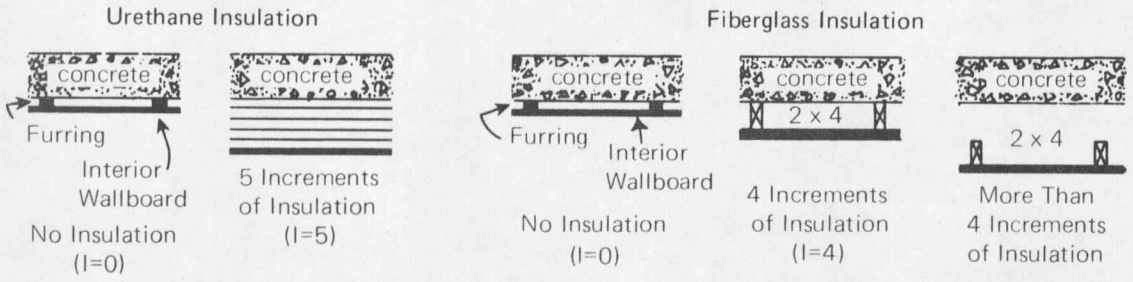

Figure 1.4 Plans of a Type 3 Wall

32. U (Overall coefficient of heat transfer) is the combined conductance of all materials in a heat flow path. It measures the total transmittance of a building unit such as a wall, so its units are the same as those for transmittance.

TERMS USED IN TABLES

1. Cfuel Cooling fuel cost in dollars/100,000 BTU
2. Comp1 Component 1
3. Comp23 Components 2 and 3
4. D Real discount rate
5. ENR Entrance cost ratio
6. EXR Excavation cost ratio
7. f Fiberglass insulation
8. Fuel Heating fuel cost in dollars/100,000 BTU
9. GF1 Glazing fraction for component 1
10. GF2 Glazing fraction for component 2

11. GR Ground ratio
12. INS Insulation type
13. L Lifetime
14. n.a. Not applicable
15. Opt. Inc. No. Optimal increment number, ie. optimal insulation level
16. P Real rate of fuel price increase
17. Pb Payback period in years
18. PVF Present value factor
19. P.V. Max. Net Savings Present value maximum net savings for the total wall or component area of the model home
20. R Thermal resistance
21. u Urethane insulation

Chapter 2

BASIC CONSIDERATIONS

This study is an analysis of specific thermal modifications to residential wall structures. Its objective is to identify physical changes to wall designs which minimize costs to the homeowner. The criteria used for determining optimal insulation levels are discussed in this chapter along with the approach used for converting streams of annual savings generated from insulation into present value amounts which can be used in the decision process.

MARGINAL ANALYSIS

The use of marginal analysis as a tool for optimization is central in the model's design. Algorithms are used to calculate the marginal savings and the marginal costs attributable to each level (or increment) of wall insulation. This is done for the wall structures considered by taking those structures in their non-insulated forms and successively adding one increment of insulation to them at a time. The term "marginal cost" or "MC" is used to mean the cost resulting from the purchase and installation of the last increment of insulation. Likewise, "marginal savings" or "MS" means the savings in heating and cooling expense realized from that last increment.

The homeowner is considered to be free to vary the levels of insulation since his ultimate aim is the minimization of his costs.

According to microeconomic theory, his return on investment will be maximized if the following conditions are met by his cost and savings functions:

$$P_I = TS_I - TC_I$$

$$P_I = S \cdot R_I - C_I \cdot X_I$$

$$P_I = S \cdot f(X_I) - C_I \cdot X_I$$

$$\frac{dP_I}{dX} = S \cdot f'(X_I) - C_I = 0$$

First order conditions require that this equality be satisfied at one value of I (or for as many values of I as the P function has local maxima and minima.)

or

$$S \cdot f'(X_I) = C_I$$

in other words

$$MS(I) = MC(I)$$

$$\frac{d^2P_I}{dX^2} = S \cdot f''(X_I) < 0$$

Second order conditions will be met at the one or more local maxima found by the first order conditions

in other words

$MS(I) - MC(I) < 0$ for any larger values of I in the local area(s) where the first order conditions are met.

where I = the insulation increment number

P_I = the present value maximum net savings resulting from I increments (or levels) of insulation

TS_I, TC_I = the total savings and total costs from I levels of

insulation

R_I = the decrease in energy flow through the wall in BTU's due to the resistance of I levels of insulation

C_I = MC(I) = the cost of the I^{th} increment in dollars/increment (This is defined as the marginal cost.)

X_I = the quantity of insulation ($R_I = f(X_I)$)

S = the fuel price in dollars/100,000 BTU

$f'(X_I)$ = the marginal product of the I^{th} level of insulation in BTU's/increment of insulation

$S \cdot f'(X_I)$ = MS(I) = the value of the marginal productivity of the I^{th} level of insulation in dollars/increment. (This is defined as the marginal savings.)

$S \cdot f''(X_I)$ = the change in the value of the marginal productivity of the insulation with respect to a change in the insulation level.

The first order conditions derived here can be expressed as MS(I)/MC(I) = 1 if only one wall is being considered. If two wall components are being optimized together, as is often the case in the model, these condtions can be expressed as $MS_1(I)/MC_1(I) - MS_2(I)/MC_2(I) = 1$ where the wall components are labeled 1 and 2.

In order for the optimality relationship between wall components 1 and 2 to hold, the thermal response of these areas must be independent

of each other. What this means is that any changes in the transmittance of one component will not alter the heat flow through an adjacent component in the integrated wall structure. This restriction is met in the model to be defined because in it the heat flow through each wall area is assumed to be parallel, and the model home's internal temperature is specified as consistant and uniform over the entire wall area. See page 57.

Figure 2.1 shows a simple example of how satisfaction of the first and second order conditions as specified by the theory, will indeed maximize return on investment. On the top of the figure total

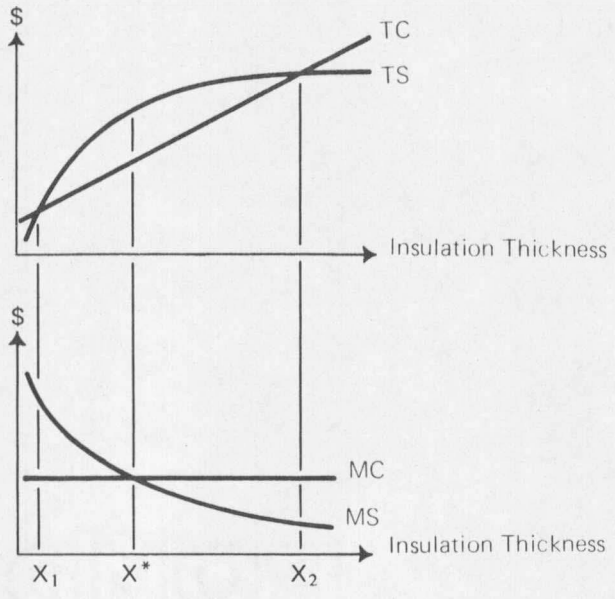

Figure 2.1 The Optimal Insulation Thickness

cost (TC) and total savings (TS) functions for insulation are plotted. Likewise, the corresponding MC and MS functions are plotted on the lower diagram. Net savings (TS - TC) is positive for any insulation thickness between X_1 and X_2 but it is maximized where the TS function rises highest above the TC function -- this occurs at X*. In the lower graph MC = MS at the insulation level X*, which satisfies the first order conditions. Second order conditions require that the net savings must be decreasing with respect to further applications of insulation. This criteria that MS - MC < 0 for additional insulation levels, is met at X* also. Therefore X* is the net savings maximizing thickness of insulation.

The illustration given in Figure 2.1 assumes continuous MS and MC functions. In reality these functions are discrete, since wall insulation is available only in a limited number of thicknesses. Feasible solutions according to the theory outlined above are still possible, however, and are found in the following manner. The model compares the marginal cost and marginal savings values for all allowable levels of insulation. Then it identifies the levels of insulation which most closely approximate theoretical first order conditions. It is important to note that the model does not locate all first order solutions but only those which satisfy second order conditions as well. (Second order conditions state that the MC curve

must intersect the MS curve from beneath.) Therefore any solution found satisfies the economic criteria for maximization. A detailed description of the method used to identify the optimal levels of insulation is given on page 42.

Due to the discrete nature of the MC function, first and second order conditions may be met at several different insulation levels. This is illustrated in Figure 2.2 where local optima exist at in. = 2, and in. = 6.

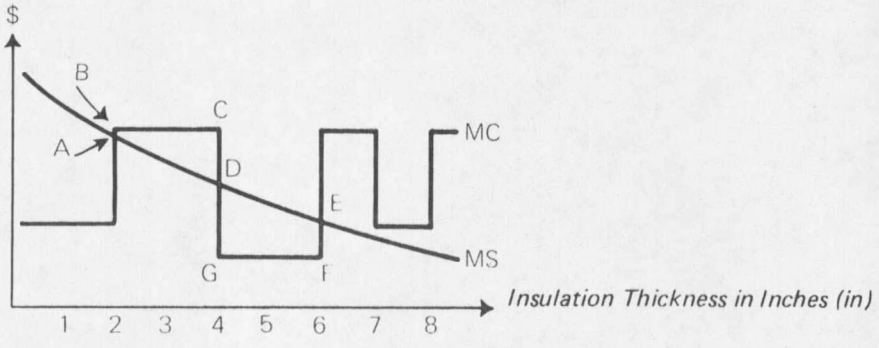

Figure 2.2 Location of the Global Optimal Solution

The determination of which of the local optima is the one where net savings are maximized over the entire range of allowable insulation levels is made by comparing the savings to the costs in the region between each optima. In Figure 2.2, the savings realized from the additional 4 inches of insulation exceed the costs incurred because Area DEFG > Area ABCD. Hence, the global optimum is at in. = 6 because

net savings are maximized there.

Figure 2.2 is not representative of actual cases but was drawn to illustrate the rationale used in locating the global optimal solution. Marginal savings functions calculated by the model are discrete due to the limited number of thicknesses in which wall insulation is manufactured. The criterion for defining the global solution is the same, however, as illustrated in Figure 2.2. See Figure 4.2 for a plot of marginal cost and savings functions in an actual case examined with the model.

PRESENT VALUE OF SAVINGS FLOWS

Because money and resources have an opportunity cost for investment, equal cash flows received at different times do not have the same value. This is the case with annual savings generated from insulation. These savings are accrued over the lifetime of the investment, and it is their present value amount which reflects the real return that a homeowner can expect from his outlay of cash.

The conversion of a sum of money (S) to be received in the future, to its present value (P.V.) at a given discount rate (D), when the number of interest periods is N, is done through use of the formula

$$P.V. = \frac{1}{(1 + D)^t} \cdot S.$$

If this sum (S), is an annual stream, then its present value can be

expressed as

$$P.V. = \sum_{t=1}^{N} \frac{1}{(1 + D)^t} \cdot S.$$

Likewise the total accumulation (A) that a sum of money (S) will become under the compounding of interest at rate (P) for N periods is

$$A = \sum_{t=1}^{N} (1 + P)^t \cdot S.$$

The application of this formula is to determine the accumulation of savings from insulation when they are being escalated at the annual rate of fuel price increase (P).

Finally the determination of the present value savings resulting from a stream of annual energy savings which are being escalated over time is, in the nomenclature introduced above,

$$P.V. = \sum_{t=1}^{L} \left(\frac{1 + P}{1 + D}\right)^t . S$$

where L is the lifetime of the investment. At no time are P and D restricted to be the real or nominal values of the fuel price increases and discount rates. The reason is the rate of inflation which separates the real from the nominal appears in both the numerator and denominator of the equation, and in effect cancels out (24, p.19). As long as one is consistant and stays with the nominal or the real values throughout, the formula will give satisfactory results. Throughout the rest of this report, P and D will be the real values.

The following discussion gives some insight into the values for

the D, P, and L variables used in this study.

Selection of D. In order to discount properly annual fuel savings over time, an appropriate rate of discounting is needed which reflects the opportunity cost to the investor. Because personal discount rates will vary between individuals according to their risk and liquidity preferences, a general value is hard to come by. In a study done by Stephen R. Petersen which is similar to this one, the real homeowner discount rate (beyond inflation) for energy conserving improvements was estimated at 1 percent (24, p. 20). In that study, the opportunity costs were considered to be the after tax real rate of return forgone on the next best alternative investment which was U.S. government 3-5 year securities available between 1952 and 1970. A somewhat higher discount rate results if the homeowner patterns his investment decisions after businesses. The long run real rate of return on business investments is estimated at 3-4 percent (25, p. 12).

It is important to note that the estimated rates of return are for the marginal or last increment. When more than a single thickness of insulation is recommended in an optimal solution, the average rate of return on the investment will exceed the discount rate chosen here. Because it takes less time to pay back the first increments, the average payback period will also be less than the expected lifetime. Thus the investment can be quite attractive.

Selection of P. Excluding major technological advances in energy production, the depletion of finite energy reserves means increasingly higher cost sources of energy must be utilized. This trend may cause the price of fuels to rise with respect to the general price level. Realizing this, Jim L. Heldenbrand in his February 27, 1974 National Bureau of Standards draft proposal, recommended an annual real energy price increase of 1 percent be used in calculating building efficiencies (9, p. 95).

Selection of L. Since the lifetime of the investment is dependent on future fuel prices and other long run economic conditions, a conservative estimate of 20 years was chosen for retrofitting existing housing in the Petersen study (24, p. 21). The NBS draft proposal mentioned above recommends a building life of at least 30 years (9, p. 95).

Thus, given the uncertainty in estimating an appropriate discount rate, rate of fuel price increase, and investment lifetime, computer runs were made for different values of these terms to check the sensitivity of the results. In following the Petersen and Heldenbrand arguments, the majority of the analysis uses the values: D = 1 percent, P = 1 percent, L = 30 years.

Chapter 3

THE MODEL

The analysis described in this report was confined to a study of thermal modifications to the solid wall area of a residence. A computerized model which simulated each wall design's total costs and thermal performance, was used to do the calculations. It is described in this chapter.

THE MODEL HOME

Various thermal modifications to wall areas were made to a theoretical building called the model home. Its specifications are given below.

The model home is a 1200 sq. ft. single story structure having 8 foot high walls 40 feet long and 30 feet wide.[3/] The particular size of 30 x 40 was chosen as it is representative of typical new construction in the study area. These dimensions were selected to demonstrate reasonable present value maximum net savings from wall insulation and from the thermal properties of the soil which are attainable from the total wall area of the residence. To investigate savings which can be

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[3/] The dimensions of the residence are the external measurements of the building. The cost/sq.ft. of the home is determined from these dimensions.

recovered utilizing the thermal properties of the soil, provision was made, through the ground ratio, to vary the wall configuration of the residence in eleven steps ranging from the all frame wall which is placed above the ground, through various concrete-frame combinations, which are in part located below the surface of the ground, to the all concrete, nearly totally submerged wall. Component 2 height was set at 7.75 percent of the total living wall height, which amounts to 7.44 inches. Two entrance doorways were defined for the building, one in a 30 and one in a 40 foot wall section. The glazed areas of the above ground walls were variable with the most common value used for the frame walls being 11 percent of the gross component 1 area as defined by the exterior dimensions and the ground ratio. In a like manner, the glass area of the exposed concrete walls was usually specified as 20 percent of the gross component 2 area.[4/] A choice of fiberglass or urethane insulation was offered for all component areas. Except where noted, the thermal resistance of the wall sections conformed to the specifications set forth in Revision No. 1 to "Minimum Property Standards for One and Two-Family Dwellings" (32).[5/]

[4/] See page 66 for an explanation of the values selected for the glazed areas.

[5/] This requirement was imposed so that the net savings from the cost minimizing wall designs found in the analysis could be compared to the savings from similar designs which conformed to the HUD Minimum Property Standards (MPS) and so that the HUD MPS requirements them-

SAVINGS REALIZED FROM WALL INSULATION

The purpose of the model was to study thermal wall designs in residential buildings with the two-fold objective of determining the optimal insulation levels and examining the effectiveness of the ground as a thermal barrier. In all cases the optimality criterion was cost minimization. To generate this information for the range

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5/continued
selves, could be appraised. With the exception of glazed areas and urethane insulated component 2 and 3 walls, each wall design met the standards set forth in the 1976 Uniform Building Code (UBC). No attempt was made, however, to have the wall designs conform strictly to the UBC as such a constraint would limit the range of wall designs which could be examined. For example, the UBC requires that all habital rooms within a dwelling with the exception of bathrooms, laundry rooms, etc., be provided with natural light through exterior glazed openings having an area of not less than 10 percent of the floor area of such rooms with a minimum of 10 square feet (11, Sect. 1405). The imposition of such a requirement on the model home would exclude the examination of all ground ratios below GR = 90 as the total glazed area of the walls would fall short of the UBC requirement at lower ground ratios. Urethane insulated component 2 and 3 walls were specified without furring as that insulation's rigid structural qualities were utilized to support the interior wallboard. The layers of urethane and the interior wallboard were fastened together with a mastic as was illustrated in Figure 1.4. Such a construction practice did not conform to the requirements set forth in the 1976 Uniform Building Code as it required that interior wallboard be attached to framing (11, Sect. 4711). This design was selected for the urethane insulated component 2 and 3 walls, however, because it lowered the cost of these areas with respect to their furred counterparts and because it more fully utilized the qualities of the insulation.

of wall designs desired, cost functions and savings functions were defined to simulate the various walls' structural and thermal characteristics. It was through these functions that the effects of consumer preferences, financial conditions, weather, and fuel prices were expressed in the optimal solutions.

The first step in determining the savings and costs resulting from insulation was to take each wall component in its non-insulated form and successively add increments of insulation to it, one at a time. To illustrate the addition of insulation to a wall component, see Figure 3.1.

The savings resulting from each additional level of insulation were estimated by a thermal engineering procedure which assumed that the conductive heat transferred across any section of the building envelope was directly proportional to the temperature difference across that section. This approach, termed "steady state", was selected over more exact periodic response methods because it adapted well to the large number of repetitive calculations required for marginal analysis.[6/] In one step, this steady state method will assess

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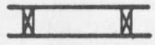
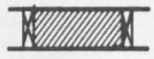
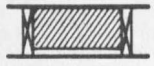
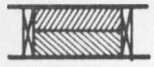
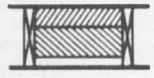
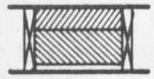
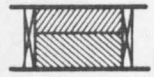
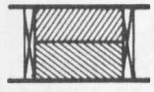
[6/] One approach to periodic response is to simulate a wall component's heat storage and thermal conductivity through a network of capacitances and resistances. Such a model will account for the load imposed on both sides of a residential wall, the randomly fluctuating hourly weather and solar load, and the periodic indoor load due to occupants, appliances, and lighting. It is a large step up in precision but its complexity and the 8766 hourly calculations

Increment Number	External Thickness	Stud Size	Insulation R of Batts or Rolls	Total R	Structural Plan
I = 0	4.5	2x4	0	0	
1	4.5	2x4	11	11	
2	4.5	2x4	13	13	
3	6.5	2x6	19	19	
4	8.25	2x8	22	22	
5	8.25	2x8	11, 13	24	
6	8.25	2x8	13, 13	26	
7	10.25	2x10	11, 19	30	
8	10.25	2x10	11, 22	33	
9	10.25	2x10	13, 22	34[1]	
10	12.25	2x12	19, 19	38	

[1] The installation of an R-13 and an R-22 batt, which have a combined thickness of 10.13 inches, in a 9.25 inch wall cavity, decreases the R value of the insulation [23 p. 5].

Figure 3.1 The Addition of Ten Increments of Insulation to Wall Type 1

the annual thermal impact on a wall component.

For above ground components, the degree day (DD) is used as a measure of the local climate for periods of heating. Cooling hours (CH) and equivalent temperature differences (TEQ) are used to simulate the climate during periods of cooling. Thus the annual heat flow through a square foot of wall component 1 is:

$$H_1 = U_1 \cdot (24 \cdot DD + CH \cdot TEQ)$$

where U_1 = the thermal conductance of wall component and

24 = 24 hours/day.

Likewise the component 2 annual heat flow is:

$$H_2 = U_2 \cdot (24 \cdot DD + CH \cdot TEQ).$$

For component 3, which is the below ground concrete wall, an equivalent temperature difference is used to generate the typical temperature drop across the concrete wall-ground combination which would be experienced during periods of heating. No summer cooling calculations are made for component 3 as no heat gains are assumed to be made through its contact with the ground. Hence the annual heat flow through component 3 is:

$$H_3 = U_3 \cdot (75 - TBSMT) \cdot 24 \cdot HD$$

6/continued
which would be necessary to determine the annual heating and cooling load for each increment of insulation, render it impractical for application in marginal analysis (34, p. 14), (1, p. 355). Examples of periodic response techniques are found in (3), (4), (12), (13), and (21).

where 75 = the inside average air temperature

TBSMT = the equivalent temperature of the soil adjacent to the below ground concrete wall

HD = the number of heating days per year.

Though the heat storage effects of the wall structure cannot be accounted for by the steady state heat flow concept, the loads calculated can still closely approximate actual wall transmissions. The following discussion appraises the trustworthiness of the steady state method of determining the loads across each wall component.

The heating loads calculated for components 1 and 2 can be expected to correlate well with actual loads because a close relationship has been observed between the number of degree days in a local climate and fuel demands (i.e. heating loads) in that climate.

The cooling loads for components 1 and 2 are calculated from two estimates -- the equivalent temperature difference, which incorporates solar effects, and the annual number of cooling hours. This approach to cooling is held to be less accurate than is the degree day approach to heating but it is used here because no better method is available for the large number of calculations required in marginal analysis.

The component 3 heating load is calculated from the temperature drop across the below ground concrete wall and the adjacent soil. This temperature difference is, in turn, calculated from the wall

transmission coefficient which is estimated as .10 since complete data on the termperature and thermal conductivity is not available (1, p. 377). Therefore this heating load calculation is considered to be the least representative of actual conditions in the simulation of thermal impacts.

The steady state methods listed here for calculating the annual heating loads are in accordance with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommended procedures. Likewise, the model's calculation of the hourly cooling loads follows ASHRAE methodology. Annual cooling loads were determined by a technique recommended by the National Association of Homebuilders.

COSTS ASSOCIATED WITH WALL INSULATION

Wall costs resulting from changes in the thermal insulation levels of the wall were defined to reflect the viewpoint of the homeowner, in contrast to viewpoints of other parties such as the Federal Government. These costs, which were specified in the Definitions Section (see page 5), are restated below:

Component 1 wall costs = (insulation costs) + (thick wall costs) + (framing costs) + (interior and exterior wallboard costs).

Component 2 and 3 wall costs = (insulation costs) + (thick wall costs) + (concrete costs) + (framing costs)+ (interior wallboard costs) +

(perimeter insulation costs).

Taking each part, one at a time, the following assumptions were made about the physical properties of the walls so costs and savings could be defined in a consistent manner throughout the model. See Appendix B for the specifications used in the model.

Insulation

Owens/Corning product specifications are used for wall insulation (23). For concrete wall construction, two types of insulation are considered -- unfaced friction fit fiberglass studding insulation, and urethane rigid insulation. The studding insulation can be purchased in resistances of R-3, R-8, R-11, R-13, R-19, and R-22. By varying the type and number of batts, the procedure used will calculate 21 different insulation levels -- up to an R-66. The urethane, having a thermal resistance of 5.56/inch, is available in several thicknesses, however, only 1 inch thicknesses were used in this study.[7/] Up to 20 levels of urethane will be considered. The maximum R allowed is 111.2.

[7/] The "R" value used for rigid urethane foam is based on a "K", i.e. conductivity, value of .18. This is the conductivity level to which unprotected urethane can easily drift as it ages out. If urethane is protected by an aluminum foil barrier, its "K" value may age to .16 or .17 (29). This method of protection was not specified for the insulation levels examined in the analysis.

The model treats components 2 and 3 as if they were one wall unit when it determines their optimal insulation levels. It does this by employing a thermal load which is the weighted average of the loads on components 2 and 3. The weighting is by wall area.

For frame wall construction, unfaced friction fit fiberglass studding insulation with resistances of R-11, R-13, R-19, and R-22 is chosen. With 19 combinations of batts, insulation levels are attainable up to R-66. Urethane rigid insulation in 1 inch thicknesses is also used in frame wall construction. As with fiberglass, 19 levels of urethane will be considered which results in a maximum R. of 105.6. Optimal insulation levels for frame walls are determined independently of the corresponding level for the component 2 and 3 (concrete) wall area.

A small airspace occurs in type 2 walls and in fiberglass insulated thick concrete walls because the batts or rolls are 15½ inches wide while the studs are 16 inches on center. This air space is illustrated between batts No. 2, 3, and 6, 7 and again between batts No. 6,7, and 10, 11 in Figure 3.2. It is ignored in the analysis because in a wall, these air spaces would be smaller than is illustrated. This is true because friction fit fiberglass batts are intentionally oversized and are composed of semi-loose material which would partially expand into the voids. With a slight increase in cost, these air spaces could be eliminated. The approach would involve installing batts

Figure 3.2 Airspace Illustration

2, 3, 6, 7, 10 and 11 next to each other. This procedure would increase the quantity of batts needed to insulate the wall by, at most 3.2 percent. Urethane insulation is assumed to be cut to fit at the construction site so no air spaces of the type described here are possible for urethane insulated walls.

Thick walls

Thick walls costs are defined as the additional costs, above and beyond framing and insulation costs, which occur when a wall is broadened. They include floor area losses and wide window sills and door jams.[8/] A discussion of each follows.

[8/] Floor area losses are valued at the marginal square foot cost of the residence. No constraint is imposed that external walls must be thickened either inward or outward because the additional floor space which is covered in either case is valued at the same marginal cost. This cost is unchanged whether the thickening is inward or outward because the primary structural areas affected are the sub floors, floor joists, and concrete slabs; the ceiling joists; and the rafters and roofs -- all of which are valued at a constant cost for small changes in their dimensions (14). Thus whether the walls are expanded outward and additional lengths of floor joists, for example, are

As the wall which adjoins the floor is made thicker, floor space valued at its marginal cost is lost. This cost is attributed to the thick wall which joins the floor by determining the total loss of floor area, multiplying it by its marginal cost/sq.ft., and then dividing this dollar figure by the number of square feet of wall area involved. Since these costs are part of making the wall more thermally efficient they are credited to that portion of the wall which is so benefitted. Therefore, the square footage of the wall area over which the costs are spread is exclusive of window and door areas.

If the residence is of the berm wall design, the component 3 wall joins the floor. In this case, the relevant wall area over which the floor area losses are spread is the component 2 and 3 wall. For conventional construction the entire wall area is component 1, hence it is the wall to which the floor area losses are credited.

Wide sills are required for windows in the thick wall designs because standard sills are made for a 2 x 4 stud wall which is 4.5 inches thick. The extra labor and materials required to build the wide sills

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8/ continued
needed, or if they are expanded inward and a greater portion of the floor joists is covered by the walls and hence cannot underlie usable floor space, the costs are the same. The mechanical (heating) and electrical systems; the interior and exterior wall areas; the windows, doors, and foundations, are a part of the average floor cost of the structure and are only slightly affected, if they are changed at all, by the thickening of the walls over the range specified in the model.

are credited to the thick walls. Since these costs vary little, if any, for walls of similar thicknesses, they have been broken down to just two values. The lower value applies to walls less than or equal to 10 inches thick and the higher figure applies to thicker walls. Wide jam sections for doors are treated in a similar manner with one cost applying to walls less than or equal to 10 inches thick and a higher cost applying to thicker walls.

The number of window sills involved is determined by calculating the total glazed area of the wall and then dividing this sum by 12 sq. ft. as windows measuring 3 feet by 4 feet were used in the model home. The portion of the door jam costs which can be attributed to each wall component is figured by determining that portion of a 3' x 6'8" doorway which is located in each component. (The 3' x 6'8" doorway size conforms to the typical front entrance door found in new construction.)

Thick wall costs are computed by different formulas depending on the value of the ground ratio. They were defined for all ground ratio cases in the "Definitions" Section and are restated here.

If GR = 100, the living wall unit is composed entirely of component 1 and the relevant thick wall formula is:

Thick wall costs for component 1 = (loss of floor area cost due to the thick component 1 wall + thick sill costs + thick jam costs)/(total square footage of the component 1 wall less the area taken by windows

and doors).

If the ground ratio is less than 100, the living wall unit consists of all three components with the component 3 area being adjacent to the floor. In this case two thick wall formulas are relevant:

Thick wall costs for component 1 = (thick sill costs + thick jam costs)/(total square footage of the component 1 wall less the area of this wall which is taken by windows and doors).

Thick wall costs for components 2 and 3 = (loss of floor area cost due to the thick component 2 and 3 wall + thick sill costs + thick jam costs)/(total square footage of the component 2 and 3 wall less the area of this wall which is taken by windows and doors).

These relationships are the formulas by which floor, sill, and jam costs incurred by a thick wall design are attributed to the relevant wall area.

Basic wall structures (framing and concrete)

Frame walls of type 1 are incremented in the thicknesses of commonly manufactured studs such as 2 x 4's, 2 x 6's, 2 x 10's, etc. The resulting wall thicknesses are, in inches: 4.5, 6.5, 8.25, 10.25, and 12.25. The usable wall cavity thicknesses are, in inches: 3.5, 5.5, 7.25, 9.25, and 11.25.

For consistency, where there is overlap, frame walls of type 2 are

made the same thicknesses as their type 1 counterparts. The resulting wall thicknesses are, in inches: 6.5, 8.5, 10.25, 12.25, 14.25, 16.25, 18.25, and 20.25. The usable wall cavity thicknesses are, in inches: 5.5, 7.25, 9.25, 11.25, 13.25, 15.25, 17.25, and 19.25. For each insulation level, the model must use only one type of frame wall. Hence for those thicknesses where type 1 and type 2 walls complement each other, the type was selected whose (thermal resistance)/(cost) was the largest.

Fiberglass insulated concrete walls have cavity thicknesses which correspond closely to those of the type 2 wall. To determine the total thicknesses of these walls, add 8 inches for the concrete and .25 inches for the interior wallboard to the cavity thickness. The usable wall cavity thicknesses are, in inches: 1, 2.5, 3.5, 5.5, 7.25, 9.25, 11.25, 13.25, 15.25, 17.25, and 19.25.

Urethane insulated concrete walls have cavity thicknesses of 1, 2, 3, 4, ... 19, and 20 inches. Again they are faced by a .25 inch interior wallboard and backed with 8 inches of concrete.

Studs 16 inch on center are used for both type 1 and type 2 walls. This results in "over construction" for the thicker walls but it is useful in this study because small insulation increments are needed. (If the studs were 24 inch on center, only R-11, R-19, and R-22 insulation would be available, consequently, the increments would be larger.)

Interior and exterior wallboard

Sheetrock is used as the interior wallboard in all wall configurations. The exterior of frame wall areas is covered with CDX sheathing and T-111 siding.

Perimeter insulation

A 2 foot strip of 2 inch styrofoam perimeter insulation is used around the outside edge of the component 3 wall. The relevant perimeter insulation formula is:

Perimeter insulation cost = (total labor and materials cost)/(total component 2 and 3 wall area of the residence less the are of this wall which is taken by windows and doors).

APPLICATION OF MARGINAL ANALYSIS IN THE DETERMINATION OF OPTIMAL INSULATION LEVELS

By methods established in economic theory for minimizing costs, the model compares the savings and the costs attributable to each increment of wall insulation to determine the level of insulation which will minimize costs to the homeowner.

The marginal savings resulting from each addition of insulation are calculated from changes in the thermal conductance of the wall. Taking component 1 for illustration, the annual savings resulting from

the I^{th} increment is:

$$MS_1(I) = (U_1(I-1) - U_1(I)) \cdot ((24 \cdot DD \cdot Fuel) + (CH \cdot TEQ \cdot Cfuel)).$$

where $U_1(I)$ = the thermal conductance of wall component 1 insulated with I increments of insulation

Fuel = heating fuel cost in dollars/100,000 BTU

Cfuel = cooling fuel cost in dollars/100,000 BTU

In a similar manner the marginal costs resulting from each increment of insulation are calculated from changes in total wall costs. Using component 1 again, the marginal cost resulting from the installation of the I^{th} increment is:

$$MC_1(I) = C_1(I) - C_1(I-1)$$

Similar relationships exist for the other components.

First order conditions for cost minimization are met when the marginal savings generated by the last increment of insulation in a specific component equals the marginal cost attributable to that last increment. This is expressed as

$$\frac{MS_1(I_1)}{MC_1(I_1)} = \frac{MS_2(I_2)}{MC_2(I_2)} = 1$$

where I_1 and I_2 = the optimal increment numbers for components 1 and 2, respectively.

Second order conditions for cost minimization are met because $MS_1(I_1) - MC_1(I_1)$ and $MS_2(I_2) - MC_2(I_2)$ are declining for increasing

increments of insulation.[9/] In other words, cost is increasing with respect to further applications of insulation.

Due to the discontinuous nature of the marginal cost and savings functions, it is possible that the first and second order conditions may be met at more than one level of insulation. Taking the actual case illustrated in Figure 4.3, page 85, these conditions are met in 6 places. At each of these places, a local optima is defined where costs are minimized over some local range. In general, however, only one of these local optima will be the global optimum where costs are minimized over the complete range of possibilities.

Roughly speaking, the computerized model takes the following steps in its search for the global solution in Figure 4.3. Starting with the first level of insulation, I=1, and proceeding to the maximum allowable increment, I=19, steps 1 - 6 are performed in a loop:

1. If $MS(I)/MC(I) \geq 1$ the program will assign the value of I to storage location A. (This condition must be satisfied at every insulation level where first and second order conditions for cost

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[9/] The marginal savings functions (MS_1 and MS_2) are declining because the amount of heat which can pass through a layer of insulation varies inversely with its thickness. Decreasing marginal savings are realized for each unit increase in insulation thickness. The marginal cost functions (MC_1 and MC_2) are defined from the model's wall cost function. They are generally constant with large discontinuous breaks. The exact value of these functions is defined by materials and labor costs and by consumer preferences.

minimization are met.)

2. At the first increment where MS(I)/MC(I) < 1, the program will begin the sums:

   Σ MS(I) = TS(I)

   Σ MC(I) = TC(I)

   (I=3 is the first level of insulation past a local optimum where first and second order conditions for cost minimization were met. TS(I) and TC(I) are used in the search for the global optimum.)

3. If MS(I)/MC(I) is always greater than 1, I=19 is the optimal increment. (This is not the case in this example.)

4. If at any level greater than 3, TS(I)/TC(I) > 1, the program will assign that value of I to storage location B.

5. The value of I in location A is compared with the corresponding value in B. If they are the same, a candidate for the global optimum insulation level has been found.

6. The process continues by comparing the candidates for the global optimum and selecting the one, I=12 in the example, which specifies least costly application of insulation, i.e. the level where TS(I) - TC(I) is the greatest.

This process of marginal analysis finds solutions which maximize net savings, i.e. minimize costs, to the homeowner. The findings would be the same if the approach had been to maximize the net savings function, TS(I) - TC(I), over the entire range of allowable insulation

levels. See Figure 2.1. Once the optimal level of insulation has been established, its net savings can be calculated by subtracting its total cost (TC) from its total present value savings (TS).

One objective of this study is to examine the effectiveness of the U.S. Department of Housing and Urban Development's "Minimum Property Standards" for thermal insulation from a cost minimizing point of view (32). To perform the analysis, these standards are selected as minimum insulation levels within the walls. Net savings are accounted for in the following manner:

1. When the optimal insulation level is lower than that referenced as meeting HUD Standards, net savings from insulation = (the present value of the stream of savings generated from the levels of insulation which exceed the optimal level but were required by the HUD Standard) - (the cost incurred from the installation of those levels). These net savings are negative.
2. When the optimal level of insulation equals that set by HUD in its Minimum Property Standards, net savings from insulation = 0.
3. If the optimal insulation level exceeds that established by the HUD standards, net savings from insulation = (the present value of the stream of savings generated from the levels of insulation which exceeded the HUD requirement but which were included in the optimal solution) - (the cost incurred from

the installation of these levels). The net savings calculated in this circumstance are positive.

For more information on how insulation net savings are defined subject to the HUD Minimum Property Standard requirements for thermal response, see the discussion beginning on page 149 where this constraint is dropped.

SAVINGS REALIZED FROM THE UTILIZATION OF THE GROUND AS A THERMAL BARRIER FOR THE WALLS

In order to distinguish the fuel savings resulting from applications of wall insulation from those attributable to the placement of the wall in relation to the ground level, the following distinction was made. Savings generated by thermal insulation were measured from the reduction in heat flow across any section of the building envelope which resulted as successive insulation levels were applied to that portion of the wall. This definition applied to both the above ground and the below ground components. In contrast, savings related to the ground level were calculated from the change in the overall heat flow through the optimally insulated walls of the model home which resulted when the wall configuration was changed. Such savings were termed "ground ratio savings".

The ground ratio concept was introduced into the model to establish a systematic method for evaluating these savings realized from the

different soil levels. Using such an approach, ground ratio savings can be defined as the sum of the present value savings to all component areas of the living wall which arise when these component areas and their insulation levels are changed from the conventional design due to the downward shift of the ground ratio. If the ground ratio is 60, these savings are generated in part from the reduction in heat flow through the component 1 wall areas which results as the component 1 wall is reduced to 60 percent of its height in the conventional design. (The area which is lost is from the conventional (GR = 100) wall design, hence it is insulated at the level which was optimal for that design.) Additional savings or losses will be realized for the remaining component 1 wall area in the GR = 60 design if the optimal insulation level for this section of the wall is higher or lower, respectively, than it was in the conventional design. A conventional wall contains no component 2 or 3 areas so as the ground ratio is reduced, the creation of these areas means the creation of additional heat loads on the living wall. These component 2 and 3 losses resulting from the downward shift of the ground ratio to 60 are added to the component 1 savings to arrive at the total ground ratio savings for the GR = 60 configuration. Mathematically ground ratio savings, for GR = 60, are defined as: (the present value of the heat flow through a square foot of optimally insulated, GR = 100, component 1 wall construction times the reduction in component 1 area

due to the downward shift of the ground ratio to 60) + ((the present value of the heat flow through a sq. ft. of optimally insulated, GR = 100, component wall construction minus the present value of the heat flow through a sq. ft. of optimally insulated, GR = 60, component 1 wall construction) times the remaining component 1 wall area at GR = 60) - (the present value of the heat flow through a sq. ft. of optimally insulated, GR = 60, component 2 wall construction times the total component 2 area at GR = 60) - (the present value of the heat flow through a sq. ft. of optimally insulated, GR = 60, component 3 wall construction times the total component 3 area at GR = 60).

COSTS INCURRED FROM THE UTILIZATION OF THE GROUND AS A THERMAL BARRIER FOR THE WALLS

Wall costs associated with berm designs reflect the structural characteristics of these designs. The three costs defined in this category are described as ground ratio costs, which reflect the dollar change in the wall structure which results as the ground ratio is shifted, net excavation and backfill costs, and net entrance costs. In contrast to costs attributed to wall insulation, these costs are not defined for particular components but instead are specified for the entire wall area, including any above ground frame portions. The reason for such a constraint is that the berm wall is considered to be an entire wall concept having both above and below ground components.

The three costs are defined below:

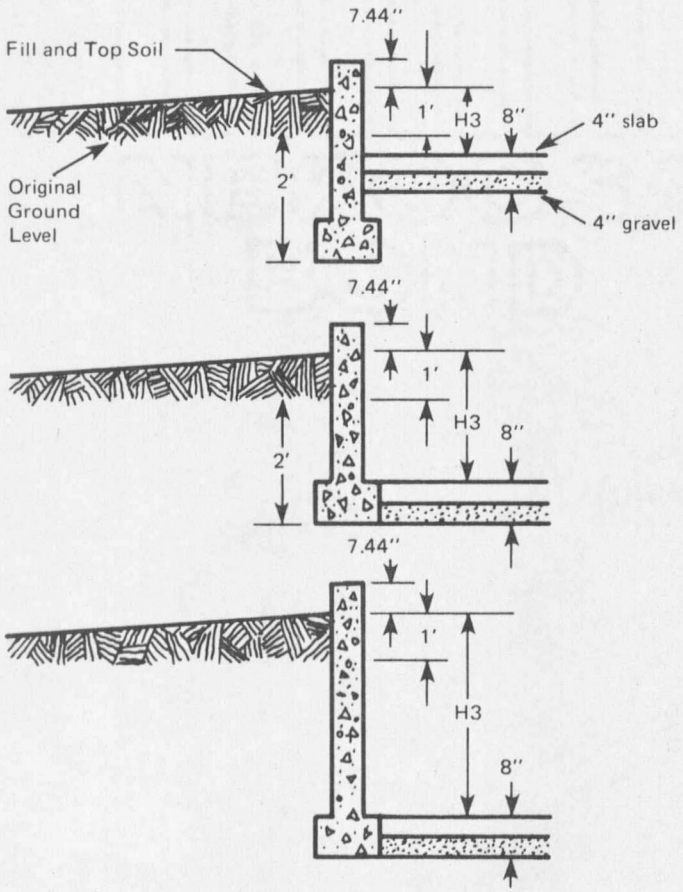
Ground ratio costs are the structural costs resulting when the ground ratio is shifted down from 100. They are defined as the berm wall cost minus the conventional wall cost. When the ground ratio is 70 they are expressed by the following relationship: ground ratio costs = (the cost/sq.ft. of the optimally insulated component 1 wall in the GR = 70 design times the total are of component 1 in the GR = 70 design + the cost/sq.ft. of the optimally insulated component 2 and 3 wall in the GR = 70 design times the total area of components 2 and 3 in the GR = 70 design) - (the cost/sq.ft. of the optimally insulated component 1 wall in the GR = 100 design times the total wall area in the GR = 100 design) - (the cost/sq.ft. of concrete foundation walls in the GR = 100 design times (the component 2 and 3 area at GR = 70 if the component 3 height at GR = 70 is less than or equal to 2.33 feet) or (the component 2 and 3 area defined by a component 2 height of 7.44 inches and a component 3 height of 2.33 feet if the component 3 height at GR = 70 exceeds 2.33 feet)). See Figure 3.3, Part II. This definition of costs is sensitive to the changes in wall structure and insulation levels which result from shifts in the ground ratio. The first two terms in this formula compute the dollar change in the living wall structure resulting from grounding. The last term in the ground ratio cost formula credits the dollar outlays made for concrete

foundation walls in the above ground design to the component 2 and 3 areas of the various berm wall designs. It is needed to compute the difference in total cost of conventional and grounded wall structures because the cost of foundations is included in both cases. Thus, in the GR = 70 example, no additional outlays for concrete, beyond those for the conventional design are made, as the total component 2 and 3 height is 2.4 feet. (The conventional structure's foundation walls are 2.95 feet tall as illustrated in Figure 3.3.) In this example, the credit computed in the third term of the ground ratio cost formula reduces total costs by the cost/sq.ft. of the concrete foundation wall multiplied by the component 2 and 3 area at GR = 70. This amounts to $2.47/sq.ft. x 304.24 sq.ft. = $751.47. The same physical properties for basic wall structures, thick wall modifications, insulation levels, interior and exterior wallboard, and perimeter insulation apply to ground ratio costs as was outlined on pages 32 - 40 where insulation costs were defined.

Net excavation costs (and backfill costs) are credited to the wall areas in a berm design because in such a configuration the soil is a part of the building envelope as it is used as a thermal barrier. To reflect changes in total cost due to grounding, these costs are computed with reference to the excavation and backfill expenditures required in the conventional wall design. The following specifications were made concerning excavation and backfill.

1. A backhoe is used to dig the footings if they are 1 foot or more below the excavation for the floor. In this case, a crawler tractor, or "cat", is used for floor excavation. (See Figure 3.3.)
2. A "cat" is used to dig the footings and floor area if the footings are less than 1 foot below the excavation for the floor. The yards moved are computed for an excavation depth which is the mean of digging to the bottom of the footings and digging only to the floor depth. (See Figure 3.3.)
3. A "cat" is used in cases where the floor excavation goes as deep as the footings. (See Figure 3.3.)
4. The backfill (and topsoil) is banked 1 foot high against the concrete. It is assumed to average 6 inches deep in an area which exceeds the house dimensions by 40 feet. A "cat" is used for backfilling.
5. Level, well drained ground is assumed for both the berm and the conventional structure.

These specifications for excavation and backfill satisfy the 1976 Uniform Building Code requirements for single family dwellings. The component 2 wall height, which is 7.44 inches after backfilling, also conforms to this code as it exceeds the minimum 6 inches required for moisture protection between the soil and the wood portions of a residential building (11, Sect. 2517).



H3 = Height of Component 3 Wall

I. If H3 ≤ 1.33 Feet

II. If 1.33 Feet < H3 ≤ 2.33 Feet

III. If H3 > 2.33 Feet

Figure 3.3 Plans for Berm Wall and Floor

Net entrance costs are the expenditures involved in constructing stairways and landings at the entryway and backdoor of the dwelling. The stairways lead up to the doorway of the conventional home and down to the doorway of the berm. As with excavation and backfill costs, these costs are defined with reference to the entrance costs for the conventional dwelling.

DETERMINATION OF THE COST MINIMIZING WALL DESIGN

A primary objective of the study is to identify cost minimizing wall designs from the viewpoint of the homeowner. The success of such an objective depends on how accurately the wall structural and thermal characteristics, as perceived by the homeowner, are modeled in the cost and savings relationships. Costs which have been specified so far have been of a structural nature as they have reflected labor and materials expenditures involved in erecting the wall designs. Such expenditures are not representative of the total costs faced by the homeowner, however, as his preferences or aversions to the various wall designs must also be taken into account. On page 54, costs reflecting the value system of the homeowner will be defined. The discussion of these costs, which are referred to as consumer preferences, is deferred until after the specification of the structural designs of the walls is complete, because these wall specifications are needed to establish a framework through which the consumer preferences can be defined. (No alteration of the cost minimizing procedures discussed in this section and on pages

40 - 45, is necessary with the inclusion of consumer preferences in the model.) The savings relationships used in the model are much less subjective than are costs as they are calculated from thermal engineering procedures whose accuracy has been verified by physcial measurement.

To determine the cost minimizing wall design, net savings from insulation had to be optimized in conjunction with net savings from the soil level. A special procedure was devised to do this because of the following relationship which exists between the optimal insulation levels and the optimal ground ratio level:

1. The optimal insulation levels and their net savings are a function of the ground ratio.
2. The optimal ground ratio level and its net savings is a function of the optimal insulation levels.

Hence, optimal insulation levels can be determined without a knowledge of the optimal ground ratio level but the reverse is not true. A solution can therefore be found without resorting to the iterative process. The procedural approach used involves first determining the insulation level which maximizes return on investment, then using this information, the ground ratio level is determined which minimizes cost. Such a methodology will maximize the TS - TC function of two variables when one variable is independent and one variable is dependent.

Net savings realized from optimal insulation levels can be added to net savings resulting from the ground ratio if the savings and costs from each are processed as described here. The optimal configuration is then determined by a process that selects the ground ratio which maximizes (ground ratio savings) - (ground ratio costs) - (net excavation costs) - (net entrance costs) + (net savings from insulation).

CONSUMER EVALUATION OF WALL DESIGN

The cost minimizing procedure that the model uses to select optimal wall designs, incorporates a provision, through a penalty function, by which the homeowner can express in dollar terms, his preferences or aversions to certain wall structures. Such an approach is necessary if the optimized wall designs are to reflect the viewpoint of the consumer. Three structural modifications were selected as representative of the various physical changes which resulted from the variation in the insulation levels and the ground ratio. Two of these structural changes involve penalty functions. The three physical changes are:

1. Lost floor area due to the thick wall design. This floor area loss is valued at the marginal square foot cost of the residence and is not assignable by the homeowner. Fee Footnote 8 on page 35.
2. Partially submerged wall configurations due to ground ratio

levels less than 100. When the ground ratio is less than 100, the homeowner is given the opportunity, through a penalty, to express his cost of owning and living in a structure which is placed partially within the ground.

3. Entryway designs required by each wall configuration. At all ground ratios below 100 the homeowner can enter. through a penalty function, his cost of using the entryway required for a particular wall design. Here the term, "entryway", refers to the steps and landings leading up to the front and back doors of a conventionally designed residence or down to these doors if the residence has berm walls.

Cost ratios are the method through which the homeowner's appraisal of the structural modifications is entered into the cost functions. To anticipate a range of different responses that a homeowner may have to changes in wall structure, values of 0, 1, and 2 were assigned to the relevant cost ratios. To illustrate the function of a cost ratio, consider the value which different consumers attach to using the various entryways which are required for each configuration. The broad range of entryways examined extend from a simple concrete block consisting of one or two steps and a landing which lead up to the doorway in a conventional wall to a long series of steps, flanked by concrete walls and joined to a landing, which lead down more than 7 feet in the GR =

0 wall. Each homeowner's cost to use these stairway designs is expressed through a particular level of the entrance cost ratio (ENR). Let the values assigned the ratio be 0, 1, and 2, then:

0 Represents a preference (or negative penalty) to the use of the entryway required for each wall configuration equal to the cost to construct the entryway.

1 Represents no costs or penalty to the consumer for using the entryway required for each wall configuration.

2 Represents an aversion (or penalty) to the use of the entryway required for each wall configuration equal to the cost to construct the entryway.

The meaning of these values becomes clear when one considers the constituent parts of the entryway costs. The total dollar figure for each entryway design is the sum of the construction cost for the design, and the homeowner's evaluation of the design. If the entrance cost ratio is 2, the total entryway cost is 2 times the construction cost of the entryway. This total is calculated from the sum of the construction cost, and 1 times the construction cost, which is the additional cost to the consumer. In the majority of the following analysis, each of these cost ratios will be assigned a value of 1. The only departure from this policy will be when the sensitivity of the net savings of a

wall design to a particular consumer preference is being examined.

The other cost ratio is the excavation cost ratio (EXR). This penalty function shows the preference or aversion of the consumer to owning and living in a residence whose ground ratio is less than 100, at a multiple of the excavation and backfill expenditures involved in the construction of such a residence.

Through both cost ratios, dollar amounts are assigned to the different wall and entryway designs. In all cases these monetary figures are used to describe a hypothetical homeowner's response and not the quality of the design.

BASIC ASSUMPTIONS

1. Consumer Preferences to Structural Modifications

   A value of 1 for each cost ratio is considered most representative of homeowner priorities in the new construction market. Therefore the cost ratios are assigned the value of one in the majority of the analysis. This number is chosen because:

   A. The effects of homeowner biases to structural modifications are removed from the results. This means that the findings describe designs which are optimized on the basis of construction costs and fuel savings alone.

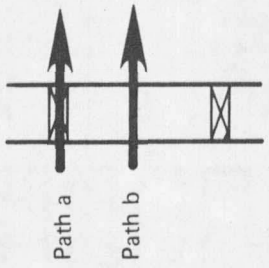
   B. The typical consumer of a new residential building is likely

to be more aware of energy costs than was his predecessor. Hence it is assumed that he will appraise all costs of a thermal design at their construction prices. Before the strong rise in fuel prices seen in recent years, energy costs had less influence in decision making involving residential construction. During that period of time, higher cost ratios may have reflected public sentiment more closely.

All decisions made by the consumer are rational and are based on cost minimizing criteria.

2. Thermal Characteristics of the Walls

In determining the thermal conductivity of the wall components, the model uses parallel heat flow paths. This assumption is not important for a wall composed entirely of homogeneous materials, but it has a significant effect on the calculated transmittance of a wall having heterogeneous materials which form heat flow paths of different conductances, such as frame walls. Take the type 1 wall shown in Figure 3.4 for illustration: According to the assumption of parallel heat flow paths, its average transmittance is $U = A_a \cdot U_a + A_b \cdot U_b$ where A_a and A_b are the fractions of the total wall area which are paths a and b respectively, and U_a and U_b are the transmittances of these paths.



Specifications:
1. *The studs are 16 inches on center*
2. *Each stud is 1.5 inches wide*

Path a – Heat Flow Through the Stud Portion of the Wall
Path b – Heat Flow Through the Non Stud Portion of the Wall
A_a – Fraction of Total Wall Area Which is Path a = $\frac{1.5 \text{ inches}}{16 \text{ inches}}$ = .094
A_b – Fraction of Total Wall Area Which is Path b = .906.

Figure 3.4 Parallel Heat Flows Through a Type 1 Wall

The simplifying assumption about the parallel nature of the heat flows is also useful in establishing a sharp boundary between the component 1, 2, and 3 portions of the wall.[10/] With these portions of the wall area clearly delineated, the calculation of the respective heat flows through each is straight forward.

10/ Heat flows through the different component areas are independent of each other. Thus the insulation level in a particular component will not influence the transmittance of its neighboring components. This means that the savings from insulation for an integrated wall area, composed of more than one component, is the sum of the thermal savings for each of the components making up the area. For more information see page 17.

Total berm wall transmittance is a function of the excavation depth because placement of a berm wall deeper in the ground changes the overall thermal load faced by the wall. This functional dependence on the excavation depth is in a smaller part recognized for berm floors around their edge where perimeter losses occur (1, p. 378). To weaken the functional relationship with the floors, and to conform to good building practices, the model employs perimeter insulation to reduce edge loss. Soil adjacent to the walls is considered to be a part of the wall's thermal structure because of the strong link between excavation depth and wall loss. For this reason also, excavation and backfill costs are included in the wall costs.

3. Structural Characteristics of the Walls

Central to the concept of thick wall costs, as they are developed here, is the assumption that marginal square foot floor costs along the edge of a dwelling are independent of changes in wall construction costs. This assumption is met because increasing the labor and materials cost of the wall due to greater insulation levels and thicker designs will not increase the per square foot cost of the sub floors, floor joists, and concrete slabs; the ceiling joists; and the rafters and roofs; which are the elements determining the residential building's marginal square foot costs.

The independence of wall costs with respect to total building costs is also expressed in the structure's dimensions. Modification of a particular wall's thickness is assumed not to change the interior length of the adjacent wall. This, of course, is true in the limit, and it is a good approximation here. For example, an increase in the thickness of a 30 foot wall in the model home by 2 inches will decrease the length and area of each adjacent 40 foot long wall by only .4 percent. Likewise the interior wallboard areas are assumed to be independent of the insulation levels.

4. Weather Variables

The thermal nature of the climate was defined in the steady state form of degree days, cooling hours, ground water temperatures, and equivalent temperature differences.

Chapter 4

RESULTS

The objective of the economic model was to maximize net savings, which was defined as total savings minus total cost, subject to various constraints. One goal of the study was the determination of optimal insulation levels within walls in a manner which was dependent on the local climate, homeowner tastes and preferences, current energy costs, and financial conditions. A second goal was the specification of the optimal ground ratio for each wall. From these two results, net savings were calculated for walls whose design, i.e. insulation level and ground ratio, was determined by recognized optimality criterion.

Optimal insulation thicknesses and the present value maximum net savings resulting from these thicknesses are listed in almost every case in the following sections. In the Ground Ratio Section, page 94 net savings are frequently listed for insulation levels as well as for the optimal insulation-ground ratio combination. Table 4.1 converts the insulation increment numbers used in this study into commercial insulation units.

In several of the tables in the following sections, there are extra columns headed Pb. In these columns are listed the payback periods for insulation. Each figure represents the years required to payback the total investment which is beyond the requirements set forth in the HUD Minimum Property Standards (MPS). In cases where the optimal level

Table 4.1

Relationships Between Insulation Levels
and Their Physical Counterparts

Increment Number	Fiberglass Insulation Comp 1[1]	Fiberglass Insulation Comp 23	Urethane Insulation All Components
I = 1	R[2]=11	R=3	R=5.56
2	13	8	5.56+5.56
3	19	11	5.56+5.56+5.56
4	22	13	5.56+5.56+5.56+5.56
5	11+13	19	etc. through
6	13+13	22	I = 20
7	11+19	11+13	
8	11+22	13+13	
9	13+22	11+19	
10	19+19	11+22	
11	19+22	13+22	
12	22+22	19+19	
13	11+19+19	19+22	
14	11+19+22	22+22	
15	11+22+22	11+19+19	
16	19+19+19	11+19+22	
17	19+19+22	11+22+22	
18	19+22+22	19+19+19	
19	22+22+22	19+19+22	
20		19+22+22	
21		22+22+22	

[1]See page 13 for a listing of the terms used in the tables.

[2]R is the thermal resistance of each insulation layer.

of insulation is less than or equal to the HUD MPS recommendations, n.a. (for not applicable) was entered. Explanation of the payback periods will be given on page 93 which deals with financial parameters.

Because simplifying assumptions have been made in modeling the walls and because structural systems can never be duplicated by mathematical formulas, the results presented in the following five sections should be interpreted as estimates of the optimal values for each wall design. Most of the tables in the following sections will contain listings of optimal levels of insulation and present value maximum net savings resulting from these levels. The optimal levels are realistic estimates of cost minimizing insulation specifications in actual wall designs but the net savings listings should only be considered as indicative of what can be expected. A recommended method of approach to diagnosing the results is to examine the relative changes instead of the absolute levels.

Unless specifically altered in a section, the cost and savings variables were assigned the following values:

I. Homeowner Preferences (Cost Variables)

1. EXR = 1 Excavation cost ratio
2. ENR = 1 Entrance cost ratio
3. GF1 = .11 Glazing fraction for component 1

   GF2 = .20 Glazing fraction for component 2

4. Summer air conditioning was not specified

5. Insulation choice was limited to fiberglass and urethane

II. Savings Variables

1. Fuel = $.251/100,000 BTU (Heating fuel cost, not adjusted for burning efficiency. See Table 4.5 and page 276.)[11/]

Cfuel = $.681/100,000 BTU (Cooling fuel cost, not adjusted for cooling efficiency. See Table 4.5 and Footnote No. 43.)

2. Weather = Bozeman, Montana climate (See Appendix B)

3. L = 30 years (Lifetime of the building)

4. P = 1 percent (Real rate of fuel price increase)

5. D = 1 percent (Real discount rate)

In the tables which follow, the present value maximum net savings (net savings for short) from the optimal, i.e. cost minimizing insulation levels is calculated using, as a point of reference, the savings derivable from the HUD Minimum Property Standard recommended level.

11/ This cost for heating fuel is comparable with Richard Stroup's projected price of $.246/100,000 BTU for residential and commercial natural gas in Montana in the year 1980. (A conversion factor of 950,000 BTU/MCF was used to convert Stroup's data to the current nomenclature. The projection is in 1976 dollars.) (28, p. 1)

Thus positive net savings imply that the HUD recommendations are too low and that higher insulation levels would minimize costs to the homeowner by bringing in additional savings over costs equal to the present value maximum net savings figure listed for the appropriate case. Likewise a negative net savings means that the HUD MPS level is too high as it increases net costs to the homeowner over the optimal level by the amount of the negative figure. A zero net savings results when the HUD recommendation is the optimal level. For an additional explanation of how insulation net savings are added subject to the MPS constraint, see Chapter 5.

Natural gas, utilized with an efficiency of heat transfer of .70, is the heating fuel (2, p. 79) (34, p. 29). Electricity is the cooling fuel. A BTU removal performance of 8000 BTU/Kwh is specified for the refrigeration unit (2, p. 85) (34, p. 29).

Abbreviations which are used extensively in the tables of the following sections are listed on page 13.

GLAZED AREAS

The glazed portion of each wall area in a residential building can be a function of several variables including the building's style, price range, and orientation; the wall's use within the building such as whether it is a bathroom wall or a living room wall; the relative cost of erecting glass versus opaque wall areas; the price of fuel, as

energy costs are becoming increasingly influential in building design; and the consumer preference for glazed areas. Since no provision could be made in the model for all these parameters, a variable glazing fraction was introduced through which a range of glazing percentages could be studied.

The glazing fraction was defined as (total glass area)/(total wall area including windows and doors). To conform with the standards set forth in the 1976 Uniform Building Code (11), a glazing fraction of .11 was selected for the majority of the analysis of component 1 wall areas. The total range of values assigned to the glazing fraction for the component 1 areas was .05, .11, .20, and .40. A glazing fraction of .20 was chosen for most component 2 areas. This relatively high value, in comparison to the specified level for component 1 areas, was selected to provide additional openings for natural light. Such glass areas were considered important for the "deeper" berm wall designs which had little exposed wall area that could be fitted with windows. The complete set of values assigned the component 2 glazing fraction was .10, .20, .40, and .60. For those living walls which were composed of both components 1 and 2, the glazing fractions were specified in the following pairs:

Component 1	Component 2
.05	.10
.11	.20
.20	.40
.40	.60

This type of pairing uses the reasoning that the same glazing theme extends over the entire wall area. Table 4.2 lists the optimal insulation levels and the present value maximum net savings resulting from the insulation when the glazing fractions are varied over the range described above. The results are calculated for three living wall categories as described by the ground ratio.

The findings in Table 4.2 are generated for non summer air conditioned homes whose heating fuel price is $.251/100,000 BTU. From the findings it is clear that in each wall category net savings decline as the glazing fraction for both components increase. The only exception to this occurs for the component 1 areas of the urethane insulated walls. There the optimal insulation level equals that recommended by HUD, so zero net savings are recorded. In all cases the downward trend in the net savings is explained through the declining areas of solid wall which result as the percentage of the wall which is glazed increases. This decline in the solid wall area reduces net savings for each component because the number of square feet of insulation which generate savings are reduced and because wall costs are

Table 4.2

Functional Dependency of Insulation Levels
And Net Savings on the Glazing Fraction
(The Fuel Price is $.251/100,000 BTU)

					Optimal Insulation R[2]		Present Value Maximum Net Savings[3] (from insulation)				
	INS.	GF1[1]	GF2	GR	Comp1	Comp23	Comp1	Pb	Comp23	Pb	Total
1.	f	.05		100	13		127.55	7.29			127.55
2.	f	.11		100	13		119.18	7.29			119.18
3.	f	.20		100	13		106.62	7.29			106.62
4.	f	.40		100	13		78.62	7.29			78.62
5.	f	.05	.10	50	13	19	64.27	7.29	108.83	24.39	173.10
6.	f	.11	.20	50	13	13	60.09	7.29	102.27	19.69	162.36
7.	f	.20	.40	50	13	13	53.81	7.29	95.09	20.08	148.90
8.	f	.40	.60	50	13	13	39.86	7.29	87.88	20.50	127.73
9.	f		.10	0		26			552.99	18.99	552.99
10.	f		.20	0		26			544.15	19.08	544.15
11.	f		.40	0		26			526.80	19.25	526.80
12.	f		.60	0		26			509.31	19.43	509.31
13.	u	.05		100	11.12		0	n.a.			0
14.	u	.11		100	11.12		0	n.a.			0
15.	u	.20		100	11.12		0	n.a.			0
16.	u	.40		100	11.12		0	n.a.			0
17.	u	.05	.10	50	11.12	11.12	0	n.a.	125.24	21.67	125.24
18.	u	.11	.20	50	11.12	11.12	0	n.a.	117.06	22.08	117.06
19.	u	.20	.40	50	11.12	11.12	0	n.a.	100.61	22.96	100.61
20.	u	.40	.60	50	11.12	11.12	0	n.a.	84.16	23.90	84.16
21.	u		.10	0		16.68			350.77	22.42	350.77
22.	u		.20	0		16.68			341.87	22.55	341.87
23.	u		.40	0		16.68			324.27	22.82	324.27
24.	u		.60	0		16.68			306.55	23.09	306.55

[1] GF1 is the component 1 glazing fraction. GF2 is the component 2 glazing fraction. See Terms used in Tables, page 13.

[2] See definition No. 24, page 10.

[3] Net savings from insulation are defined with respect to the HUD "Minimum Property Standards" constraint given on page 43.

increased. The effect of the change in wall costs (i.e. the total costs for insulation) on optimal insulation levels and net savings, is demonstrated in lines 5 and 6 of Table 4.2. From line 5, we see that the optimal insulation value for fiberglass in components 2 and 3 is R-19 when the component 2 glazing fraction is .10. When this glazing faction is changed to .20, costs for insulation become high enough to cause the optimal component 2 and 3 insulation level to fall to R-13. Figure 4.1 illustrates this effect with curve shifts for a hypothetical case. The functional dependency between the optimal insulation level and the glazing fraction comes from the thick wall and perimeter insulation portions of the wall cost formulas as these relationships contain component areas in their denominators. Sufficient for this analysis is the understanding that through these relationships the shape of the marginal cost function is changed when the glazing ratio is varied.

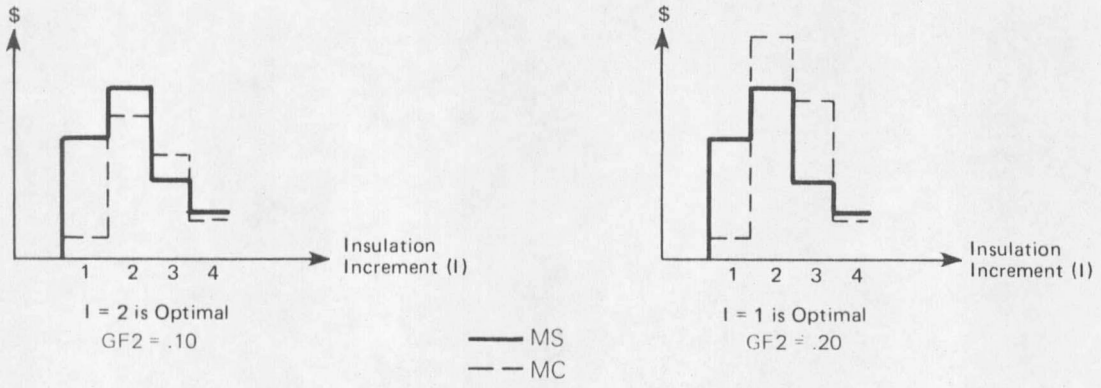


Figure 4.1 Reduction of the Optimal Insulation Level Due to the Upward Shift of the Marginal Cost Curve

Fiberglass insulation generated more savings than urethane when the two were used under comparable conditions. For component 1 areas this result follows from the HUD Minimum Property Standard recommendation. Positive savings are shown for fiberglass because its optimal insulation level exceeds that specified by the HUD MPS. No net savings resulted for urethane because the HUD recommendation and the optimal levels are the same. For the component 2 and 3 areas, fiberglass was usually the optimal choice because its lower cost/unit of thermal resistance more than offset urethane's higher resistance/inch of thickness. In other words the compactness of the urethane could be exchanged for the lower cost of the fiberglass to the net benefit of the homeowner.

To summarize, for the fuel price tested ($.251/100,000 BTU) little functional relationship was observed between the optimal insulation levels and the glazing fractions. Increasing the glass areas of the walls resulted in reduced net savings. Fiberglass insulation was demonstrated to yield greater net savings than urethane in the cases tested.

SUMMER AIR CONDITIONING AND CLIMATE

In the last section, heating loads were used to represent the total thermal loads on the walls. In this section the effect of an added cooling load on the overall optimal insulation levels and on the savings

resulting from these levels is investigated. Tests are run for the Bozeman, Montana climate and for two others -- one mildly less severe and one mildly more severe than the climate at Bozeman. The milder and harsher climates are used to establish bounds within which the Bozeman climate can be expected to fit with a certain probability. Annual weather conditions of 7000 degree days, 515 cooling hours, which depict the Billings, Montana climate; and 9800 degree days, 175 cooling hours, which represent conditions at Butte, Montana, were chosen for the bounds on the Bozeman climate which was set at 8343 degree days and 225 cooling hours.

Table 4.3 lists the effects which added air conditioning has on optimal insulation levels and on net savings. Results are tabulated for the Bozeman climate and for the two variations described above.

For the fuel prices tested, the results listed in Table 4.3 show that the optimal R-value is unchanged when the cooling load is added to the total thermal load on the walls. This conclusion is expected when one examines the relative sizes of the heating and cooling loads on each component. Table 4.4 gives these heating and cooling loads for Bozeman.

From Table 4.3 we note that the largest change in the absolute level of the net savings resulting from the addition of air conditioning is for Billings (see lines 7-12). This result also suggests that the optimum residential insulation levels are more sensitive to air

Table 4.3

Functional Dependency of Optimal Insulation Levels and Net Savings on Climate and Air Conditioning. (The Heating Fuel Price is $.251/100,000 BTU. The Cooling Fuel Price is $.681/100,000 BTU. Fiberglass Insulation is Used in all Components.)

	Summer Air Conditioning	GR	Climate	Optimal Insulation R		Present Value Maximum Net Savings (from Insulation)				
				Comp1	Comp23	Comp1	Pb	Comp23	Pb	Total
1.	no	100	Bozeman	13		119.18	7.29			119.18
2.	yes	100	Bozeman	13		121.12	7.20			121.12
3.	no	50	Bozeman	13	13	60.09	7.29	102.27	19.69	162.36
4.	yes	50	Bozeman	13	13	61.07	7.20	102.61	19.67	163.68
5.	no	0	Bozeman		26			544.15	19.08	544.15
6.	yes	0	Bozeman		26			544.90	19.07	544.90
7.	no	100	Billings	13		93.83	8.69			93.83
8.	yes	100	Billings	13		98.28	8.41			98.29
9.	no	50	Billings	13	13	47.31	8.69	92.75	20.34	140.05
10.	yes	50	Billings	13	13	49.56	8.41	93.52	20.38	143.08
11.	no	0	Billings		26			523.34	19.35	523.34
12.	yes	0	Billings		26			525.03	19.33	525.03
13.	no	100	Butte	13		146.67	6.21			146.67
14.	yes	100	Butte	13		148.19	6.16			148.19
15.	no	50	Butte	13	19	73.95	6.21	119.57	23.83	193.51
16.	yes	50	Butte	13	19	74.71	6.16	120.03	23.81	194.74
17.	no	0	Butte		26			566.74	18.79	566.74
18.	yes	0	Butte		26			567.31	18.89	567.31

conditioning loads in climates where the cooling load is a larger portion of the total thermal load.

Table 4.4

Comparison of the Relative Size of the Heating and Cooling Loads on a Square Foot of Wall Area in the Bozeman, Montana Climate

Component No.	Heating Load	Cooling Load	Heating to Cooling Ratio
1	24·DD (24·8343)	TEQ·CH (13.6·225)	65.4 to 1
2	24·DD (24·8343)	TEQ·CH (6.3·225)	141.3 to 1
3	(75-TBSMT)·24·HD [(75-14)·24·334]	None	n.a.

Table 4.5 lists the effect air conditioning has on net savings for the walls of an "all electric" home. Net savings from wall insulation for a natural gas heated and electric cooled home are shown in Table 4.6. Net savings from wall insulation for a propane heated and electric cooled home is shown in Table 4.7. All results are for the Bozeman climate. Fiberglass and urethane insulation are tested.

In conclusion, for climates similar to the one in Bozeman, the air conditioning load is so much smaller than the heating load, that its inclusion in the thermal load calculations is not likely to

Table 4.5

Functional Dependency of Optimal Insulation Levels and Net Savings on Air Conditioning and Insulation in an All Electric Home[1]

	Summer Air Conditioning	GR	Insulation	Optimal Insulation R		Present Value Maximum Net Savings (from insulation)				
				Compl	Comp23	Compl	Pb	Comp23	Pb	Total
1.	no	100	f	13		167.48	5.58			167.48
2.	yes	100	f	13		168.82	5.54			168.82
3.	no	100	u	16.68		14.27	28.81			14.27
4.	yes	100	u	16.68		16.61	28.62			16.61
5.	no	50	f	13	19	84.44	5.58	274.08	18.82	358.52
6.	yes	50	f	13	19	85.11	5.54	274.49	18.81	359.60
7.	no	50	u	16.68	16.68	7.20	28.81	281.57	20.63	288.77
8.	yes	50	u	16.68	16.68	8.38	28.62	282.12	20.62	290.49
9.	no	0	f		33			1022.09	16.49	1022.09
10.	yes	0	f		33			1022.65	16.49	1022.65
11.	no	0	u		16.68			764.19	17.26	764.19
12.	yes	0	u		16.68			764.75	17.25	764.75

[1] $.328/100,000 BTU is equivalent to the price of electric heat in Bozeman, Montana as set by the Montana Public Service Commission Schedule R-75, issued 3/15/77. (This price for electric heat is adjusted downward from the rate structure quotation by .70 which is the heating efficiency factor for fossil fuels. Since electric heat is considered 100 percent efficient, this step is necessary in order to make the price of electricity meaningful when it is compared to other fuels.) $.200/100,000 BTU is the corresponding price for electric cooling because the coefficient of performance for electric air conditioning units reduces the equivalent fuel cost by a factor of 2.345. (In the terminology used in this study, this fuel cost amounts to $.469/100,000 BTU.)

Table 4.6

Functional Dependency of Optimal Insulation Levels and Net Savings on Air Conditioning and Insulation in a Natural Gas Heated-Electric Cooled Home[1]

	Summer Air Conditioning	GR	Insulation	Optimal Insulation R		Present Value Maximum Net Savings (from insulation)				
				Comp1	Comp23	Comp1	Pb	Comp23	pb	Total
1.	no	100	f	13		75.89	10.06			75.89
2.	yes	100	f	13		77.24	9.94			77.24
3.	no	100	u	11.12		0	n.a.			0
4.	yes	100	u	11.12		0	n.a.			0
5.	no	50	f	13	13	38.26	10.06	20.48	27.15	58.74
6.	yes	50	f	13	13	38.94	9.94	20.71	27.12	59.65
7.	no	50	u	11.12	5.56	0	n.a.	0	n.a.	0
8.	yes	50	u	11.12	5.56	0	n.a.	0	n.a.	0
9.	no	0	f		19			216.12	22.11	216.12
10.	yes	0	f		19			216.54	22.10	216.54
11.	no	0	u		11.12			86.99	25.88	86.99
12	yes	0	u		11.12			87.39	25.86	87.39

[1] $.182/100,000 BTU is the price of natural gas heat in Bozeman, Montana as set by the Montana Public Service Commission Schedule RG-75, issued 3/15/77. $.469/100,000 BTU is the price for electric cooling.

Table 4.7

Functional Dependency of Optimal Insulation Levels and Net Savings on Air Conditioning and Insulation in a Propane Heated-Electric Cooled Home[1]

	Summer Air Conditioning	GR	Insulation	Optimal Insulation R		Present Value Maximum Net Savings (from insulation)				
				Comp1	Comp23	Comp1	Pb	Comp23	Pb	Total
1.	no	100	f	13		221.42	4.42			221.42
2.	yes	100	f	13		222.76	4.40			222.76
3.	no	100	u	16.68		108.33	22.82			108.33
4.	yes	100	u	16.68		110.66	22.71			110.66
5.	no	50	f	13	26	111.63	4.42	488.51	17.94	600.14
6.	yes	50	f	13	26	112.31	4.40	489.01	17.93	601.32
7.	no	50	u	16.68	16.68	54.61	22.82	518.05	16.35	572.66
8.	yes	50	u	16.68	16.68	55.79	22.71	518.59	16.34	574.39
9.	no	0	f		34[2]			1621.40	13.29	1621.40
10	yes	0	f		34			1621.97	13.29	1621.97
11.	no	0	u		22.24			1292.73	16.23	1292.73
12.	yes	0	u		22.24			1293.38	16.23	1293.38

[1] $.414/100,000 BTU is the price of propane in Bozeman, Montana in mid 1977. $.469/100,000 BTU is the price for electric cooling.

[2] See Figure 3.1, Increment No. 9.

influence optimal insulation levels. The increase in net savings that comes from air conditioning is the result of the compressor savings attributable to the optimal use of insulation. Tables 4.8 and 4.9 list the changes in net savings resulting from air conditioning when the heating and cooling fuel prices are varied.

FUEL PRICE SENSITIVITY

Optimal thermal wall designs are sensitive to fuel costs. This result comes from the cost minimization criterion which was employed by the model. According to this criterion, the optimal level of insulation is that amount which minimizes costs from the entire application. Here and throughout the report, net savings are defined as savings minus costs, where savings are the reductions in BTU flows through a wall section due to insulation multiplied by the respective fuel price, and costs are given as those expenditures which are necessary to raise the thermal resistance of the wall to the specified level.

Tables 4.8 and 4.9 list the functional dependency of the optimal levels of insulation and the resulting net savings on the fuel price. In each table four fuel prices are examined in three different wall configurations. Air conditioning is included as an option in all cases so that its influence on insulation levels and net savings can be examined. The data given here is intended to supplement the results

Table 4.8

Functional Dependeney of Fiberglass Insulation Levels
And Net Savings on the Heating and Cooling Fuel Prices

	Summer Air Conditioning	GR	Fuel[1]	CFuel[2]	Optimal Insulation R		Present Value Maximum Net Savings (from insulation)				
					Compl	Comp23	Compl	Pb	Comp23	Pb	Total
1.	no	100	.167	.454	13		66.48	10.96			66.48
2.	yes	100	.167	.454	13		67.78	10.83			67.78
3.	no	50	.167	.454	13	13	33.52	10.96	2.70	29.59	36.22
4.	yes	50	.167	.454	13	13	34.17	10.83	2.92	29.56	37.10
5.	no	0	.167	.454		19			148.41	24.09	148.41
6.	yes	0	.167	.454		19			148.82	24.08	148.82
7.	no	100	.251	.681	13		119.18	7.29			119.18
8.	yes	100	.251	.681	13		121.12	7.20			121.12
9.	no	50	.251	.681	13	13	60.09	7.29	102.27	19.69	162.36
10.	yes	50	.251	.681	13	13	61.07	7.20	102.61	19.67	163.68
11.	no	0	.251	.681		26			544.15	19.08	544.15
12.	yes	0	.251	.681		26			544.90	19.07	544.90

[1]Heating fuel costs are in dollars/100,000 BTU.

[2]Cooling fuel costs are in dollars/100,000 BTU.

Table 4.8, Continued

	Summer Air Conditioning	GR	Fuel[1]	CFuel[2]	Optimal Insulation R		Present Value Maximum Net Savings (from insulation)				
					Compl	Comp23	Compl	Pb	Comp23	Pb	Total
13.	no	100	.334	.908	13		171.24	5.48			171.24
14.	yes	100	.334	.908	13		173.84	5.41			173.84
15.	no	50	.334	.908	13	19	86.33	5.48	287.53	18.48	373.87
16.	yes	50	.334	.908	13	19	87.64	5.41	388.33	18.46	375.97
17.	no	0	.334	.908		33			1063.61	16.20	1063.61
18.	yes	0	.334	.908		33			1064.71	16.19	1064.71
19.	no	100	.501	1.362	13		276.00	3.65			276.00
20.	yes	100	.501	1.362	13		279.89	3.61			379.89
21.	no	50	.501	1.362	44	26	283.38	22.28	743.84	14.32	1027.22
22.	yes	50	.501	1.362	44	26	297.05	22.01	745.29	14.81	1042.33
23.	no	0	.501	1.362		34			2233.29	10.99	2233.29
24.	yes	0	.501	1.362		34			2234.95	10.98	2234.95

Table 4.9

Functional Dependency of Urethane Insulation Levels
And Net Savings on the Heating and Cooling Fuel Prices

	Summer Air Conditioning	GR	Fuel	C Fuel	Optimal Insulation R		Present Value Maximum Net Savings (from insulation)				
					Compl	Comp23	Compl	Pb	Comb23	Pb	Total
1.	no	100	.167	.454	11.12		0	n.a.			0
2.	yes	100	.167	.454	11.12		0	n.a.			0
3.	no	50	.167	.454	11.12	5.56	0	n.a.	0	n.a.	0
4.	yes	50	.167	.454	11.12	5.56	0	n.a.	0	n.a.	0
5.	no	0	.167	.454		11.12			34.81	28.20	34.81
6.	yes	0	.167	.454		11.12			35.20	28.18	35.20
7.	no	100	.251	.681	11.12		0	n.a.			0
8.	yes	100	.251	.681	11.12		0	n.a.			0
9.	no	50	.251	.681	11.12	11.12	0	n.a.	117.06	22.98	117.06
10.	yes	50	.251	.681	11.12	11.12	0	n.a.	117.63	22.06	117.63
11.	no	0	.251	.681		16.68			341.87	22.55	341.87
12.	yes	0	.251	.681		16.68			342.68	22.54	342.68

Table 4.9, Continued

	Summer Air Conditioning	GR	Fuel	C Fuel	Optimal Insulation R Compl	Comp23	Present Value Maximum Net Savings (from insulation) Compl	Pb	Comb23	Pb	Total
13.	no	100	.334	.908	16.68		20.83	28.29			20.83
14.	yes	100	.334	.908	16.68		25.36	27.94			25.36
15.	no	50	.334	.908	16.68	16.68	10.50	28.29	298.07	20.26	308.58
16.	yes	50	.334	.908	16.68	16.68	12.79	27.94	299.12	20.24	311.91
17.	no	0	.334	.908		16.68			797.10	16.95	797.10
18.	yes	0	.334	.908		16.68			798.18	16.94	798.18
19.	no	100	.501	1.362	16.68		203.47	18.86			203.47
20.	yes	100	.501	1.362	16.68		210.27	18.63			210.27
21.	no	50	.501	1.362	16.68	22.24	102.58	18.86	781.76	16.17	884.35
22.	yes	50	.501	1.362	16.68	22.24	106.01	18.63	783.59	16.15	889.60
23.	no	0	.501	1.362		22.24			1884.55	13.41	1884.55
24.	yes	0	.50.	1.362		22.24			1886.42	13.40	1886.42

of the last section on air conditioning.

Net savings, as the tables demonstrate, rise for higher fuel prices. This happens because the savings generated by a particular amount of insulation are directly proportional to fuel price and outstrip costs as fuel prices increase. Optimal insulation levels may also increase, but their amount of change is dependent on the shape of the MC and MS functions and on the amount of shift in the MS function. For urethane insulated walls, the transition to higher optimal insulation levels is fairly smooth as the fuel price rises. This is not true for the component 1 levels of fiberglass insulation as is illustrated by the large jump which occurs between lines 15 and 21 of Table 4.8. In Figures 4.2 and 4.3, the MC and MS functions are drawn to scale to illustrate the setting for such a transition. Figure 4.2 illustrates the marginal cost and savings functions which yield the data shown on line 15 of Table 4.8 while Figure 4.3 shows the corresponding information for line 21.

By visual inspection of Figure 4.2, one can verify that the optimal increment is 2, which corresponds to an R-value of 13 and a total wall resistance of 14.88. This can be seen by comparing the net savings which occur at each of the local maxima, i.e. at I = 2, 4, 8, 12, and 15. After such an inspection, one can see that 2 is the global maxima because at this level of insulation the area under the marginal savings curve exceeds the area under the marginal cost

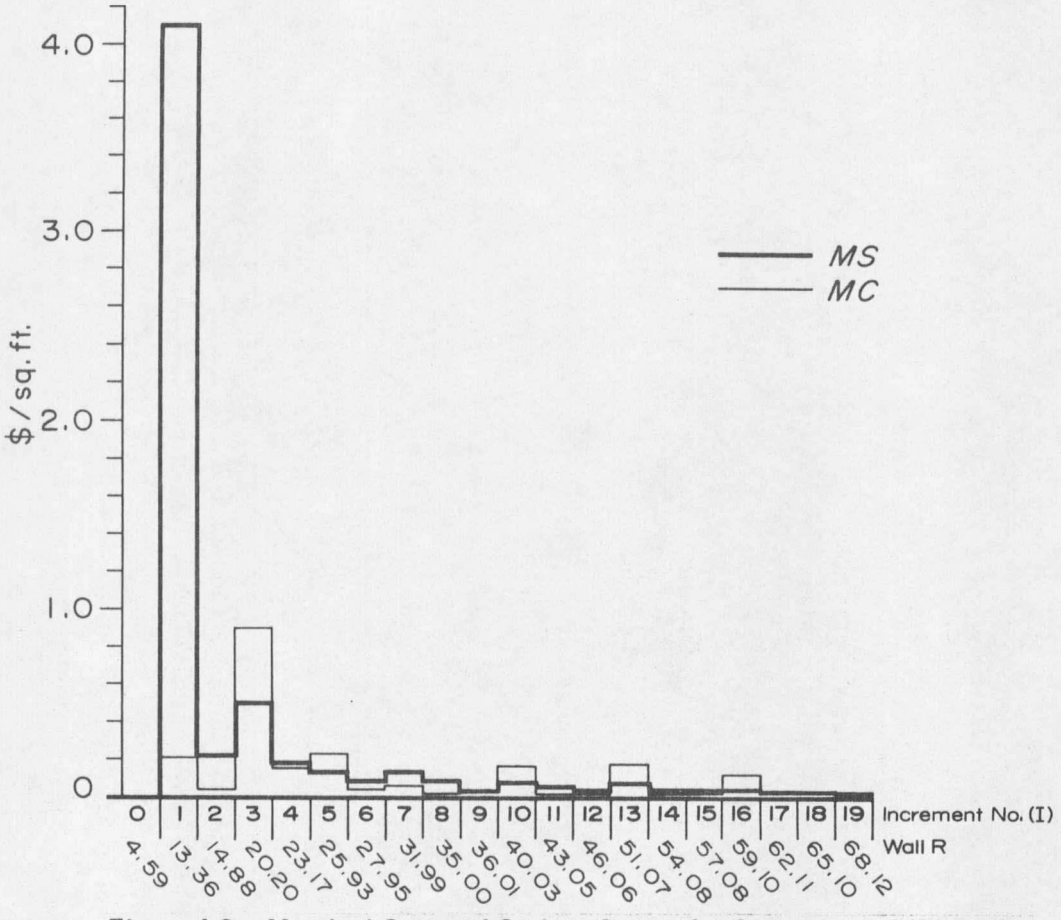


Figure 4.2 Marginal Cost and Savings Curves for Component 1 When The Heating Fuel Price is $.334/100,000 BTU.

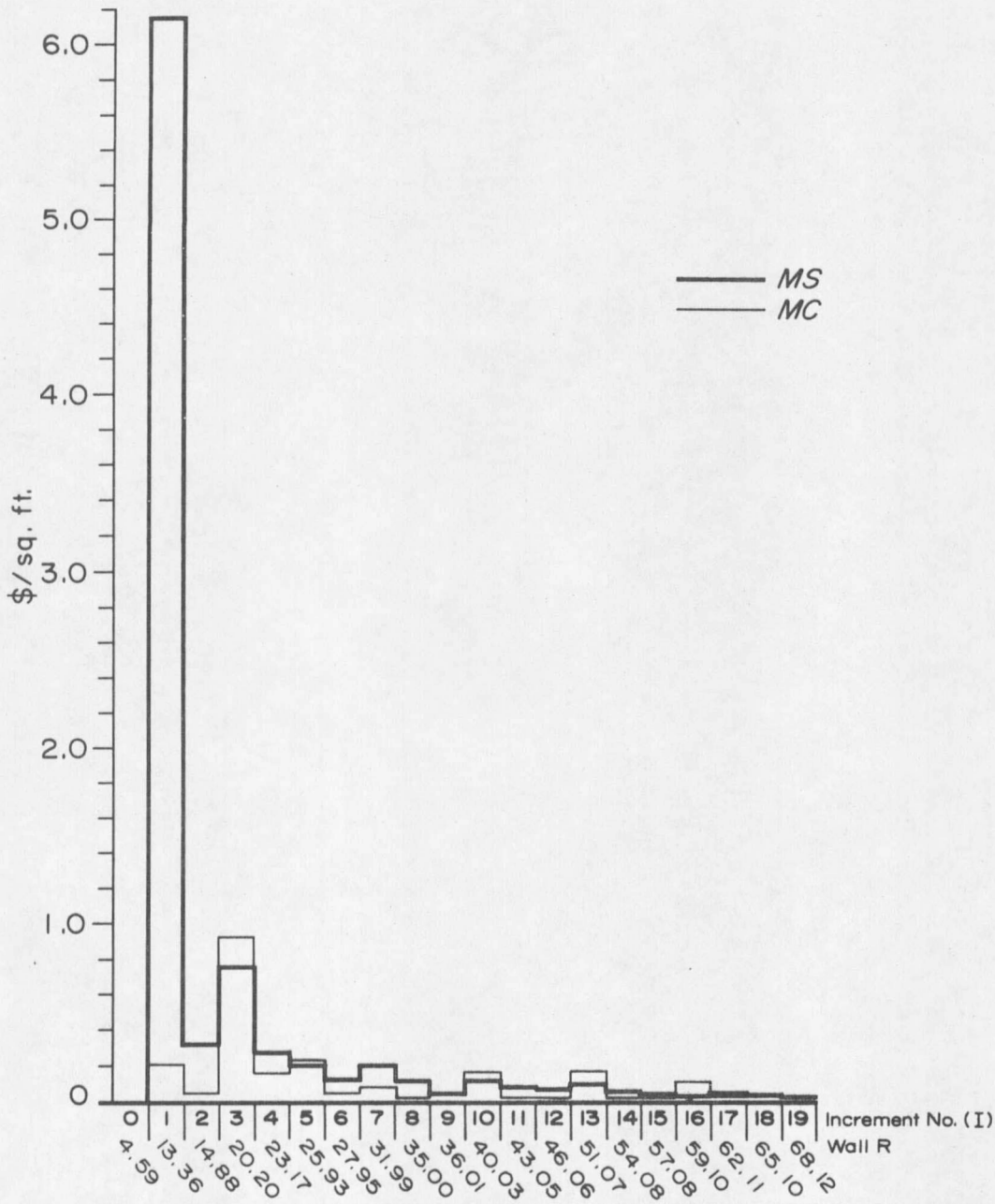


Figure 4.3 Marginal Cost and Savings Curves for Component 1 When The Heating Fuel Price is $.501/100,000 BTU.

curve by the greatest amount. In Figure 4.3 the optimal increment is 12, or R-44, for the same reason.

These results are different, however, if the ground ratio is 100. (See lines 13 and 19 of Table 4.8.) In this case the component 1 wall area is adjacent to the floor so floor area losses are added to the component 1 thick wall costs at each insulation level where a thicker wall is required. This change has the effect of pushing up the MC curve drawn in Figures 4.2 and 4.3 at the third, fourth, seventh, tenth, eleventh, thirteenth, fifteenth, and seventeenth increments enough to keep the optimal level of insulation down to R-13, when the fuel price is $.501/100,000 BTU.

In conclusion, optimal insulation levels and the resulting net savings are sensitive to fuel prices. Details are well summed up in Tables 4.8 and 4.9.

BUILDING LIFETIME (L), REAL RATE OF FUEL PRICE INCREASE (P), REAL DISCOUNT RATE (D), YEARS TO PAYBACK (Pb)

For reasons given in Chapter 2 both the real rate of fuel price increase and the real discount rate were set at 1 percent while the lifetime of the model wall was assigned to be 30 years. These values were used in all previous sections and will be used in the one following to determine the optimal insulation levels and the resulting

net savings. In this section the results of a sensitivity analysis on these parameters is shown. For brevity only fiberglass insulation is examined.

Table 4.10 lists net savings and insulation levels for lifetimes of 20, 30, and 40 years. The values listed in the second column correspond to the multiplier, or discount factor, which converts annual energy savings valued at today's energy prices to the present value of the stream of savings accruing over the lifetime of the wall. This multiplier, which is called the present value factor (PVF), was derived in Chapter 2. It is,

$$PVF = \sum_{t=1}^{L} \left(\frac{1 + P}{1 + D}\right)^t$$

which reduces to

$$PVF = L$$

when P = D. From the table we see that greater net savings, and in come cases, higher insulation levels result when the lifetime is lengthened. These results come from the upward shift in the marginal savings curve brought about by the increased lifetime period.

Table 4.11 is a sensitivity listing of net savings and insulation levels for difference combinations of the real rate of fuel price increase (P) and the real discount rate (D) As in Table 4.10, variations are due to shifts in the marginal savings function. The

Table 4.10

Sensitivity of Fiberglass Insulation Levels and Net Savings to the Lifetime of the Investment (The Fuel Price is $.251/100,000 BTU)

	L	PVF	GR	Optimal Insulation R		Present Value Maximum Net Savings (from insulation)				
				Comp1	Comp23	Comp1	Pb	Comp23	Pb	Total
1.	20	20	100	13		66.69	7.29			66.69
2.	20	20	50	13	13	33.63	7.29	3.09	19.69	36.72
3.	20	20	0		19			149.92	16.03	149.92
4.	30	30	100	13		119.18	7.29			119.18
5.	30	30	50	13	13	60.09	7.29	102.27	19.69	162.36
6.	30	30	0		26			544.15	19.08	544.15
7.	40	40	100	13		171.66	7.29			171.66
8.	40	40	50	13	19	86.55	7.29	289.93	24.59	375.57
9.	40	40	0		33			1068.23	21.55	1068.23

Table 4.11

Sensitivity of Fiberglass Insulation Levels and Net Savings to the Real Rate of Fuel Price Increase and to the Real Discount Rate (The Fuel Price is $.251/100,000 BTU. The Lifetime is 30 years.)

						Optimal Insulation R		P.V. Maximum Net Savings (from insulation)		
	P	D	P-D	PVF	GR	Comp1	Comp23	Comp1	Comp23	Total
1.	.01	.01	0	30	100	13		119.18		119.18
2.	.01	.01	0	30	50	13	13	60.09	102.27	162.36
3.	.01	.01	0	30	0		26		544.15	544.15
4.	.02	.01	.01	35.08	100	13		145.82		145.82
5.	.02	.01	.01	35.08	50	13	19	73.52	196.68	270.20
6.	.02	.01	.01	35.08	0		26		797.11	797.11
7.	.01	.02	-.01	25.85	100	13		97.37		97.37
8.	.01	.02	-.01	25.85	50	13	13	49.09	61.07	110.16
9.	.01	.02	-.01	25.85	0		19		370.68	370.68
10.	.04	.01	.03	48.75	100	13		217.60		217.60
11.	.04	.01	.03	48.75	50	13	26	109.71	470.62	580.33
12.	.04	.01	.03	48.75	0		34		1578.55	1578.55
13.	.01	.04	-.03	19.68	100	13		64.99		64.99
14.	.01	.04	-.03	19.68	50	13	8	32.77	0	32.77
15.	.01	.04	-.03	19.68	0		19		137.69	137.69
16.	.07	.01	.06	82.88	100	34		621.04		621.04
17.	.07	.01	.06	82.88	50	66	34	729.92	1388.39	2118.32
18.	.07	.01	.06	82.88	0		44		3655.47	3655.47
19.	.01	.07	-.06	13.85	100	13		34.43	0	34.43
20.	.01	.07	-.06	13.85	50	13	8	17.36	0	17.36
21.	.01	.07	-.06	.3.85	0		8			0

Table 4.11, Continued

	P	D	P-D	PVF	GR	Optimal Insulation R Comp1	Optimal Insulation R Comp23	P.V. Maximum Net Savings (from insulation) Comp1	P.V. Maximum Net Savings (from insulation) Comp23	P.V. Maximum Net Savings (from insulation) Total
22.	.05	.02	.03	48.51	50	13	26	109.06	464.62	573.69
23.	.06	.03	.03	48.27	50	13	26	108.43	458.78	567.21
24.	.02	.05	-.03	19.75	50	13	13	32.96	.62	33.58
25.	.03	.06	-.03	19.82	50	13	13	33.16	1.34	34.50
26.	.08	.02	.06	82.00	50	66	34	711.40	1362.74	2074.13
27.	.09	.03	.06	81.13	50	66	34	693.39	1337.80	2031.19
28.	.02	.08	-.06	13.94	50	13	8	17.59	0	17.59
29.	.03	.09	-.06	14.03	50	13	8	17.82	0	17.82

lifetime used is 20 years.[12/]

[12/] A close inspection of the net savings listed in lines 11, 22, and 23, for example, of Table 4.11 will reveal that they are not the same even though P - D is the same. This discrepancy arises because P and D are different distances from zero and because finite time periods are used in the compounding. The further from the origin, i.e. zero, that P and D are, or the larger the time period, the more exaggerated this difference will be. In the limit, where the compounding is continuous, this discrepancy goes to 0. Table 4.12 compares the present value factors shown in Table 4.11 with their continuous counterparts which were calculated using the formula

$$PVF = \sum_{t=1}^{L} e^{(P - D)t}.$$

The differences that result from the continuous and the discrete time periods are explained graphically in Figure 4.4. This figure shows the accumulation of a sum in the two cases. The smooth curve shows how an investment of "a" dollars will increase at continuously compounded interest at rate r. The formula for this curve is

$$Y = ae^{rt}.$$

The stepped curve shows how this same investment will grow if the interest is compounded in ten periods. Its formula is

$$Y = a \sum_{t=1}^{10} (1 + r)^t.$$

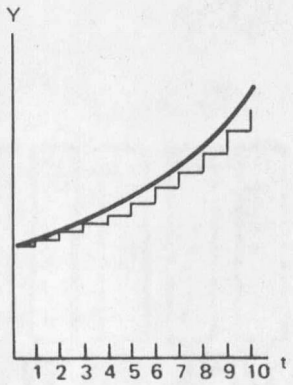


Figure 4.4 Growth of an Investment When the Compound Interest is Added Continuously and in Ten Time Periods

Table 4.12

Continuous and Annually Compounded
Present Value Factors

	Present Value Factor (PVF)			
P-D	Continuous Value	Table 4.11 Values (Annually Compounded)		
.01	35.16	35.08		
-.01	25.79	25.85		
.03	49.39	48.75	48.51	48.27
-.03	19.49	19.68	19.75	19.82
.06	86.71	82.88	82.00	81.13
-.06	13.50	13.85	13.94	14.03

The years to payback an investment are figured from the present value of the stream of savings accruing over the lifetime of the investment and from the costs of the investment.[13/] In this report payback periods were listed for the optimal investments under a wide variety of conditions. They were calculated for the investment beyond the HUD Minimum Property Standard recommendations and are found in the tables of the various sections under columns headed "Pb". In all tables, the abbreviation "n.a.", for not applicable, is used for the two cases where the payback period cannot be defined. These cases are when the net savings are negative and when they are zero.

[13/] Years to payback (Pb) are derived from the investment's present value factor, its costs, and the annual savings (S) that it generates:

$$PV = \sum_{t=1}^{L} \left(\frac{1 + P}{1 + D}\right)^{t} .S$$

where PV = the present value of the stream of savings accumulated over the lifetime of the investment.

Eliminating the summation,

$$PV = \frac{1 + P}{1 + D} \cdot \left[1 - \left(\frac{1 + P}{1 + D}\right)^{L}\right] . S \quad \text{(See 24, p. 19)}$$

Solving for L

$$L = \frac{\log\left[1 - \frac{PV}{S}\left(\frac{D-P}{1+P}\right)\right]}{\log\left(\frac{1 + P}{1 + D}\right)}$$

Equating costs with present value savings,

Payback periods for the total investment are shorter than their counterparts which are concerned only with insulation levels beyond the MPS because the first increments of insulation have a higher rate of return than do succeeding increments. This can be demonstrated by examining the net savings functions, which can be defined as MS - MC, for the first increments of insulation in Figures 4.2 and 4.3. Thus the total investment in wall insulation can be quite attractive as the average rate of return may exceed the homeowner discount rate whenever two or more thicknesses of insulation are in the optimal solution.

GROUND RATIO

A ground ratio was formulated to describe the composition of the living wall units. Its value corresponded to the percentage of the total living wall height which was component 1. In Figure 4.5, the ground ratio is given for three living wall configurations.

In previous sections, the composition of the living wall units was examined only in regard to how it influenced optimal insulation levels and the net savings resulting from these levels. No attempt was made to measure the resultant savings from the different wall

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13/Continued

$$Pb = L = \frac{\log\left[1 - \frac{\text{Costs}}{S}\left(\frac{D - P}{1 + P}\right)\right]}{\log\left(\frac{1 + P}{1 + D}\right)}$$

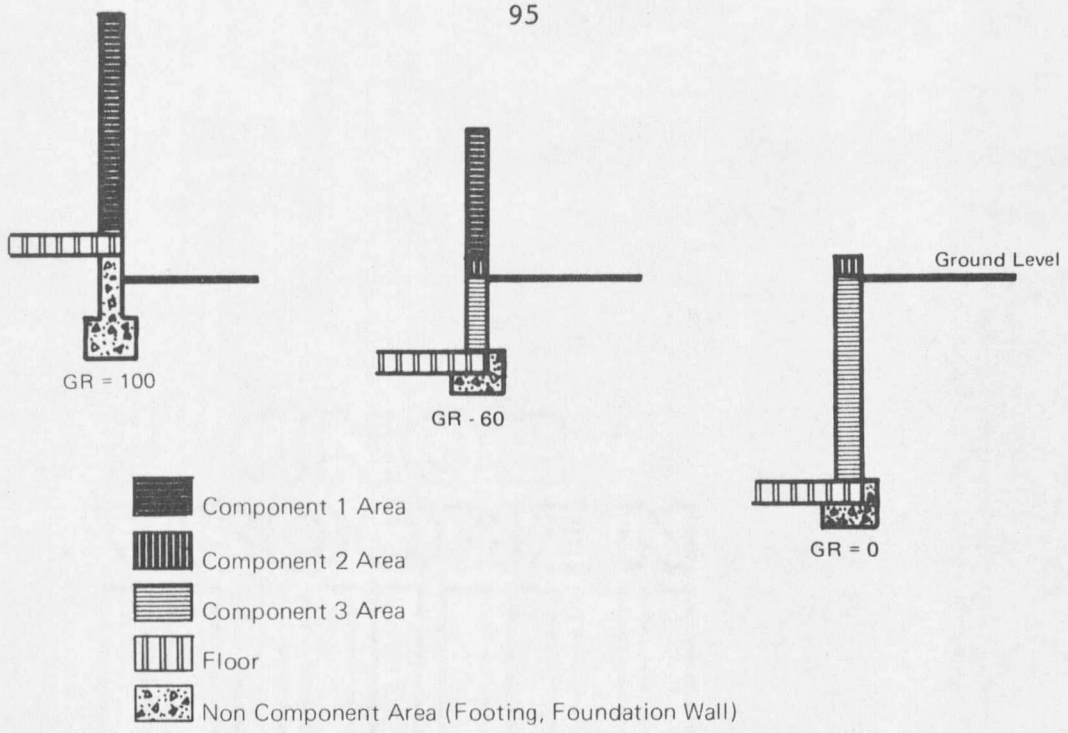


Figure 4.5 The Ground Ratio (GR) For Three Wall Configurations

configurations when the soil was incorporated as a part of the thermal envelope. In those sections, only three ground ratios were considered for living wall units -- they were GR = 100, 50, and 0. The subsection immediately following takes some of the study areas of the previous sections and extends their results to all eleven wall configurations (GR = 100, 90, 80, 70, 60, 50, 40, 30, 20, 10, 0). Included are tables showing the functional dependency of the net savings levels on insulation types, air conditioning, and fuel prices. Further on, savings attributable to the ground ratio are discussed and listed. Finally using cost minimization criteria described earlier, net savings from the ground ratio are combined with those from the insulation to

determine optimum ground ratio and insulation level combinations.

Net Savings From Insulation

Tables 4.13 and 4.14 list net savings from insulation for all eleven ground ratios. The results are similar to those found in earlier sections. For example, the influence of air conditioning on net savings is very small in all cases. This result agrees with the conclusions in the section on summer air conditioning. The sensitivity of the results to fuel prices is also clearly demonstrated.

The model wall specifications which yielded the greatest net savings for each case in Tables 4.13 and 4.14 are listed in summary tables numbered 4.15 and 4.16. The function of Tables 4.15 and 4.16 is to provide, in a line by line summary, the insulation and ground ratio specifications of the optimal net savings cases. The table to which each of the summary tables refers is clearly listed.

The results in Tables 4.13 and 4.14 show the sensitivity of net savings to several variables. To demonstrate better the trends in the insulation net savings function under a range of conditions, Figures 4.6 and 4.7 were drawn from selected cases in Tables 4.13 and 4.14 respectively. Figure 4.6 for example, was drawn for lines 1, 3, and 5 of Table 4.13. For an explanation of the characteristic shape of the curves in Figure 4.6, see Table 4.17 which is a breakdown of the component net savings from the case where the fuel price is $.334/100,000 BTU. The downward shift of the .251 and .167 curves

Table 4.13

Functional Dependency of Net Savings from Fiberglass Insulation on Air Conditioning, Fuel Price, and the Ground Ratio

	Summer Air Conditioning	Fuel[1]	Cfuel[2]	Present Value Maximum Net Savings from Insulation										
				100	90	80	70	60	50	40	30	20	10	0
1.	no	.167	.454	66.48	-2.76	53.30	46.71	40.11	36.22	50.27	64.34	78.32	106.04	148.11
2.	yes	.167	.454	67.78	-1.00	54.34	47.62	40.90	37.10	51.02	64.97	78.82	106.58	148.82
3.	no	.251	.681	119.18	102.80	95.54	105.37	133.93	162.36	233.25	304.94	376.44	451.39	544.15
4.	yes	.251	.681	121.12	105.44	97.10	107.07	135.44	163.68	234.64	306.14	377.44	452.20	544.90
5.	no	.334	.908	171.24	154.26	158.56	201.66	270.06	373.87	477.59	613.92	750.59	901.90	1063.61
6.	yes	.334	.908	173.84	156.60	161.07	203.93	272.42	375.97	479.44	615.69	752.10	904.75	1064.71
7.	no	.501	1.362	276.00	458.90	516.67	641.13	817.42	1027.22	1260.58	1512.93	1764.51	2023.09	2233.29
8.	yes	.501	1.362	279.89	483.90	539.04	661.32	835.21	1042.33	1273.18	1522.85	1771.74	2027.56	2234.95

[1] Heating fuel costs are in dollars/100,000 BTU.

[2] Cooling fuel costs are in dollars/100,000 BTU.

Table 4.14

Functional Dependency of Net Savings from Urethane Insulation on Air Conditioning, Fuel Price, and the Ground Ratio

	Summer Air Conditioning	Fuel	Cfuel	Present Value Maximum Net Savings from Insulation										
				100	90	80	70	60	50	40	30	20	10	0
1.	no	.167	.454	0	0	0	0	0	0	0	0	6.69	20.58	34.81
2.	yes	.167	.454	0	0	0	0	0	0	0	0	7.07	20.96	35.20
3.	no	.251	.681	0	0	0	34.45	75.85	117.06	158.14	199.14	240.01	284.94	341.87
4.	yes	.251	.681	0	0	0	35.00	76.41	117.63	158.71	199.71	240.67	285.75	342.68
5.	no	.334	.908	20.83	18.77	71.46	139.65	212.55	308.58	404.40	500.16	595.79	695.59	797.10
6.	yes	.334	.908	25.36	22.85	75.81	143.57	216.33	311.91	407.29	502.61	597.80	697.13	798.18
7.	no	.501	1.362	203.47	232.04	353.78	523.42	691.86	884.35	1080.89	1277.38	1473.64	1677.43	1884.55
8.	yes	.501	1.362	210.27	239.14	360.73	529.74	697.53	889.60	1085.47	1281.30	1476.89	1680.00	1886.42

Table 4.15

Insulation and Ground Ratio Specifications
For the Optimal Net Savings Cases in Table 4.13

	GR	Insulation R	
		Comp1	Comp23
1.	0		19
2.	0		19
3.	0		26
4.	0		26
5.	0		33
6.	0		33
7.	0		34
8.	0		34

Table 4.16

Insulation and Ground Ratio Specification
For the Optimal Net Savings Cases in Table 4.14

		Insulation R	
	GR	Comp1	Comp23
1.	0		11.12
2.	0		11.12
3.	0		16.68
4.	0		16.68
5.	0		16.68
6.	0		16.68
7.	0		22.24
8.	0		22.24

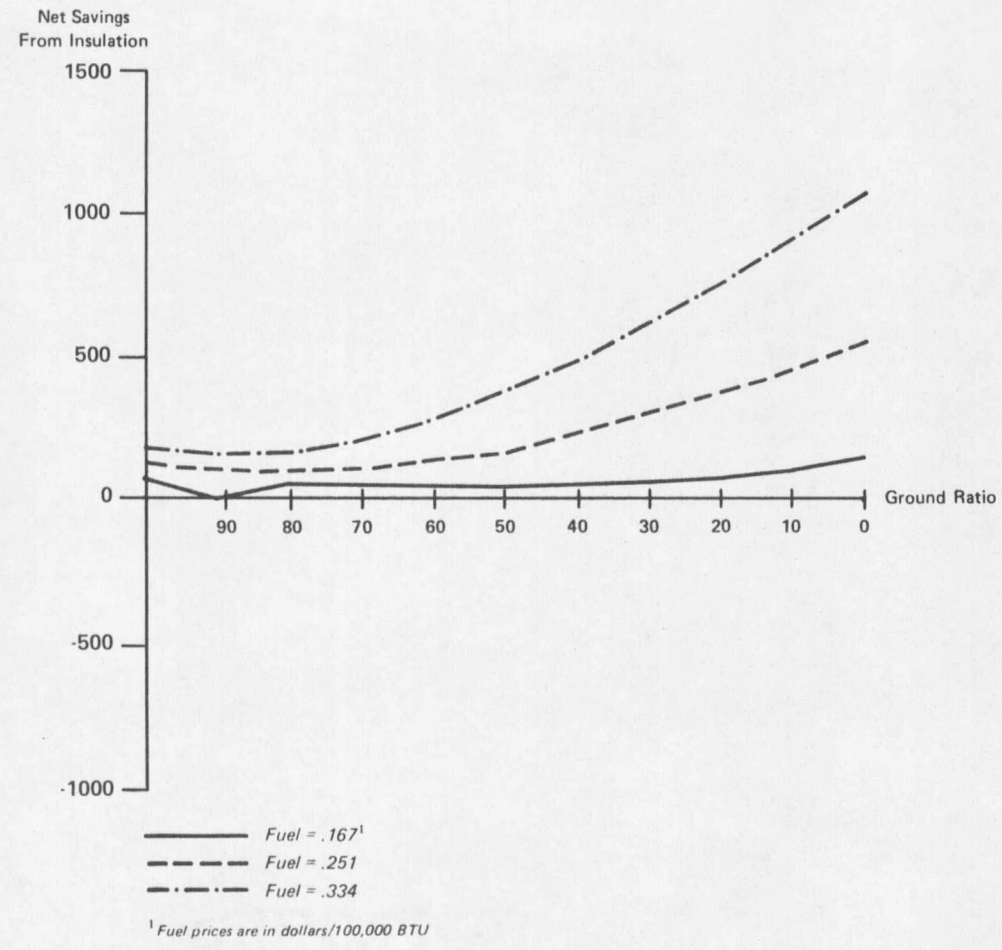
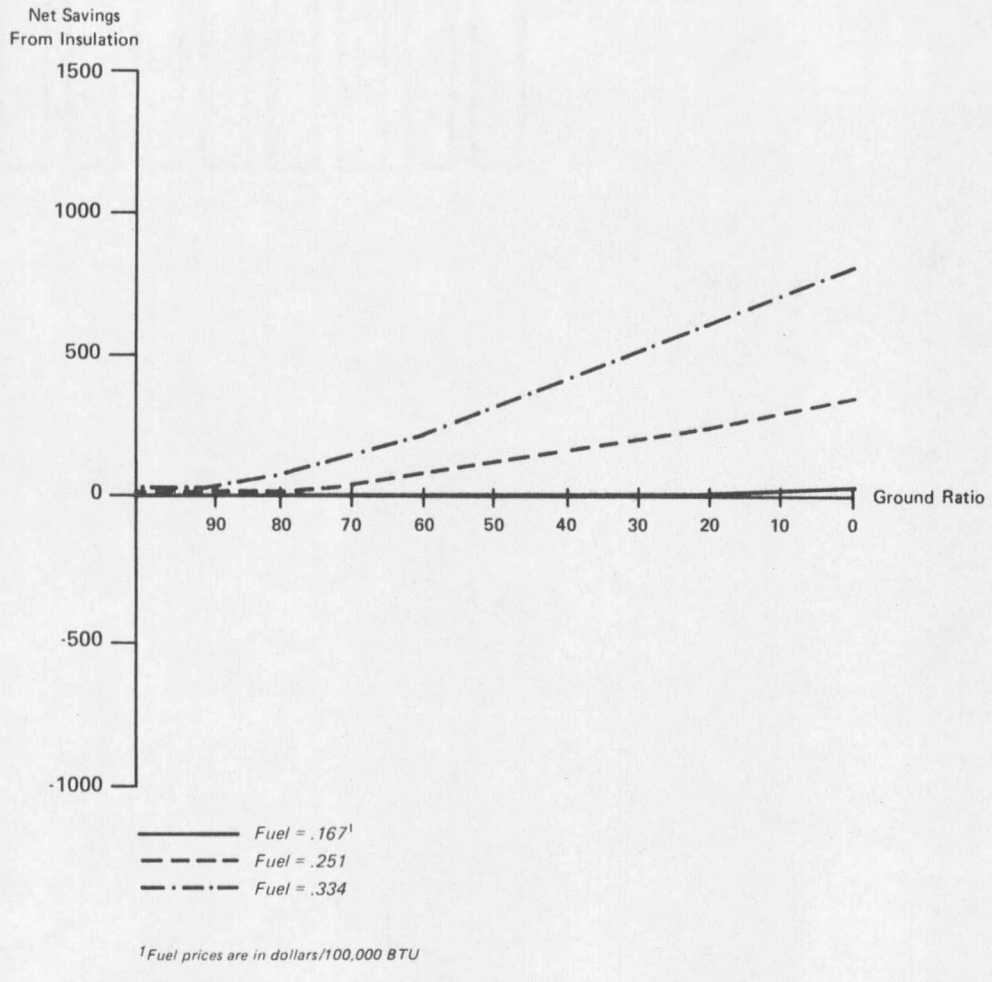


Figure 4.6 Functional Dependency of Net Savings from Fiberglass Insulation on the Ground Ratio and on the Fuel Price.



[1] *Fuel prices are in dollars/100,000 BTU*

Figure 4.7 Functional Dependency of Net Savings from Urethane Insulation on the Ground Ratio and on the Fuel Price.

Table 4.17

Funcational Dependency of Optimal Fiberglass Insulation Levels and Net Savings on the Ground Ratio (The Fuel Price is $.334/100,000 BTU)

		Optimal Insulation R		P.V. Maximum Net Savings (from insulation)		
	GR	Comp1	Comp23	Comp1	Comp23	Total
1.	100	13		171.24		171.24
2.	90	13	8	154.26	0	154.26
3.	80	13	13	137.28	21.28	158.56
4.	70	13	13	120.30	81.37	201.66
5.	60	13	19	103.32	166.75	270.06
6.	50	13	19	86.33	287.53	373.87
7.	40	13	19	69.35	408.24	477.59
8.	30	13	26	52.37	561.55	613.92
9.	20	13	26	35.39	715.20	750.59
10.	10	44	26	26.43	875.47	901.90
11.	0		33		1063.61	1063.61

from the .334 curve in Figure 4.6 is due to the decline in net savings for both the component 1 and component 2 and 3 areas. This decline is the result of the lower fuel prices. (Fuel prices are in dollars/ 100,000 BTU.)

The net savings generated by urethane insulation are similar to the savings from fiberglass. They generally increase as a larger portion of the wall area of the model home is placed within the ground. This can be seen from the basic shape of the curves plotted in Figure 4.7. These savings increase as the ground ratio declines because the positive return to the insulation from the increasing component 2 and 3 area outweighs the declining returns from the decreasing component 1 area. This same trend was shown for fiberglass in Table 4.17.

It is important to note that the net savings illustrated here for both types of insulation are measured using the HUD "Minimum Property Standards" constraint as a starting point. This procedure was explained on page 44. A different trend in the insulation net savings results when the HUD constraint is dropped. This is seen best in Figures 4.33 and 4.34 which are found on pages 161 and 162.

The discussion so far has involved no concepts which haven't been covered in previous sections. A good summary of the findings presented in this subsection is embodied in the curves drawn in Figures 4.6 and 4.7. In the subsection following, savings available to the homeowner from the thermal resistance of the soil are described

and listed.

Ground Ratio Savings

The investigation of possible thermal savings realized from different wall configurations would not be complete without an examination of the effect which the ground ratio has on the total thermal load faced by the walls of the model home. To this point in the analysis, all savings which have been investigated have been generated by thermal insulation which was applied to the wall components in the various configurations dictated by the ground ratio.

For review, the savings accruing from the change in the overall fuel cost load which results when the wall configuration is changed, are called the ground ratio savings. As with ground ratio costs, these savings are calculated with respect to optimally insulated conventional wall construction. They are defined as the sum of the present value savings due to all component areas of the living wall which arise when areas and insulation levels are changed due to the downward shift of the ground ratio. For a ground ratio of 60, these savings are generated in part from the reduction in the heat load on the component 1 wall due to the decrease in its area resulting from the 40 percent lowering of its height. The area which is lost is from the conventional wall design, hence it was insulated at the level which was optimal for conventional wall construction. Additional savings will be generated

from the remaining component 1 wall area of the GR = 60 configuration, if the optimal level of insulation for this section of the wall is higher than it was in the conventional design. (Such savings are a distinct possibility since thick wall costs arising from lost floor area are no longer a part of the component 1 insulation costs as the component 1 area no longer adjoins the floor.) Losses will be posted for this section of the living wall if the optimal level of insulation declines from the GR = 100 value. A conventional wall design contains no component 2 or 3 areas so as the ground ratio is reduced, the creation of these areas means the creation of additional heat loads on the living wall. These component 2 and 3 losses, resulting from the downward shift of the ground ratio to 60, are added to the component 1 ground ratio savings to arrive at the total ground ratio savings for the living wall configuration. Mathematically ground ratio savings are described on page 46.

To illustrate the source of ground ratio savings, consider an example where the ground ratio is 60, the fuel price is $.251/100,000 BTU, the insulation is fiberglass, and no summer air conditioning is specified:

$1.4472 = the present value dollar fuel savings realized over the lifetime of the wall from the loss of 1 square foot of component 1 wall area when it is insulated to its optimal level of 2 increments (R-13).

$1.6269 = the present value dollar fuel loss realized over the lifetime of the wall from the gain of 1 square foot of component 2 wall area when it is insulated to its optimal level of 4 increments (R-13).

$2.2939 = the present value dollar fuel loss realized over the lifetime of the wall from the gain of 1 square foot of component 3 wall area when it is insulated to its optimal level of 4 increments (R-13).

379.54 sq. ft. = the total reduction in the component 1 wall area of the model home due to the downward shift of the ground ratio from 100 to 60.

65.72 sq. ft. = the total gain in the component 2 wall area of the model home due to the downward shift of the ground ratio from 100 to 60.

345.72 sq. ft. = the total gain in the component 3 wall area of the model home due to the downward shift of the ground ratio from 100 to 60.

$1.4472 · 379.54 = $549.28 = ground ratio savings for component 1

-$1.6269 · 65.72 = $106.92 = ground ratio savings for component 2

-$2.2939 · 345.12 = -$793.05 = ground ratio savings for component 3

$549.28 + (-$106.92) + (-$793.05) = -$350.69 = the total ground ratio savings for GR = 60.

Thus, the fuel costs over the lifetime of this residence increase by $350.69 when its wall configuration is changed from the conventional above ground design to the GR = 60 design.

Wall Costs

Wall costs, as discussed earlier, fall into two categories -- those associated with thermal insulation levels and those which arise from the ground ratio. How the costs are defined in each of these categories is crucial in the determination of the optimal conditions. For example, the results of previous sections demonstrated clearly how important thick wall costs arising from lost floor area were in influencing optimal insulation levels and net savings. In a like manner the method used to define ground ratio costs will determine the net savings and optimality of each ground ratio level. The definition of these costs is the topic of this subsection.

Costs associated with the ground ratio can be classified as structural and as consumer preferences. Those which fall in the structural category are the physical costs which arise when the wall configuration is changed from the conventional design. Three costs are defined in this category:

Ground ratio costs are the construction costs of the wall unit resulting when the wall configuration is changed through a downward shift of the ground ratio from 100. They are defined as the berm wall cost minus the conventional wall cost. Ground ratio costs are calculated by the following relationship, which was also expressed on page 46:

Ground ratio costs = (the cost/sq. ft. of the optimally insulated component 1 wall in the berm wall configuration times the total component 1 wall area in the berm configuration plus the cost/sq.ft. of the optimally insulated componenent 2 and 3 wall in the berm configuration times the total area of these components in the berm configuration) - (the cost/sq.ft. of the optimally insulated component 1 wall in the GR = 100 design times the total wall area in the GR = 100 design) - (the cost/sq.ft. of concrete foundation walls in the GR = 100 design times (the component 2 and 3 area in the berm configuration if the component 3 height in that design is less than or equal to 2.33 feet) or (the component 2 and 3 area defined by the component 2 height of 7.44 inches and a component 3 height of 2.33 feet if the component 3 height in the berm design exceeds 2.33 feet)). Such a definition of costs is sensitive to the changes in wall structure and insulation levels which result from shifts in the ground ratio.

Excavation costs are the expenditures made for excavation and backfill

when a particular wall configuration is constructed. Net excavation costs are the change in total excavation cost due to grounding. They are calculated with reference to the excavation (and backfill) costs required in the conventional design.

Entrance costs are the expenses which result from the construction of steps and landings leading up to the doorways in conventional wall designs or down to the doorways in berm wall designs. Net entrance costs are the change in total entrance costs resulting from grounding. They are defined as the difference between the entrance costs for the designs in question and the entrance costs for the conventional design.

Costs which reflect the consumer's preferences or aversions to a particular wall configuration are broken into two categories so that the consumer is more able to express his choices. These definitions of cost employ cost ratios and were introduced on page 54. They are briefly repeated here for convenience:

The excavation cost ratio (EXR) was devised so that the consumer's evaluation of a particular ground ratio could be expressed as a function of the net excavation costs.

In parallel fashion, the entrance cost ratio (ENR) provides a medium through which different responses to the entryways necessitated by each wall configuration could be entered into the cost functions along with

the net entryway construction costs.

Both EXR and ENR are set at 0, 1, and 2, to anticipate possible responses of the consumer. A value of 0 for either ratio represents a preference for the condition equal to, and thus counterbalancing, the construction cost. Other values for the ratios can be interpreted from the guidelines given on page 56.

The wall costs discussed here are incorporated into the cost minimization scheme discussed in the next subsection. The values assigned to the cost ratios are listed along with the presentation of the results.

Methodology for Optimizing Insulation Levels and Ground Ratios

Costs are minimized when the net savings from insulation are optimized together with the net savings from the ground ratio. A special procedure was devised to do this as the optimal ground ratio and the savings realized from it are dependent on the insulation level of each component. The following two statements explain the interdependencies:

1. The optimal insulation levels and the net savings from insulation are a function of the ground ratio.
2. The optimal ground ratio level and the net savings from the ground ratio are a function of the optimal insulation levels.

Thus, optimal insulation levels for each of the components can be found

at each ground ratio value without a knowledge of the optimal ground ratio level. Using this as a starting point, the procedure then determined the ground ratio level which minimized costs.

To illustrate this procedure more clearly, consider the costs and savings defined in the previous subsections. As shown there, wall costs and wall savings fall into two categories: those associated with the insulation levels and those associated with the ground ratio. The definitional separation of costs and savings into two parts is central to the success of the procedure outlined above.

Insulation levels within the walls are optimized through a procedure which compares the costs for each level with the benefits in fuel savings derived from such an investment. The costs in each case take into account the wall configuration as defined by the ground ratio, the labor and materials involved, and the floor area alterations in the event of thickened wall designs. In short, they reflect the changes in wall structure which results from added insulation levels. Savings from insulation show the change in thermal response of the wall structure which results from each added level. Both the savings from and the costs for each insulation level depend on the ground ratio because the insulative quality of the soil alters the component 3 heat load and thus imposes different requirements on the insulation system for each wall configuration.

Optimal ground ratio levels are determined by a process which

globally compares cost and savings over all combinations. The savings, in this case, reflect changes in the overall thermal loads which result from altered wall configurations composed of optimally insulated components. Ground ratio costs are sensitive to changes in wall structure and optimal insulation levels which result when the ground ratio is varied. The optimal configuration is determined by a procedure that selects the ground ratio which maximizes (ground ratio savings) - (ground ratio costs) - (net excavation costs) - (net entrance costs) + (net savings from insulation).

Net Savings

Ground ratio savings (GRS) are the savings recoverable from changes in thermal loads which result as the wall configuration is changed in response to a declining ground ratio. These savings are calculated for insulated components which meet or exced MPS requirements.[14/] Table A.1 in Appendix A lists these savings for sixteen selected

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[14/] When the optimal level of insulation for a component does not meet the MPS requirement, a negative net savings results from the resource expended to meet that requirement. Such a loss is a part of the insulation's net savings and is not reflected in ground ratio savings.

cases.[15] Figures 4.8 - 4.11 were drawn to illustrate more clearly the trends which took place in eight of these cases.

The overall downward slope of the ground ratio savings curves illustrated in Figures 4.8 - 4.11 demonstrates that the trade-off of component 1 for component 2 and 3 areas as the ground ratio declines, leads to increasing thermal loads on the total wall area and hence

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[15] Table A.1 is one of the several computer generated appendix tables used in this presentation. Its terminology is similar to that of previously listed tables. In its first two columns are listed the values of the cost ratios established by the consumer's preferences. Column three titled "IN" is a listing of the insulation type where "F" stands for fiberglass and "U" for urethane. The fourth column is a listing of heating fuel costs in terms of dollars/100,000 BTU. Whenever electric refrigeration air conditioning is specified, as is depicted by a "YES" on column five, cooling fuel costs are used which reflect the overall fuel price. The correspondence is:

Fuel	Cooling fuel price in $/100,000 BTU
.167	.454
.251	.681
.334	.908
.501	1.362

The headings in columns six and on show the ground ratio value for each configuration. The figures in columns 6, 7, 8, etc., correspond to the heading of the table. For Table A.1 the listings are ground ratio savings while for Table A.3 the values are net savings for the entire wall design, i.e., net savings from insulation and the ground ratio. This notation applies to Tables A.1, A.3 - A.24, and A.43 - A.54. The remaining appendix tables are for use in conjunction with Tables A.1, A.3 - A.24, and A.43 - A.54. They define, in summary form, the savings maximizing wall designs for each case considered in these tables. Table A.2, for example, provides a line by line summary of the optimal ground ratio and component insulation levels for each case described in Table A.1. The table to which each Summary Table refers is clearly listed. Use Table 4.1 on page 63 to convert the insulation increment numbers shown in the Summary Tables into commercial units. All tables labeled by an "A" are contained in Appendix A.

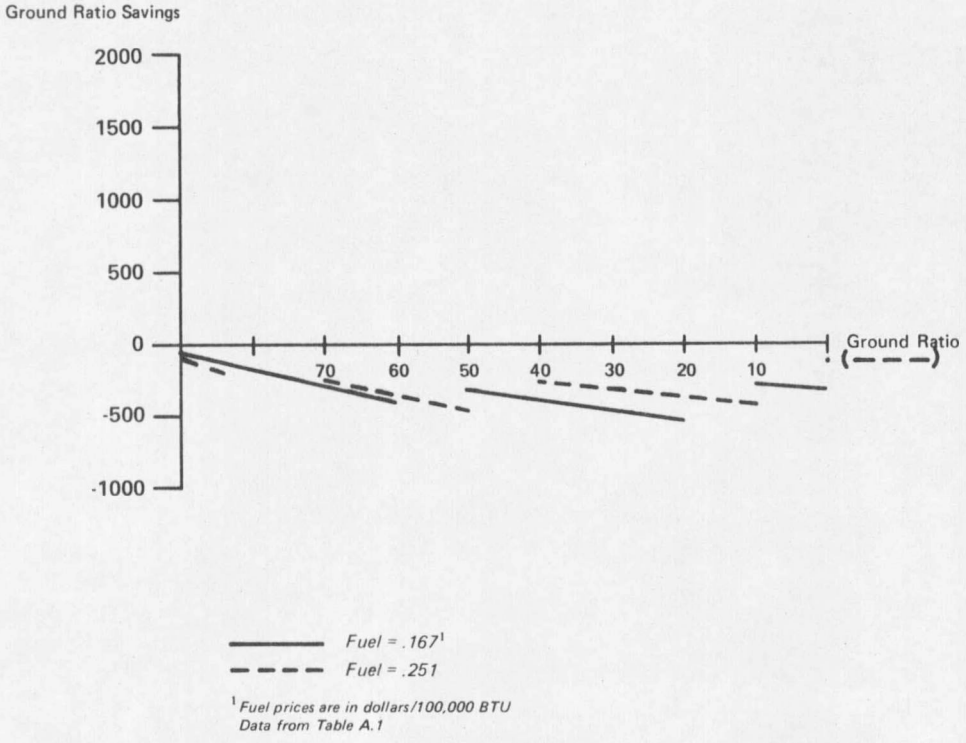
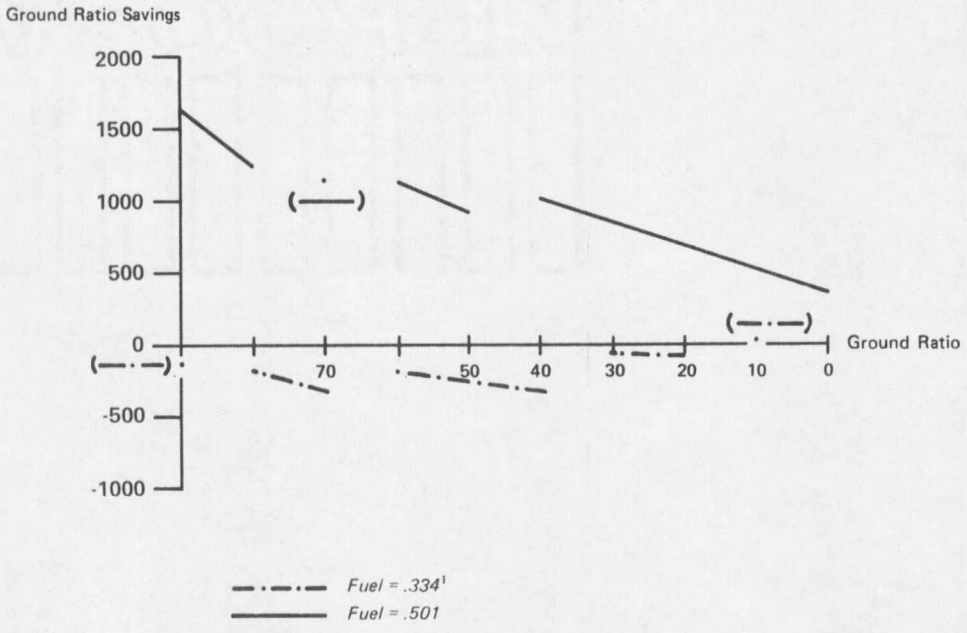


Figure 4.8 Functional Dependency of Ground Ratio Savings on the Ground Ratio and on the Fuel Prices. (The Fuel Prices are $.167/100,000 BTU and $.251/100,000 BTU. Fiberglass Insulation is Used.)



[1] *Fuel prices are in dollars/100,000 BTU*
Data from Table A.1

Figure 4.9 Functional Dependency of Ground Ratio Savings on the Ground Ratio and on the Fuel Prices. (The Fuel Prices are $.334/100,000 BTU and $.501/100,000 BTU. Fiberglass Insulation is Used.)

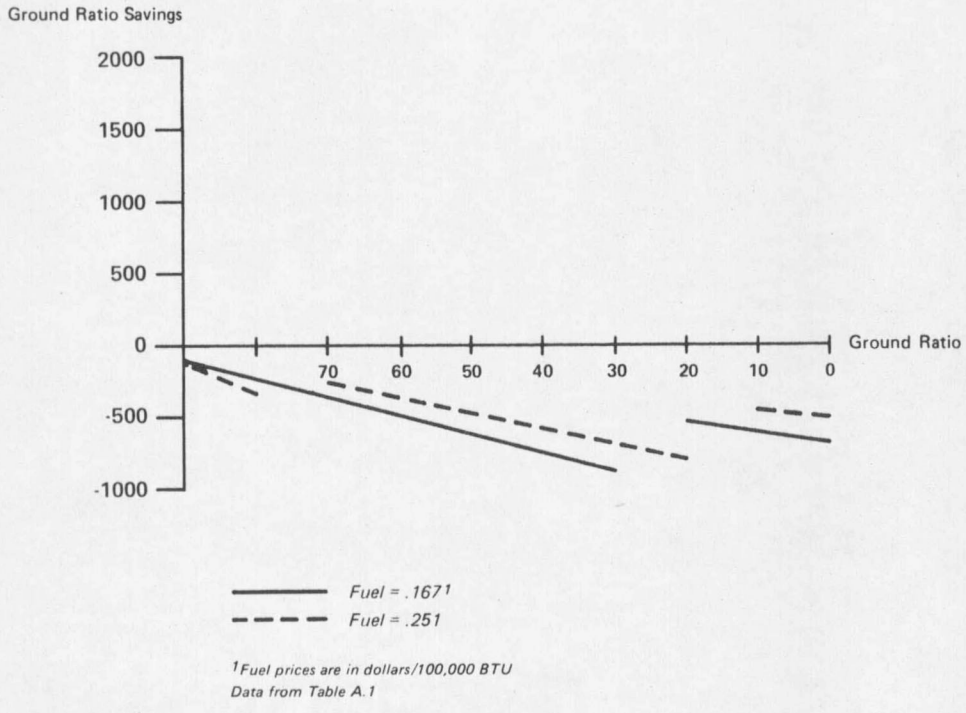
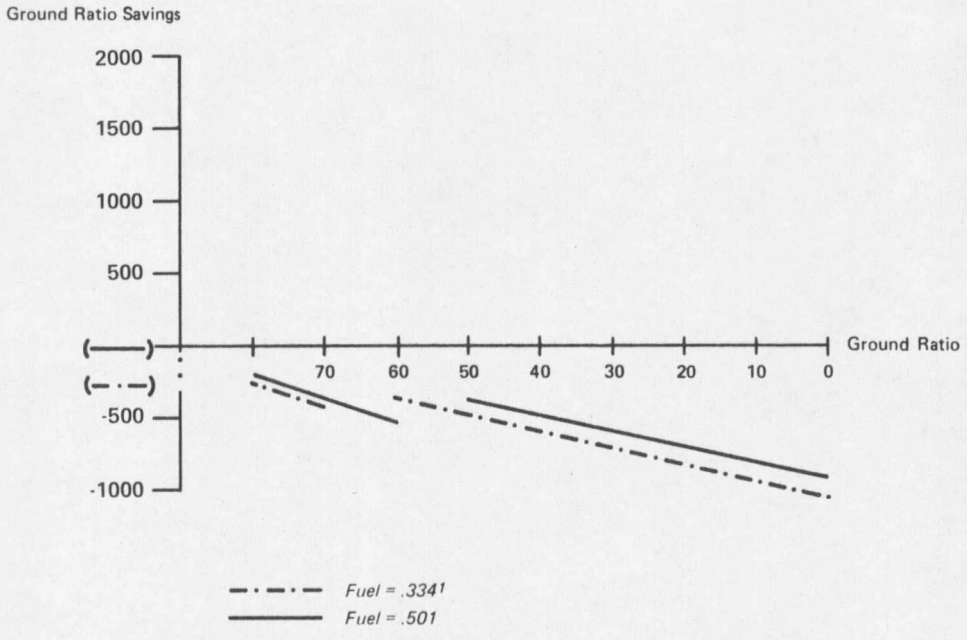


Figure 4.10 Functional Dependency of Ground Ratio Savings on the Ground Ratio and on the Fuel Prices. (The Fuel Prices are $.167/100,000 BTU and $.251/100,000 BTU. Urethane Insulation is Used.)



[1]Fuel prices are in dollars/100,000 BTU
Data from Table A.1

Figure 4.11 Functional Dependency of Ground Ratio Savings on the Ground Ratio and on the Fuel Prices. (The Fuel Prices are $.334/100,000 BTU and $.501/100,000 BTU. Urethane Insulation is Used.)

increased fuel usage. This perhaps surprising result is the same for most cases listed in Table A.1. A more detailed discussion on fuel usage is given further on in this section.

As was specified by the model, HUD Minimum Property Standards for insulation were assumed to be met by all wall components. This assumption is important in explaining the shape of the curves in Figure 4.8. Each break in the .251 curve in this figure is the result of changing insulation specifications for the wall components. At this fuel price, the optimal insulation R-value for component 1 is 13 over the entire ground ratio range. For components 2 and 3, R-3 is the optimal level for GR = 90. An insulation resistance of 8 is specified for components 2 and 3, however, because the walls are required to have thermal resistances high enough to meet the HUD Minimum Property Standards. At the lower ground ratio of 80, the optimal insulation level for components 2 and 3 is R-8. It rises from R-8 to R-13 for these components when the ground ratio declines to 70. This shift in insulation levels increases the ground ratio savings at GR = 70 because the increased amount of insulation reduced the heat flow through components 2 and 3. It results in the discontinuity shown in the .251 curve between GR = 80 and GR = 70. Another break occurs between GR = 50 and GR = 40 in the same curve because the optimal component 2 and 3 insulation level changes from R-13 to R-19 when the ground ratio shifts from 50 to 40. The final break in the .251 curve is located

between GR = 10 and GR = 0 because the optimal component 2 and 3 insulation level rises from R-19 at GR = 10 to R-26 at GR = 0. The shape of the other curves illustrated in Figures 4.8 - 4.11 is explained in a similar way.

Ground ratio savings for each berm design are measured with respect to the fuel usage in the conventional case. Thus, when a conventional wall configuration is changed, in the grounding process, to a more heavily insulated berm configuration, positive ground ratio savings are possible at ground ratios of 90 and below. The high placement of the .501 curve in Figure 4.9 at all ground ratios between 90 and 0 is the result of increased thermal resistance of the component 1 wall due to grounding. The optimal insulation level for this wall area is R-13 in the conventional configuration and R-44 in all grounded configurations.[16/]

The savings resulting from the changing wall configuration are just one part of the total net savings formula for thermal wall designs. The other parts, which have been defined earlier, are combined with the ground ratio savings in the following manner to

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16/ Higher optimal levels of insulation are possible for component 1 walls in wall designs characterized by ground ratios of 90 and less because these walls can be thickened to accommodate greater levels of insulation with no cost penalty from floor area losses. See page 35 for the relevant thick wall cost formulas.

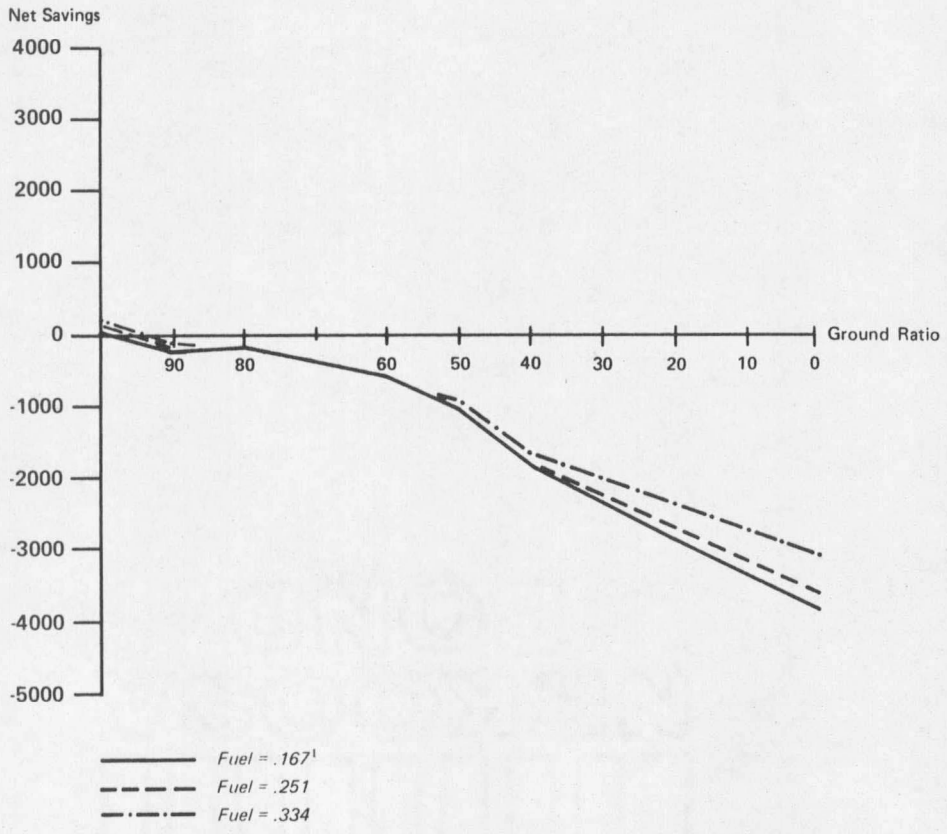
form the total net savings expression for insulation and the ground ratio: net savings = (ground ratio savings) - (ground ratio costs, which are the structural costs which arise when the wall configuration is changed) - (net excavation costs times the excavation cost ratio) - (net entrance costs times the entrance cost ratio) + (net savings from insulation).

Tables A.3 - A.24 show net savings realized under various constraints when the walls are optimally insulated and the ground ratio is varied from 100 to 0. Selection of the highest net savings level for each case serves to locate the cost minimizing ground ratio. Summary descriptions of the physical wall designs which yield the greatest net savings in Tables A.3 - A.24, are given in Summary Tables A.25 - A.42. These summary tables list, for each case, the optimal ground ratio and the insulation levels for the components at this ground ratio. (No listing is given in the components 2 and 3 column of these tables when GR = 100 because the component 2 and 3 wall area is 0.)

Figures 4.12 - 4.15, 4.17, 4.18, 4.20, 4.21, 4.26, 4.27, 4.31, and 4.32 are drawn for certain cases in Tables A.3 - A.24 to illustrate more clearly the findings. Without exception, at ground ratios below 60, the curves slope downward in all figures showing that the net savings of the wall designs selected in the figures monotonically decline with the ground ratio over the GR - 60 - 0 range. An evident

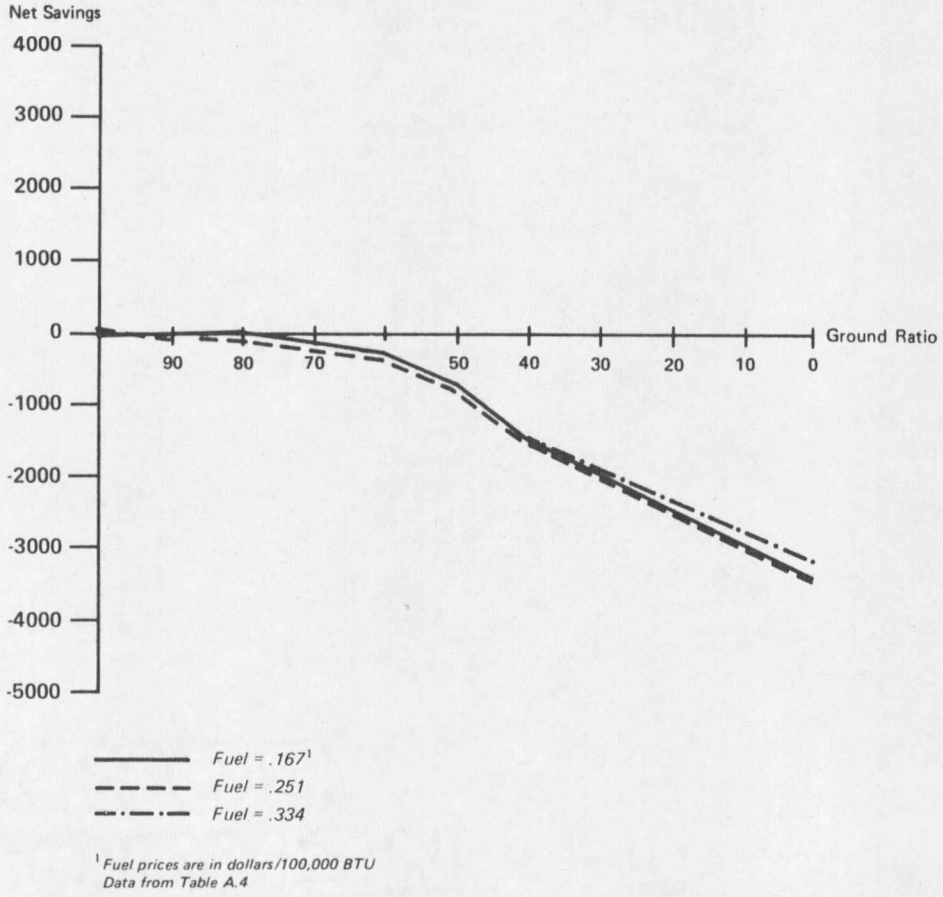
feature in many of the figures is the fairly flat or even upward humped shape of the net savings curves in the upper ground ratio range defined approximately by GR = 100 - 70. Net savings are reasonably constant over this range of wall configurations because the relative change in costs and benefits due to grounding are approximately equal, thus counterbalancing each other. A breakdown of the cost and savings elements of the net savings function is given for several examples further on in this section. A feature which is manifest in all these figures is the depressed portions of each curve which are evident at ground ratios of 40 or less. (This can most easily be seen by the increased negative slope which occurs in all curves between GR = 50 and GR = 40.) This additional loss is the result of an additional wall cost which depresses the net savings from wall configurations having a ground ratio of 40 or less. The source of this cost is the additional extenditures required to pour a concrete wall greater than 4 feet high. Thus, whenever the combined component 2 and 3 wall height exceeds 4 feet, which happens first at GR = 40, this additional cost depresses the net savings of the wall design.

Figures 4.12 and 4.13 were drawn for parallel cases in Tables A.3 and A.4. The differeneces in identically labeled curves in the two figures are the result of the different net savings for total wall units which utilize urethane insulation versus those which use fiberglass insulation.



[1] *Fuel prices are in dollars/100,000 BTU*
Data from Table A.3

Figure 4.12 Functional Dependency of Net Savings on the Ground Ratio and on the Fuel Price. (Fiberglass Insulation is Used.)



[1] *Fuel prices are in dollars/100,000 BTU*
Data from Table A.4

Figure 4.13 Functional Dependency of Net Savings on the Ground Ratio and on the Fuel Price. (Urethane Insulation is Used.)

At the fuel prices illustrated in Figures 4.12 and 4.13, the net savings generated by wall configurations employing optimal levels of urethane exceed those from comparable designs insulated with optimal amounts of fiberglass at all ground ratios of 90 and below.[17] When the fuel price is .167 this difference amounts to $220.58 to $504.34 over the lifetime of the wall. At the higher fuel prices of .251 and .334, savings from the urethane design exceed those from fiberglass by $103.81 to $361.42 and $57.67 to $284.75, respectively. These results are illustrated in the figures by the higher placement of the Figure 4.13 curves, with respect to those in Figure 4.12. Fiberglass insulation generates greater net savings than urethane in conventional wall designs as is shown in the figures and in the GR = 100 columns of Tables A.3 and A.4.

For the four fuel prices examined in Tables A.3 and A.4, the least reduction in net savings resulting from the downward shift in the ground ratio from 100 to 0 occurs at the highest fuel price, and the largest reduction generally occurs at the lowest fuel prices. This observation suggests that wall configurations designed to utilize the thermally insulative properties of the soil may become increasingly attractive as fuel prices rise. For both insulation types, two factors

[17] If GR = 0 and the fuel price is .334, savings from the fiberglass design exceed those from the urethane counterpart by $18.46.

influence this trend in net savings:

1. Ground ratio savings which measure the change in the overall fuel cost load which results when the wall configuration is changed, generally decline for the higher fuel prices illustrated in Figure 4.13, for example. This trend can be seen best in the .167 curve of Figure 4.10 and in the .334 curve of Figure 4.11. These curves shift downward when the fuel price is raised because the total thermal load on all wall configurations having a GR of 90 or less is greater than it is for conventional construction, which is the point of reference for ground ratio savings.

2. Ground ratio costs for a given wall configuration increase for some higher fuel prices. These costs, which reflect the change in the overall cost of the living wall unit due to modifications in its component areas caused by the downward shift of the ground ratio from 100, are lowest for the .167 fuel price. For this fuel price, at GR = 0, ground ratio costs for the urethane insulated design result from the addition to the living wall structure of the 1062.6 square feet of component 2 and 3 area having two layers of R-5.56 insulation and costing $4.8592/sq.ft. and from the elimination of 956.8 square feet of component 1 area having two layers of R-5.56 of insulation and costing $3.0700/sq. ft. When the fuel price is .251 and GR = 0, these costs are

based on the 956.8 square feet of component 1 wall having two layers of R-5.56 insulation and costing $3.0700/sq.ft. which is eliminated from the wall structure when the ground ratio is shifted to 0 and on the 1062.6 square feet of component 2 and 3 wall having three layers of R-5.56 insulation and costing $5.3191/sq/ft. which is added to the structure. At the fuel price of .334 ground ratio costs result from the 956.8 square feet of component 1 area containing three layers of R-5.56 insulation and costing $3.4300/sq.ft. which is eliminated from the wall design due to the downward shift of the ground ratio from 100 to 0 and from the 1062.6 square feet of component 2 and 3 wall having three layers of R-5.56 insulation and costing $5.3191/sq.ft. which is added to the wall structure. Also included in ground ratio costs is a term which credits the dollar outlays made for concrete foundation walls in the conventional wall design to the component 2 and 3 areas of the various berm wall designs. The amount of this credit is dependent only on the ground ratio. It is not influenced by the optimal insulation levels of the component 2 and 3 wall. At GR = 0 the dollar value of this term is $933.51. A less technical description of ground ratio costs is given on page 142 in the upcoming discussion of net savings from wall configurations having reduced heat losses through the soil. See page 45 for the definition of ground ratio

costs.

These two factors account for the similarity of the net savings levels at all fuel prices which is illustrated in Figure 4.13. They are strong enough to reduce the effect of the increased net savings from insulation which results from the higher fuel prices. (See Figure 4.7 and lines 1, 3, and 5 of Table 4.14 for the net savings from insulation in these cases.)

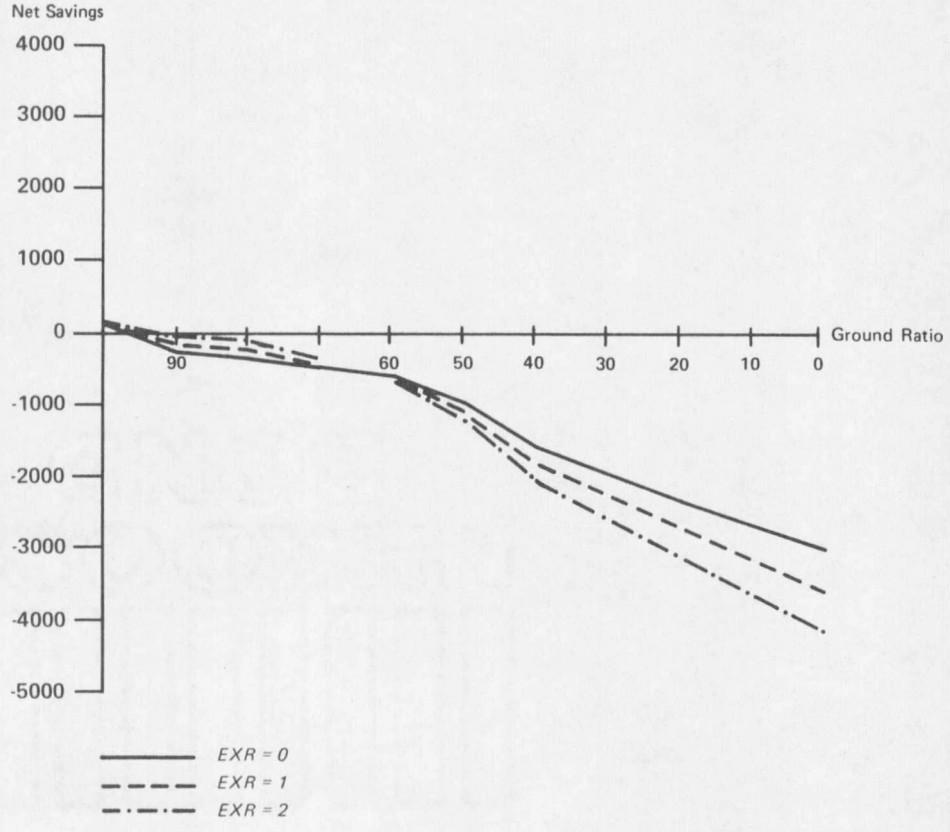
A comparison of lines 1, 3, and 5 of Table A.4 with line 7 of the same table will show that the above illustrated trend in net savings is strengthened at the fuel price of .501 so that losses are not as great as at the lower fuel prices. The reason is the net savings from insulation is much greater at this fuel price. (See Table 4.14.) These increased savings are partly the result of higher insulation levels being optimal. Ground ratio costs are also higher at this fuel price than at any of the lower prices, due to the higher levels of insulation, but these costs do not outweigh the additional savings.

The trends illustrated in Figure 4.12 reflect underlying factors which are similar to those explained for Figure 4.13. Therefore, the above discussion is useful in describing the curve shifts shown in this figure also.

In conclusion, the net savings of the various wall configurations

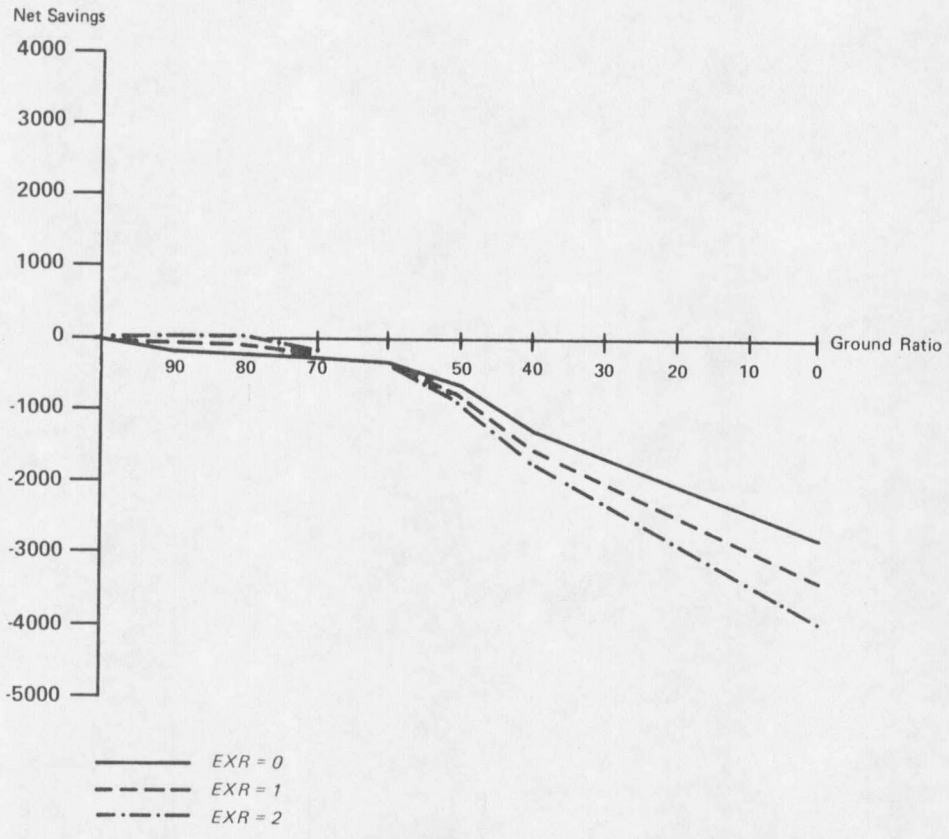
are sensitive to fuel prices but because of ground ratio savings, ground ratio costs, and net savings from insulation, no strong overall trend was evident for the fuel price range tested. Wall configurations insulated with urethane had generally higher net savings than their fiberglass counterparts at all ground ratio levels of 90 and below when the fuel price was in the .167 to .334 range. At the fuel price of .501, fiberglass insulated walls generated greater net savings than urethane designs.

Figure 4.14 shows the sensitivity of net savings to differing values of the excavation cost ratio when the fuel price is .251 and the insulation is fiberglass. Figure 4.15 describes the same cases as Figure 4.14 with one difference: the insulation is urethane. The overall shape of the curves in both figures is defined by factors described earlier. The generally widening distance between adjacent curves which occurs with the declining ground ratio, is the result of differing excavation (and backfill) costs, as the consumer sees them. The twist in the net savings curves plotted in both figures occurs because excavation costs for each grounded configuration are computed with reference to the excavation cost required in the conventional wall design. (See page 49 .) At ground ratios of 90 - 70, less excavation is required than in the conventional case where the excavation for the crawl space and the footings goes two feet below



Data from Table A.5

Figure 4.14 Functional Dependency of Net Savings on the Ground Ratio and on the Excavation Cost Ratio.(The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used.)



Data from Table A.6

Figure 4.15 Functional Dependency of Net Savings on the Ground Ratio and on the Excavation Cost Ratio. (The Fuel Price is $.251/100,000 BTU. Urethane Insulation is Used.)

grade. Thus, at these ground ratios the net excavation cost is negative which results in greater net savings at excavation cost ratios of 1 and 2. The set of net excavation costs, for the excavation cost ratio (EXR) of 1, is given in Figure 4.16. For clarity they were plotted on a reversed vertical scale so that their influence on the overall net savings levels shown in Figures 4.14 and 4.15 could more easily be seen. In this particular case excavation costs account for the shift in the net savings curves from EXR = 0 to EXR = 1 and EXR = 2 in Figures 4.14 and 4.15. See page 54 for an explanation of cost ratios.

The response of net savings to changing values of the entrance cost ratio is plotted in Figures 4.17 and 4.18. As before Figure 4.17 is for fiberglass while Figure 4.18 is for urethane insulation. In both cases the fuel price is .251. The gap between curves in these figures is a function of the ground ratio in a very similar manner to the cases described in Figures 4.14 and 4.15. The plot of entrance costs measured with respect to the conventional configuration is given in Figure 4.19. The case illustrated is for an entrance cost ratio of 1. Again, a reversed vertical scale is used as in Figure 4.16.

In summary, Tables A.5 - A.8 show the effect of consumer evaluations to two structural changes -- namely the placement of each wall configuration in relationship to the ground level and the entryway

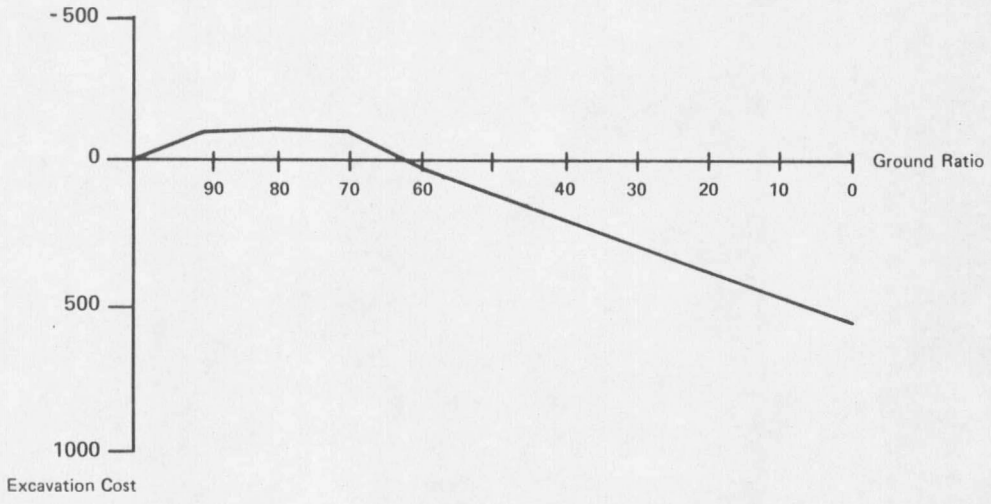
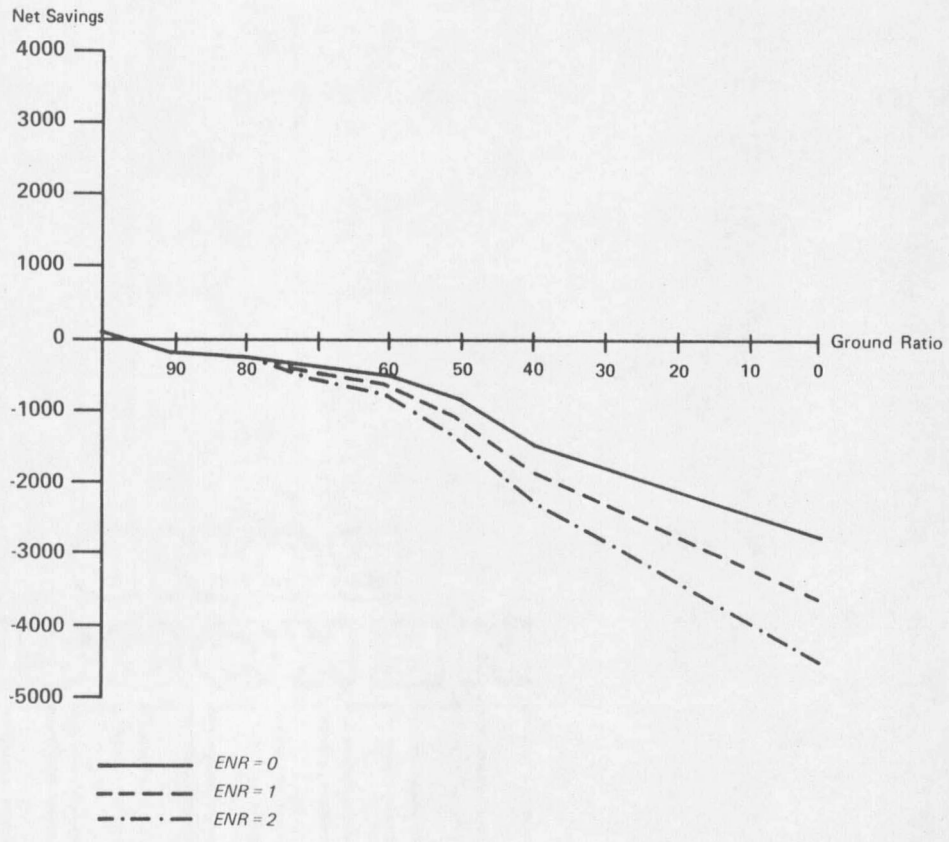
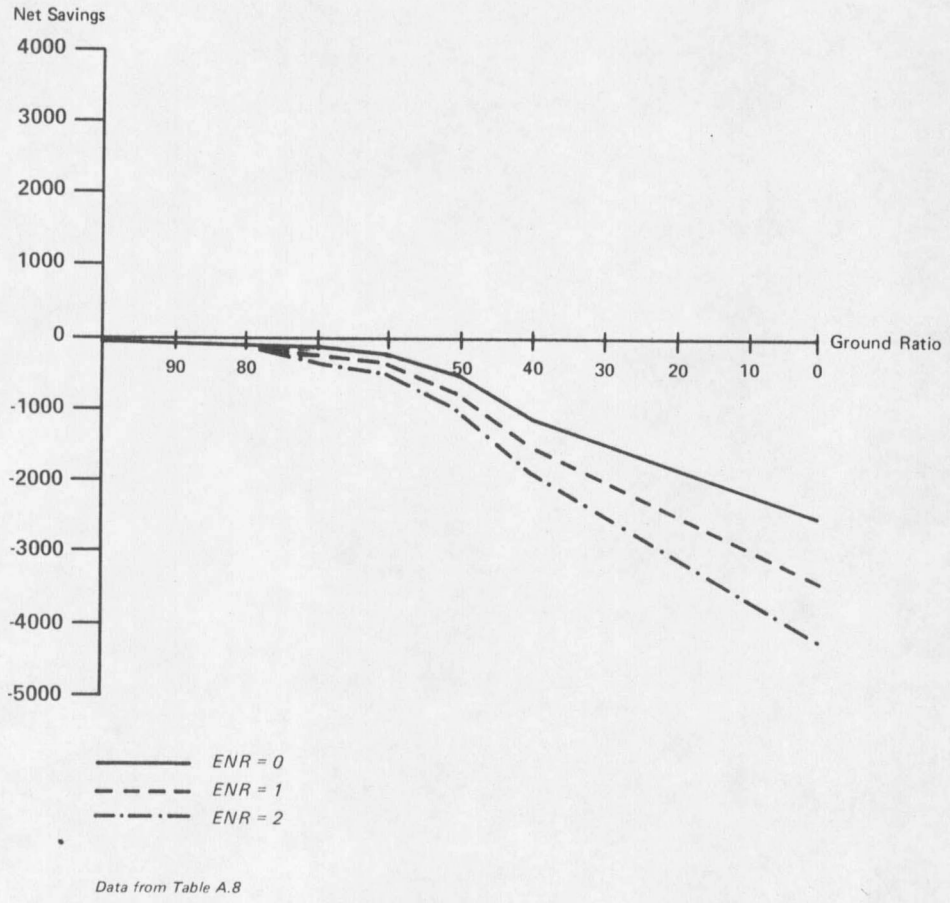


Figure 4.16 Functional Dependency of Net Excavation Costs on the Ground Ratio when the Excavation Cost Ratio is 1.



Data from Table A.7

Figure 4.17 Functional Dependency of Net Savings on the Ground Ratio and on the Entrance Cost Ratio. (The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used.)



Data from Table A.8

Figure 4.18 Functional Dependency of Net Savings on the Ground Ratio and on the Entrance Cost Ratio. (The Fuel Price is $.251/100,000 BTU. Urethane Insulation is Used.)

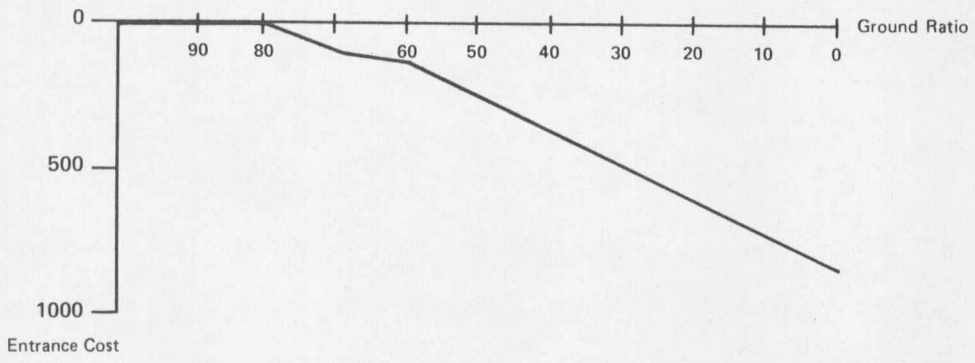


Figure 4.19 Functional Dependency of Net Entrance Costs on the Ground Ratio when the Entrance Cost Ratio is 1.

design required by each configuration. The major trends in this sensitivity analysis were outlined in Figures 4.14, 4.15, 4.17, and 4.18. In all cases the wall configurations have the greatest net savings when the apparent cost to the consumer for these two structural changes is the least.

The trends shown in Figures 4.12 - 4.15, 4.17 and 4.18 involved permutations in fuel prices, insulation type, and consumer preference to different structural designs. During that analysis simulated thermal loads on the components were calculated by the ASHRAE procedure. HUD Minimum Property Standards for wall insulation were also assumed to be met. In the remainder of this section, these two assumptions are relaxed in order that the conclusions may be examined over a broader range of possibilities. Figures 4.20, 4.21, 4.26, 4.27, 4.31 and 4.32 summarize the findings.

In order to investigate more thoroughly the net savings of different wall configurations, thermal loads having different emphasis were placed on the wall components. The purpose in such was to simulate different balances in the overall above ground and below ground thermal loads than would be considered using common steady state engineering procedures. The application of these variable loads also served a purpose of revealing soil characteristics at which wall configurations other than those of conventional design would be

worthwhile investments. In all cases the component heat load balance was varied by changing the equivalent temperature difference across the component 3 wall - soil combination.[18] Only reduced heat flows were considered as only in such cases was there any possibility of demonstrating sizable positive net savings for wall configurations having a ground ratio less than 100.[19] Insulation levels used in this analysis were optimized for each level of heat flow.

From Figures 4.20 and 4.21 it is clear that wall configurations optimized for reduced component 3 heat loads will yield greater net savings, when used with these reduced loads, than those configurations which are designed for, and used with, the full component 3 heat load estimates recommended by ASHRAE. However, for the heat loads tested, significant losses are still shown for all wall configurations having a ground ratio of 90 or less. Such findings suggest the possible

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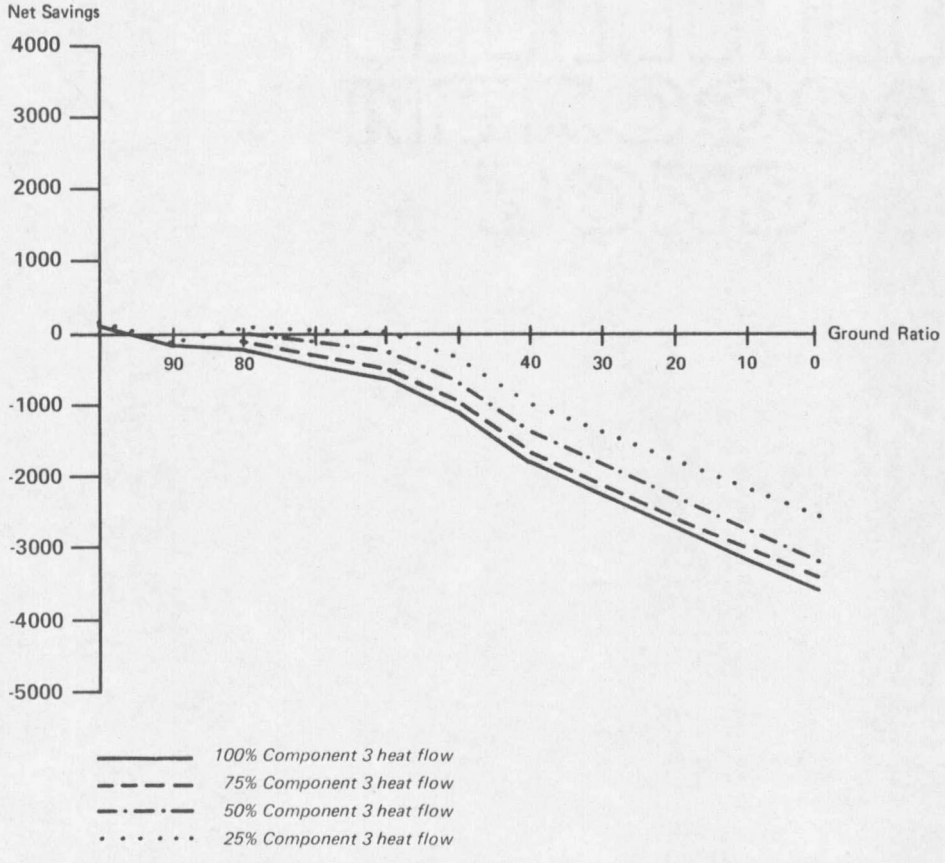
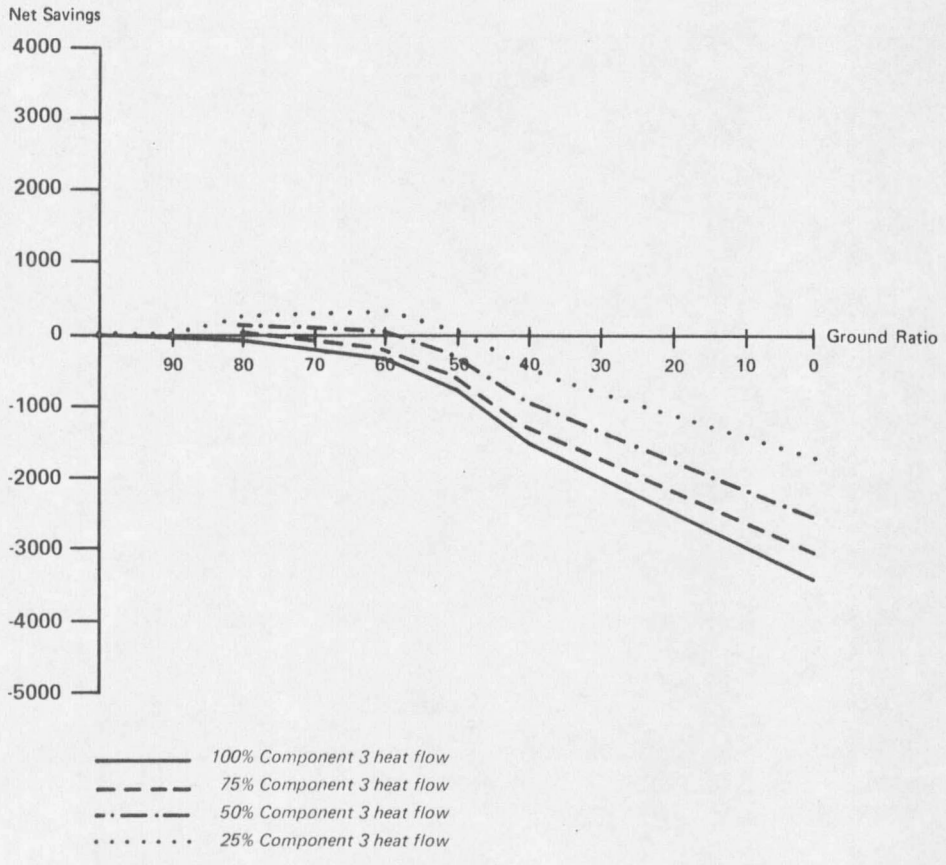
[18] The ASHRAE simulated temperature drop across the below ground wall for all heating days was 61°F for the Bozeman, Montana climate where the ground water was 42°F and the inside wall temperature was 75°F (1, p.377). Halving this temperature difference would effectively halve the component 3 heat load. For further discussion on the ground water temperature, see Footnote No. 39 in Appendix B.

[19] The terminology used to describe reduced component 3 heat flows involved percentages. Thus, a 100 percent component 3 heat flow is equivalent to engineering standards as set forth in the ASHRAE Handbook of Fundamentals for below ground concrete walls enclosing a heated space (1, p. 378). A 50 percent component 3 heat flow means the below grade wall loss through the concrete walls surrounding a heated space is one-half of that calculated by ASHRAE procedures.



Data from Tables A.9, A.10, A.11, and A.12

Figure 4.20 Functional Dependency of Net Savings on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used.)



Data from Tables A.13, A.14, A.15, and A.16

Figure 4.21 Functional Dependency of Net Savings on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Urethane Insulation is Used.)

benefits from improved thermal performance in berm wall designs are more than offset by the added cost of such a design. As the net savings of each wall configuration is determined by the relationship, net savings = (ground ratio savings) - (ground ratio costs) - (net excavation costs) - (net entrance costs) + (net savings from insulation) the response of each factor in this formula to a changing thermal load must be examined before the curve shifts shown in Figures 4.20 and 4.21 can be explained. Following is a breakdown showing the influence of each factor on net savings:

1. Ground ratio savings (GRS) are a measure of the changes in fuel expenditures which result as the wall configuration is changed.[20] Figures 4.22 and 4.23 describe the GRS functions for the four heat flow cases in each of the examples. The upward shift of this function for each decline in component 3 heat flow is the result of the decreased thermal load on the wall structure. The amount of the shift corresponds to the resulting decrease in fuel expenditures. This change is the primary cause for the increase in net savings shown in Figures 4.20 and 4.21 for each reduction in heat flows. For an explanation of the characteristic shape of the

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[20] A negative ground ratio savings value implies losses resulting from increased fuel use.

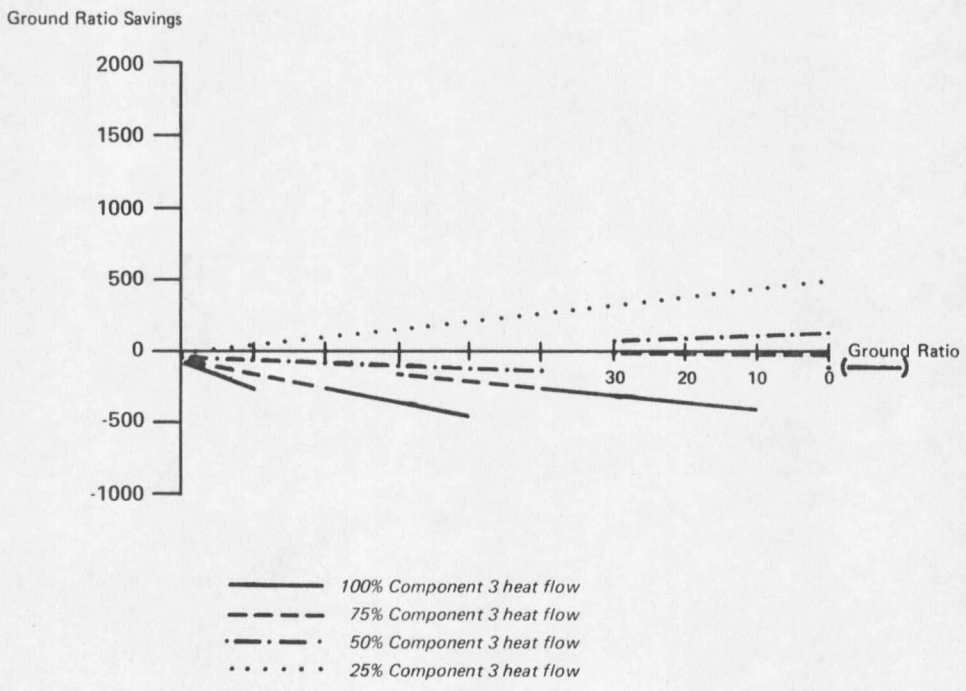
ground ratio savings curves illustrated in these figures, see page 114.

2. Ground ratio costs reflect the dollar change in the wall structure which results as the ground ratio is shifted downward. For a "half buried" residence, ground ratio costs are defined as the additional construction cost for optimally insulated wall areas and foundation systems in the GR = 50 design over the cost of walls and foundations of conventional design. The following dollar amounts illustrate these costs in the GR = 50 configurations of Figures 4.20 and 4.21:

$441.28 is the ground ratio cost for fiberglass insulated walls if the component 3 heat flow is 100 percent or 75 percent of engineering estimates. In this case R-13 is optimal for components 1, 2, and 3.

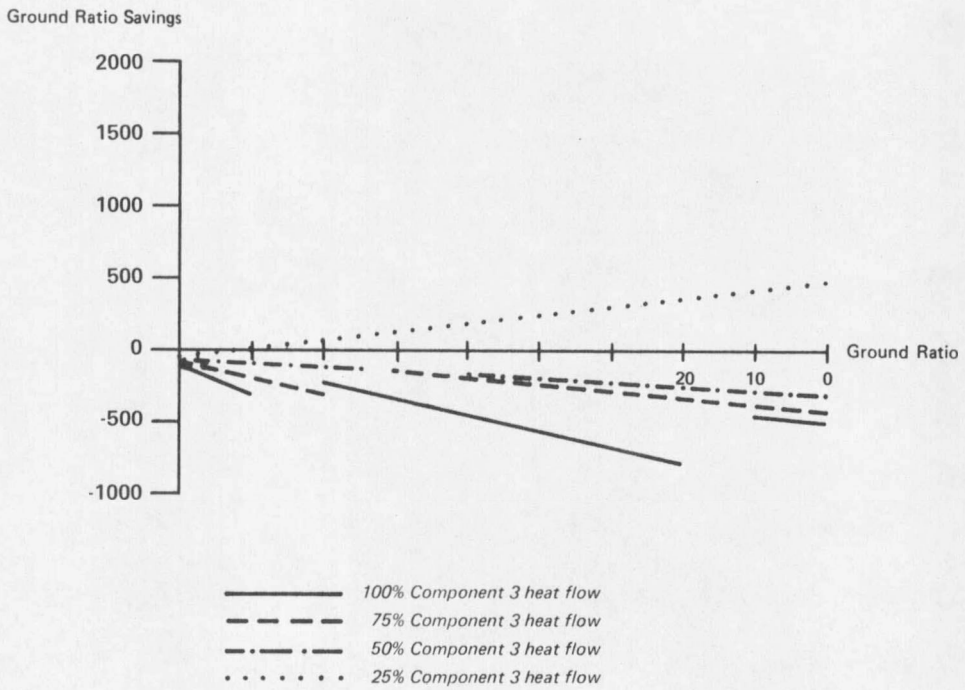
$246.01 is the ground ratio cost for fiberglass insulated walls if the component 3 heat flow is 50 percent or 25 percent of engineering estimates. In this case, R-13 is optimal for component 1 and R-8 is optimal for components 2 and 3.

$34.40 is the ground ratio cost for urethane insulated walls if the component 3 heat flow is 100 percent or 75 percent of engineering estimates. In this case, two layers having a total R-value of 11.12 are optimal for components 1, 2,



Data from Tables A.43, A.44, A.45, and A.46

Figure 4.22 Functional Dependency of Ground Ratio Savings on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used.)



Data from Table A.47, A.48, A.49, and A.50

Figure 4.23 Functional Dependency of Ground Ratio Savings on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Urethane Insulation is Used.)

and 3.

-$292.13 is the ground ratio cost for urethane insulated walls if the component 3 heat flow is 50 percent or 25 percent of engineering recommendations. In this case, two layers (R-11.12) are optimal for component 1 and one layer (R-5.56) is optimal for components 2 and 3.

Thus, for example, at GR = 50 when the component 3 wall loss is 100 percent and 75 percent of the estimated recommended by ASHRAE and urethane insulation is used, ground ratio costs depress the 100 percent and 75 percent net savings curves in Figure 4.21 by $34.40. Ground ratio costs also contribute to the shifts which are shown between the 100 and 75 percent and the 50 and 25 percent curves in this figure. The reason is that the optimal component 2 and 3 insulation level is R-11.12 when the component 3 heat flow is 100 or 75 percent of engineering estimates, and R-5.56 for all lower heat flows. Thus ground ratio costs are least (-$292.13) in the 50 percent and 25 percent heat flow cases -- depressing those net savings by the smallest amount.

3. Excavation and Entrance costs alter the net savings shown in Figure 4.20 and 4.21 for each wall configuration. Figures 4.16 and 4.19 show their magnitude as they are applied in this example. These costs are a constant for each heat flow case, so they are not responsible for the upward shifts in the net savings curves

which result from the reduced heat flows. The origin of such shifts lies primarily with ground ratio savings and insulation net savings.

4. Net savings from insulation for each wall configuration decline when the thermal load faced by the living wall unit is reduced. The reason for the reduced return on insulation investment is that the savings derived from each increment decline with the thermal load and because fewer increments are optimal in some cases. Thus, net savings from insulation for reduced thermal loads depress total wall configuration net savings. Figures 4.24 and 4.25 demonstrate their role in the overall placement of the curves in Figures 4.20 and 4.21.

The results presented in Tables A.9 - A.16 and summarized here suggest that the costs incurred in constructing wall configurations which utilize the thermal properties of the soil frequently outweigh the benefits derived from such a wall design even when reduced fuel usages do result. These findings are based on a wide range of soil conditions, which broadly altered the thermal balance across the components. In all cases net savings were shown to be less for "deeply bured" designs, defined by a ground ratio below 50, than for conventional configurations. More detail is given on the findings in Summary Tables A.31 - A-38 which list the insulation and ground ratio specifications for the optimal net savings situations in Tables A.9 - A.16.

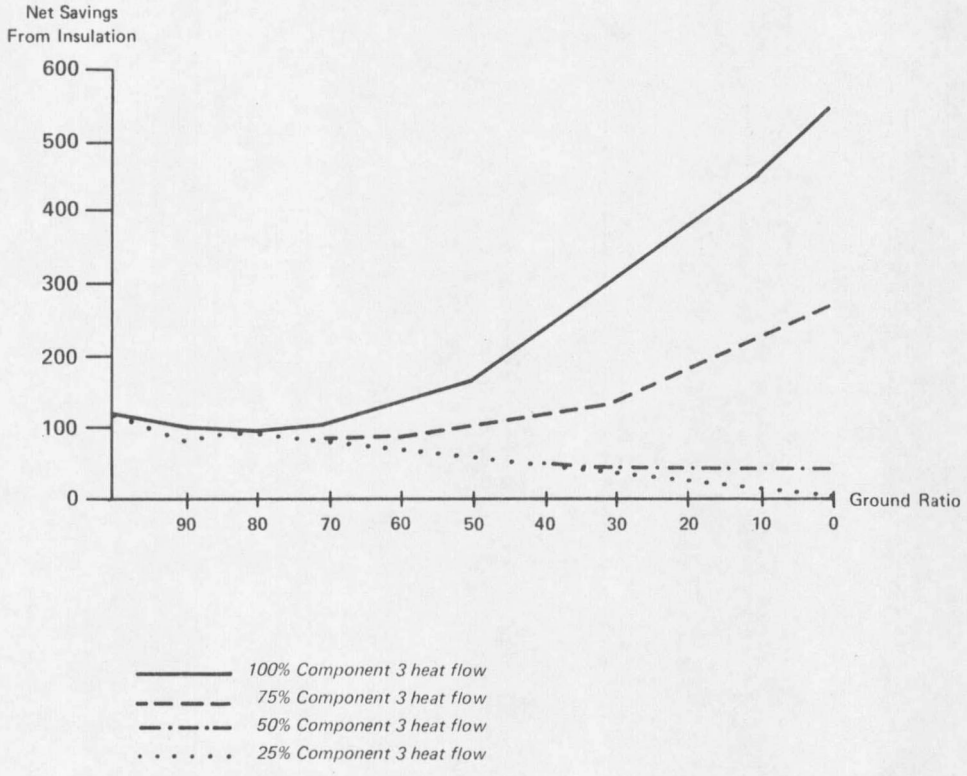


Figure 4.24 Functional Dependency of Net Savings from Insulation on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used.)

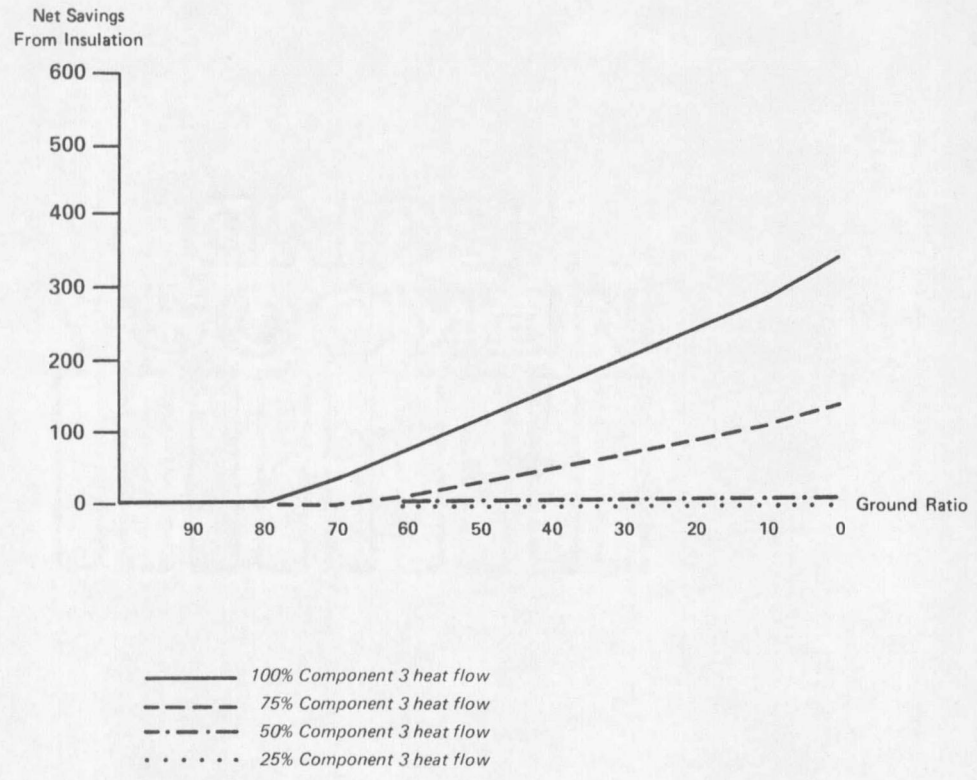
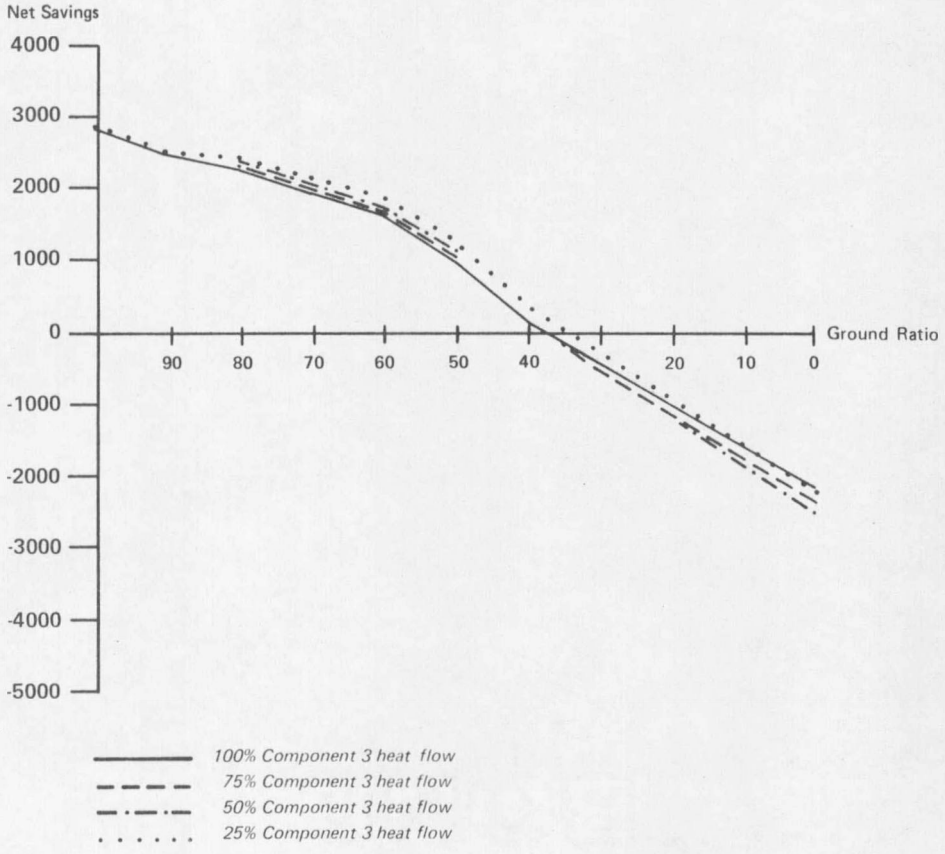


Figure 4.25 Functional Dependency of Net Savings from Insulation on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Urethane Insulation is Used.)

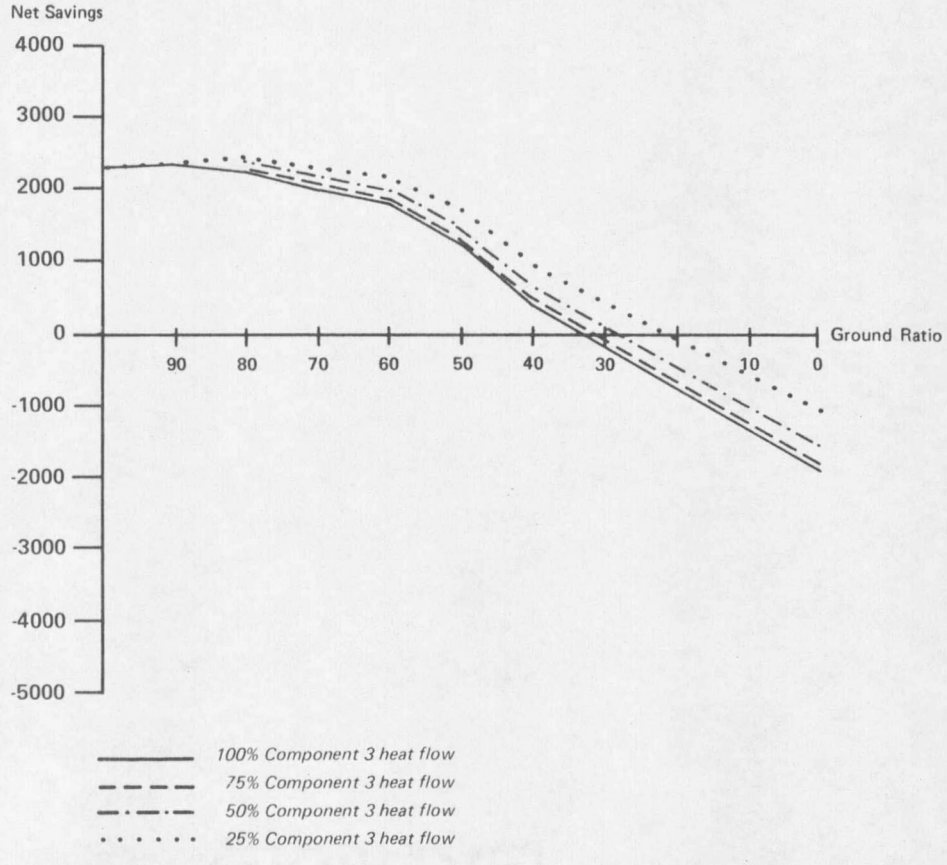
All findings presented so far have shown maximum net savings from a specific configuration when the fuel price and consumer preferences are predetermined and the HUD Minimum Property Standards for the thermal properties of the walls are assumed to be met. The purpose in starting from the MPS Standards was to provide a point of reference typical of modern construction from which net savings from varying wall designs could be compared. Such a requirement also helped identify the source of and quantify the magnitude of losses and gains resulting from specific structural modifications to a wall meeting these standards. In the following analysis, this constraint is dropped so that the total return of all thermal modifications to the wall structure can be appraised. The results are presented in Tables A.17 - A.24 and summarized in Figures 4.26, 4.27, 4.31 and 4.32.

Figures 4.26 and 4.27 show the net savings recoverable from each wall configuration when the fuel price is .251 and the component 3 heat flow is varied downward. The amounts shown are with reference to zero insulation as the MPS restrictions are dropped. Conclusions which can be drawn from these illustrations are generally applicable to other fuel prices, even to the approximate placement and slope of the curves. Figures 4.26 and 4.27 are to be compared to Figures 4.20 and 4.21 respectively, as the latter figures describe identical cases with the exception of the MPS requirement. Following is a list describing the change in each factor making up the total net savings



Data from Tables A.17, A.18, A.19, and A.20

Figure 4.26 Functional Dependency of Net Savings on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used. No Minimum Property Standard Requirements are Imposed for Thermal Response.)



Data from Tables A.21, A.22, A.23, and A.24

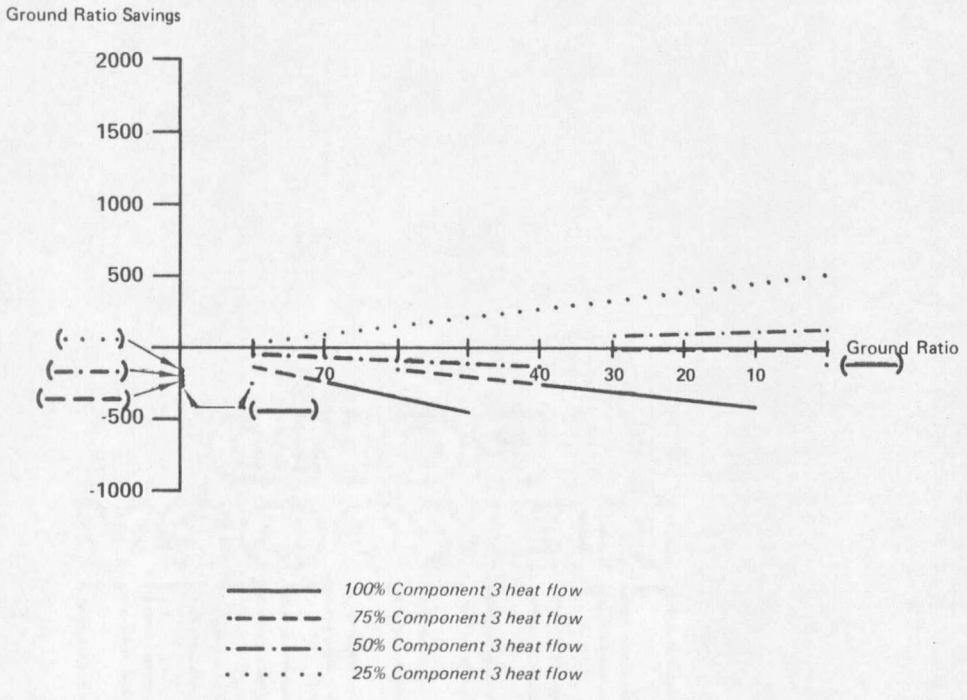
Figure 4.27 Functional Dependency of Net Savings on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Urethane Insulation is Used. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

formula due to the dropping of this constraint:

1. Ground ratio costs for fiberglass insulated walls are unchanged except at GR = 90 where they are lower because the MPS requirement of R-8 insulation does not have to be met for component 2 and 3 wall areas. Thus, in all heat flow cases shown in Figure 4.26, at GR = 90 the component 2 and 3 insulation level is R-3. Urethane insulation levels are unchanged when the MPS constraint is dropped. Thus, the corresponding ground ratio costs for the urethane designs illustrated in Figure 4.27 are the same as they were for the example illustrated in Figure 4.21.

2. Net excavation and entrance costs are unchanged by the dropping of the thermal requirement for the walls set forth in the HUD MPS.

3. Ground ratio savings for fiberglass wall designs reflect the lower insulation levels in the component 2 and 3 wall areas at GR = 90 by being more negative at that point. (The HUD Standard required more insulation than was optimal at this ground ratio.) Figure 4.28 describes the resulting GRS function. The additional discontinuous portions in it, in comparison to its Figure 4.22 counterpart, arise from the optimal insulation level for component 2 and 3 shifting from R-3 to R-8 as the ground



Data from Tables A.51, A.52, A.53, and A.54

Figure 4.28 Functional Dependency of Ground Ratio Savings on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

ratio declines from 90 to 80. No change took place in the ground ratio savings function for urethane insulated walls because those insulation levels are unchanged when the MPS constraint is dropped. Therefore the GRS curves drawn in Figure 4.23 are applicable to this example.

4. Net savings from insulation move dramatically upwards as a comparison of Figure 4.29 with Figure 4.24 and Figure 4.30 with Figure 4.25 shows. The reason is that the first levels of insulation always have a higher net savings than have succeeding levels because the majority of the heat flow is stopped in them.[21] The increase in net savings from insulation came from the different point of reference from which the savings were counted. An illustration as to how insulation net savings are defined when the Minimum Property Standard requirement is imposed is given in the following three cases:

   1) In the event that the optimal increment is less than that required by HUD to meet its standards, the net savings from insulation is a loss amounting to the difference between the cost incurred in installing those levels of insulation which exceed

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[21] Decreasing energy savings are generated with each additional unit of resistance which is added to a wall structure because the amount of energy which passes through a section of insulation varies as the reciprocal of its thickness.

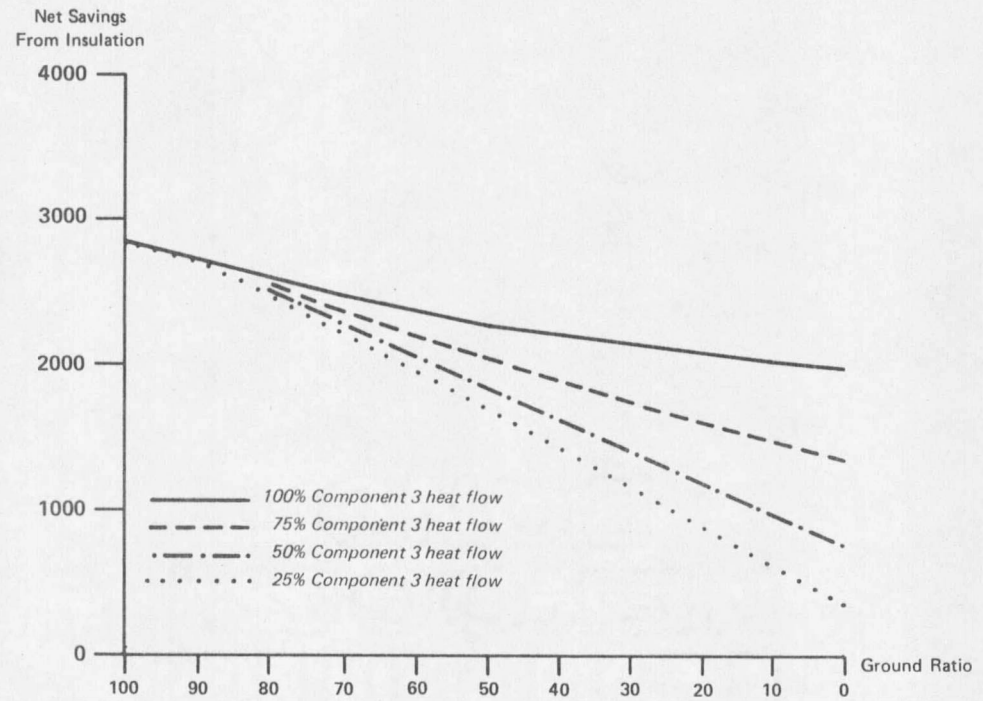


Figure 4.29 Functional Dependency of Net Savings from Insulation on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

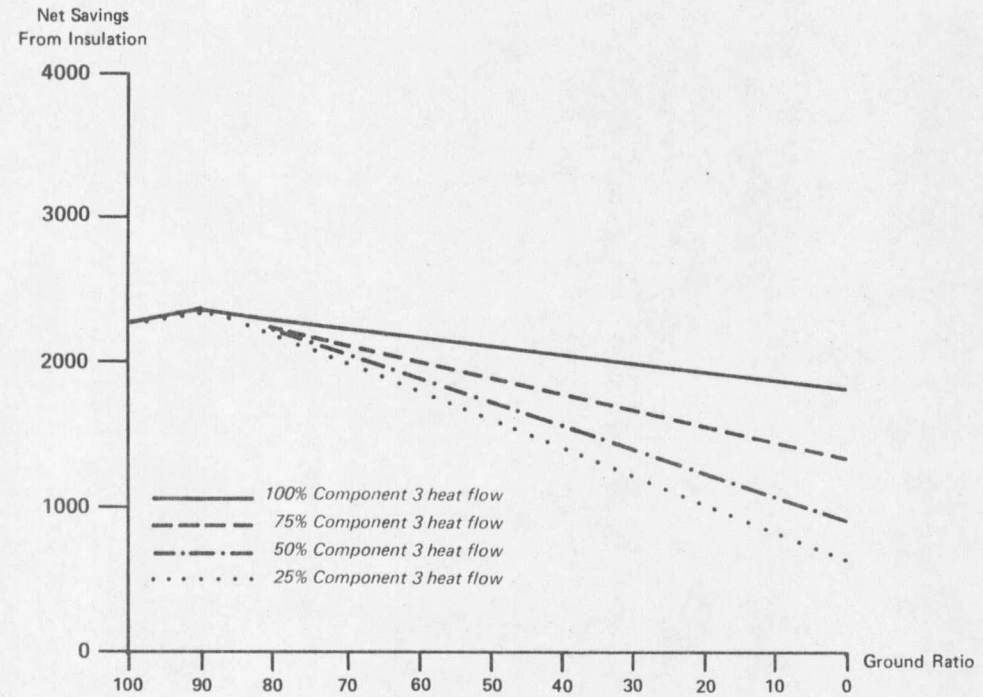


Figure 4.30 Functional Dependency of Net Savings from Insulation on the Ground Ratio and on the Component 3 Heat Load. (The Fuel Price is $.251/100,000 BTU. Urethane Insulation is Used. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

the optimal level but are required by the HUD Standard, and the present value of the stream of savings generated by these levels.

2) If the optimal increment equals the HUD requirement, the insulation net savings is zero.

3) In the cases where the optimal level exceeds that specified by HUD, net savings from insulation are calculated from the total savings minus total cost relationship for the levels beyond those so specified.

With the elimination of these restrictions, net savings were calculated relative to zero levels of insulation.

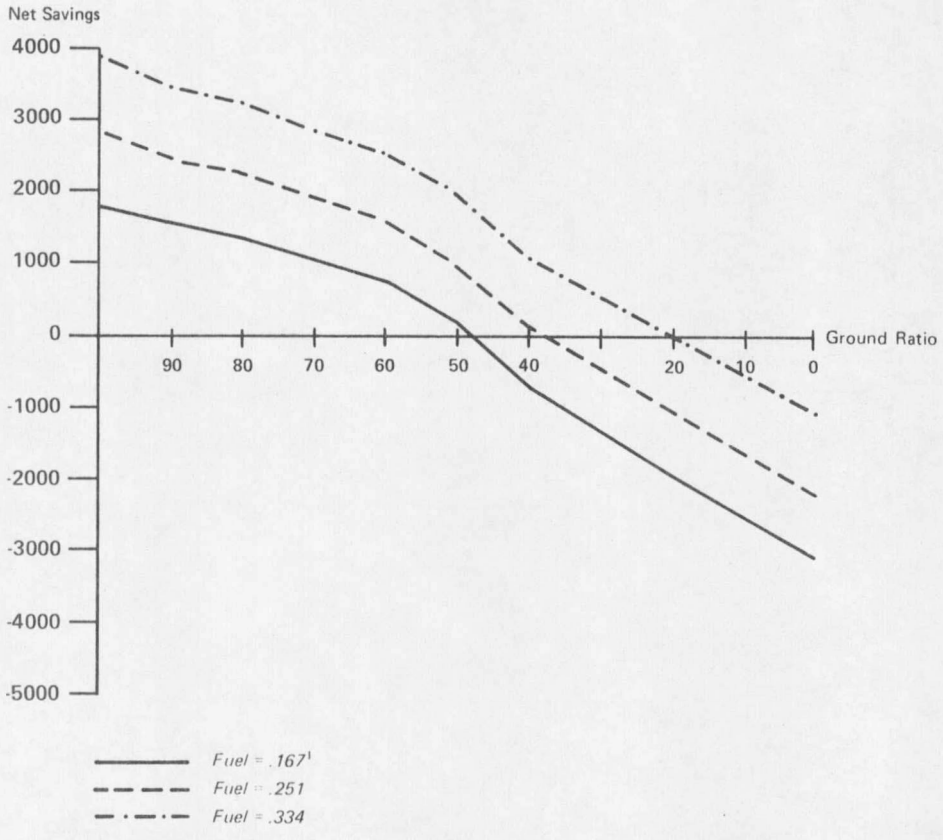
The combined effect of these factors results in the overall shape of the curves and the curve shifts shown in Figures 4.26 and 4.27. Here as before, the optimum wall structures, according to cost minimizing criterion, are the conventional and the "mostly above ground" designs. This conclusion also applies to the other fuel prices tested. Exact net savings for all cases are presented in Tables A.17 - A.24. Summary descriptions of the net savings optimizing wall structures are listed in Tables A.31, A.32, and A.39 - A.42.

The results of a sensitivity analysis of net savings from different wall configurations to fuel prices when the HUD MPS constraint is relaxed is given below. A parallel presentation to this was completed earlier in this section. That analysis, which involved Figures 4.12 and 4.13,

was a summary of the sensitivity of net savings from different wall designs to three fuel prices when the HUD Standards were used to define the minimum levels of insulation in each wall design. The results from the current analysis are presented in Figures 4.31 and 4.32 and in Tables A.17 and A.21.

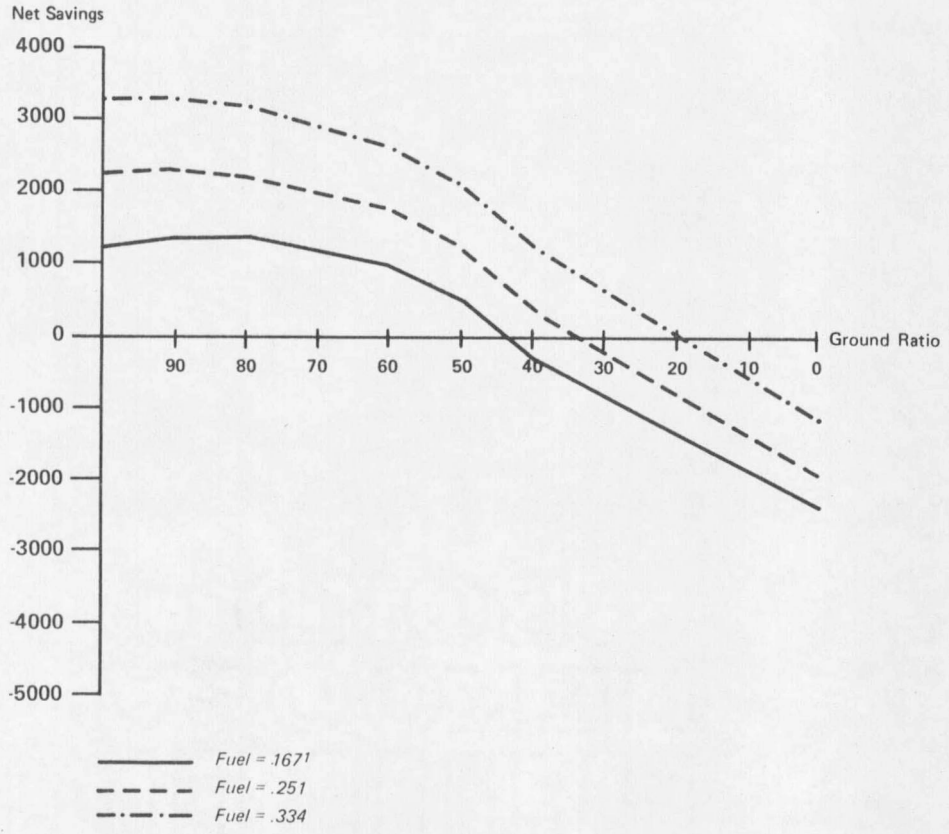
Using the graphs in Figures 4.12 and 4.13 as references, two differences in the curves drawn in Figures 4.31 and 4.32 stand out. The first is the positive net savings shown for the higher ground ratio configurations. The second noteworthy change between the curves in the four figures, is the appearance in Figures 4.31 and 4.32 of a stronger trend towards greater net savings at the higher fuel prices. Both differences are largely the result of changes in the net savings from insulation. Insulation net savings at the .167, .251, and .334 fuel prices are shown in Figures 4.33 and 4.34.

From Figures 4.31 and 4.32, the conclusion can be drawn that wall configurations designed to utilize the thermal resistance inherent in the soil do not become increasingly attractive as the fuel prices rise. This can be seen from the slope of the net savings curves in the two figures which show that the least reduction in net savings resulting from grounding occurs at the lowest fuel price and the greatest reduction generally occurs at the highest fuel price. See Tables A.17 and A.21 which show net savings for the different wall designs at all four fuel prices, including .501, for further information on this



[1] Fuel prices are in dollars/100,000 BTU
Data from Table A.17

Figure 4.31 Functional Dependency of Net Savings on the Ground Ratio and on the Fuel Price. (Fiberglass Insulation is Used. No Minimum Property Standard Requirements are Imposed for Thermal Response.)



[1] *Fuel Prices are in dollars/100,000 BTU*
Data from Table A.21

Figure 4.32 Functional Dependency of Net Savings on the Ground Ratio and on the Fuel Price. (Urethane Insulation is Used. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

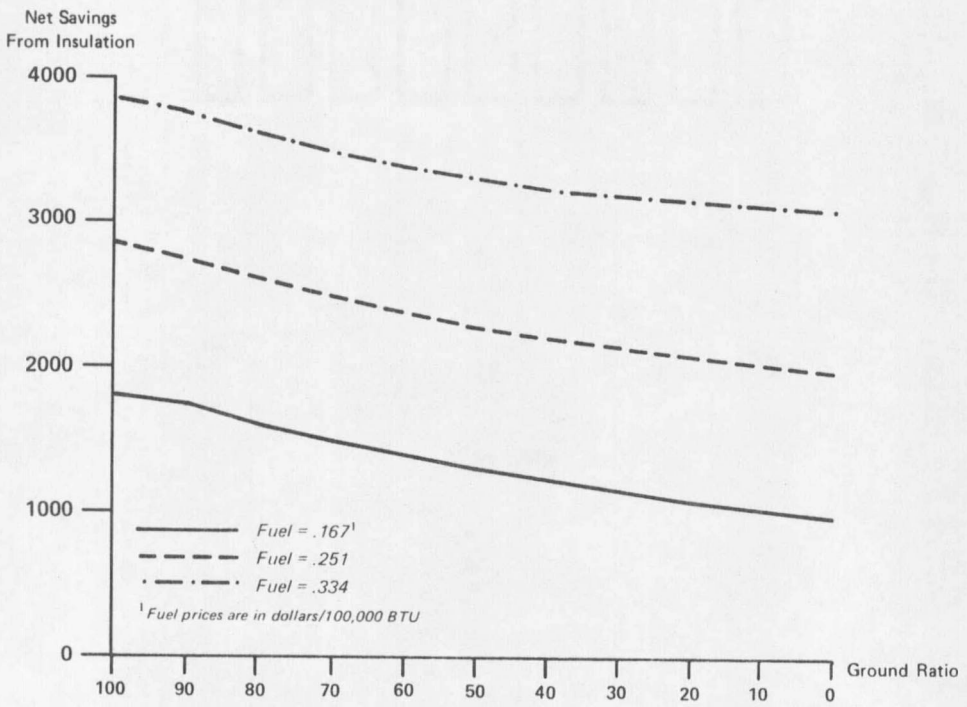


Figure 4.33 Functional Dependency of Net Savings from Insulation on the Ground Ratio and on the Fuel Price. (Fiberglass Insulation is Used. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

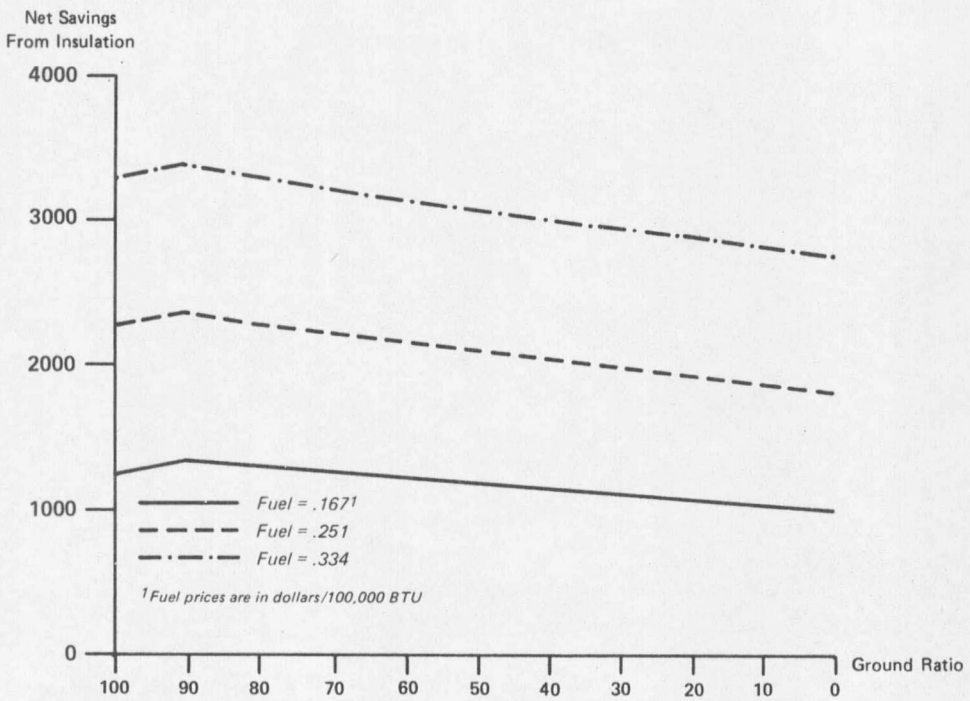


Figure 4.34 Functional Dependency of Net Savings from Insulation on the Ground Ratio and on the Fuel Price. (Urethane Insulation is Used. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

trend. These results refute those for the parallel cases shown in Figures 4.12 and 4.13 and in Tables A.3 and A.4. There a small increase in the attractiveness of grounding as a function of fuel price rises was seen, as evidenced by the decreasing negative slope of the net savings curves. The large upward shifts of the net savings curves of Figures 4.31 and 4.32 at the higher fuel prices are the result of the increased net savings from insulation. These shifts were much smaller in the parallel net savings curves plotted in Figures 4.12 and 4.13. The reason for the difference between the curves illustrated in Figures 4.12 and 4.13 and those shown in Figures 4.31 and 4.32 is that in Figures 4.31 and 4.32 net savings are derivable from optimal thermal modifications to the wall structure while in Figures 4.12 and 4.13 net savings are measured with respect to MPS requirements and are based on insulation levels which must meet these standards. Put in other terms, net savings are greater and more responsive to fuel price changes in Figures 4.31 and 4.32 because 1), all energy conserving resources are optimally allocated, and 2), all net savings are accounted for as zero insulation is the standard of comparison.

The concept of solid wall areas is crucial to the proper interpretation of the ground ratio results presented here. Throughout this section the scope of the analysis has been limited to the performance characteristics and costs of the solid portions of each wall configura-

tion. Because of this, the net savings displayed, refer only to these areas and do not include the heat flows associated with or the costs incurred by the window and doorway portions of each living wall unit. As such, the findings presented should be interpreted as estimates of actual physical returns a homeowner could expect from the solid wall portions of his residence. (Complementary information on the window and door area of each configuration is necessary for a complete appraisal of potential net savings from wall areas.) The slope of each net savings curve shown in the various figures was influenced by this consideration, since the total solid wall area increased as the ground ratio was lowered. To illustrate, 11 percent of the conventional wall was usually specified as glazed. Such a large area of glass became impractical for lower ground ratio values and was impossible to achieve at GR = 0, where only 7.75 percent of the living wall height was defined as being above ground. To adjust for this, the model was designed to reduce the glazed area of the wall at lower ground ratio values. The result of this general decrease in the glazed wall area, which resulted as the ground ratio was lowered, was an increase in the solid wall area to make up the difference. For example, the conventional design having two entry doorways and being 11 percent glazed, contains 956.8 square feet of solid wall area through which the model calculates heat flows. At GR = 0 the solid wall area of the two doorway wall configuration, having 20 percent of

its component 2 wall area glazed, amounted to 1062.6 square feet. This increase in wall area affects the net savings from the various berm wall designs shown in the tables and figures of this section. Figures 4.35 and 4.36 are drawn to show the effect of this changing wall area on the overall slope of the net savings curves for the .251 cases illustrated in Figures 4.12 and 4.13. The curves having the steepest overall slopes in Figures 4.35 and 4.36 are from Figures 4.12 and 4.13. Their solid wall area specifications are set by the model used throughout this analysis. The other curves are a plot of net savings for a wall whose solid area is independent of the ground ratio value. In the illustration this wall consists of the 1200 square feet of area which results if all windows and doors are eliminated in the 30 x 40 foot model home.

As is shown in Figures 4.35 and 4.36, the amount of solid wall area which is included in each configuration does influence net savings. Thus, adjustments made for these changing wall areas may change some conclusions drawn in this section as to which wall configurations have the largest net savings. However, the effect on net savings in the relevant (upper) ground ratio range is small. To make such an analysis complete, costs and heat flows for the glass and doorway areas must be accounted for. Such an undertaking, though, is beyond the scope of this study.

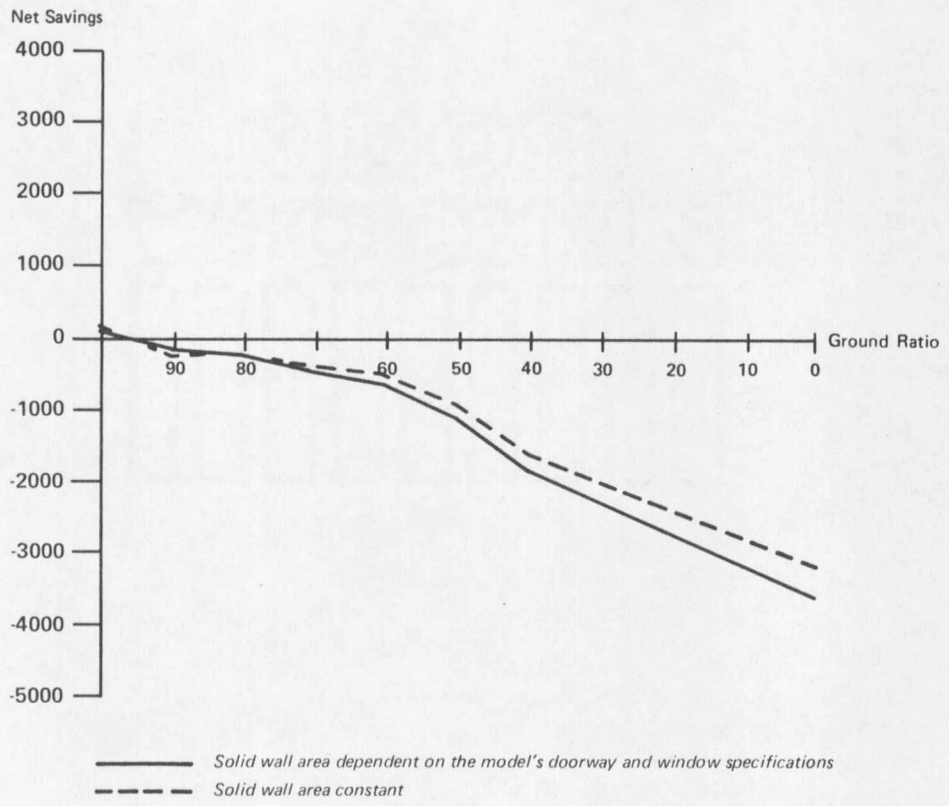


Figure 4.35 Functional Dependency of Net Savings on the Ground Ratio and on the Solid Wall Area. (The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used.)

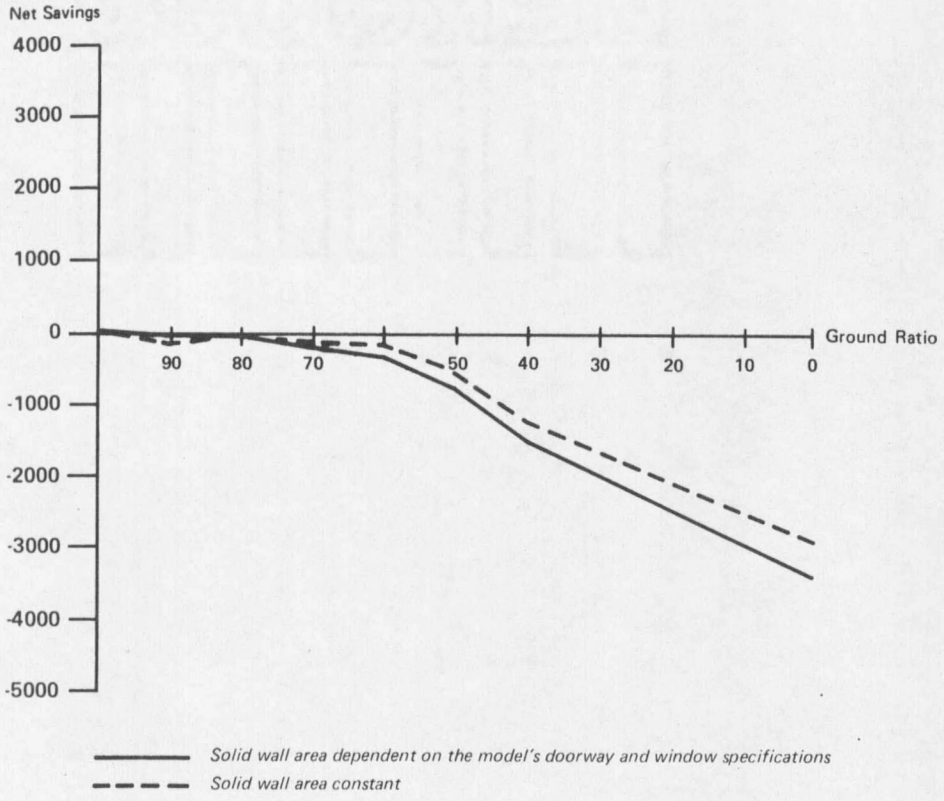


Figure 4.36 Functional Dependency of Net Savings on the Ground Ratio and on the Solid Wall Area. (The Fuel Price is $.251/100,000 BTU. Urethane Insulation is Used.)

Fuel Usage

Throughout this section, the net savings of each wall design was the criterion by which wall configurations subjected to different thermal stresses, fuel prices, and consumer preferences were evaluated.[22] Such an approach provided a global overview of each wall's performance. An alternative basis by which wall structures can be appraised is on their fuel usage.[23] This type of information, which

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[22] Net savings figures calculated through the formula, net savings = (ground ratio savings) - (ground ratio costs) - (net excavation costs times the excavation cost ratio) - (net entrance costs times the entrance cost ratio) + (net savings from insulation), are intended to be used as decision criterion and in fact do provide a useful reference from which different designs can be appraised. They do not, however, reflect the total cost of each wall structure and to have them do so would conflict with the goal set forth in this study. This is true because the objective of this study is not to appraise the need for walls, but rather, the need for thermal modifications to the walls. Thus, the net savings of the conventional design is calculated from the costs incurred in installing specific levels of insulation and the savings realized from these levels. (The original cost of the 2 x 4 frame wall, meeting HUD Minimum Property Standards for thermal insulation, is assumed to be a part of the total building cost.) All structural changes required to convert the conventional wall structure to one having a lower ground ratio value, are classified in the category of thermal modifications because the purpose in such changes is for the examination of wall designs which utilize soil as a part of the thermal envelope of the residence. Thus, the construction cost of the HUD MPS insulated 2 x 4 frame wall is not included in the net savings figures of any of the wall configurations.

[23] Fuel usages for walls are simulated values based on steady state conditions defined by degree days, cooling hours, and equivalent temperature differences. These weather parameters are only estimators of actual thermal loads and do not include solar effects, except in the equivalent temperature difference concept for cooling

is especially useful to those in energy planning, is available in the form of relative fuel usages from the thirteen ground ratio savings tables listed in Appendix A. To derive this information from the tables take the negative of the dollar value given for the design in question. The resulting figure is the present value of the change in the fuel usage from the conventional design which this new configuration requires. For example, if the ground ratio is 50 and the case is described by line 1 of Table A.1, $305.59 is the present value to the consumer of the additional fuel expenditures, over a GR = 100 design in the same case, which he must make if he were to purchase a new home having such a configuration and then live in it for the lifetime of the investment. The results listed in the tables are quite conclusive -- other than for a few exceptions involving reduced component 3 heat flows, fuel expenditures are shown to increase as the residence is placed deeper and deeper within the ground. Such a trend prevails because thick wall costs in the component 2 and 3 wall areas decrease the return from key levels of insulation effectively holding the optimal levels down. Thus, as the ground ratio declines, the overall heat flow through the wall configuration increases, resulting in greater fuel expenditures.

23/ continued
loads, or infiltration levels. Inclusion of these factors in the thermal load calculations may vary the wall's portion of the total heat load faced by the building.

The second reason for such an increase in fuel usage is related to the change in total solid wall area which results as the ground ratio declines. This was discussed on page 163 and it is sufficient here to note that this increase in wall area is the source of a part of the increased heat flows shown in the figures as the declining ground ratio savings curves. Figures 4.37 and 4.38 show that holding the solid wall area constant will change the ground ratio savings curves. Details for these cases are given in the explanation of Figures 4.35 and 4.36 as the cases described here correspond to the ones illustrated in those figures. Figures 4.22, 4.23 and 4.28 summarize fuel usage for various designs under a wide range of component 3 heat flows. (It is important to note in these figures that a declining curve depicts increasing fuel usage.) A comparison of the curves in Figure 4.22, which list ground ratio savings for wall configurations whose insulation levels are optimized subject to the constraint that they must meet HUD Minimum Property Standards with those in Figure 4.28, which show ground ratio savings for all designs whose insulation levels are optimized but not subject to any MPS constraint, reveals the effect of the HUD Standards on the fuel usage of the wall configurations when the fuel price is .251. Further ground ratio savings data is given in Tables A.43 - A.54 and in Table A.1.

To determine the present value of total fuel consumption for any wall configuration given in Tables A.43 - A.54 or Table A.1, subtract

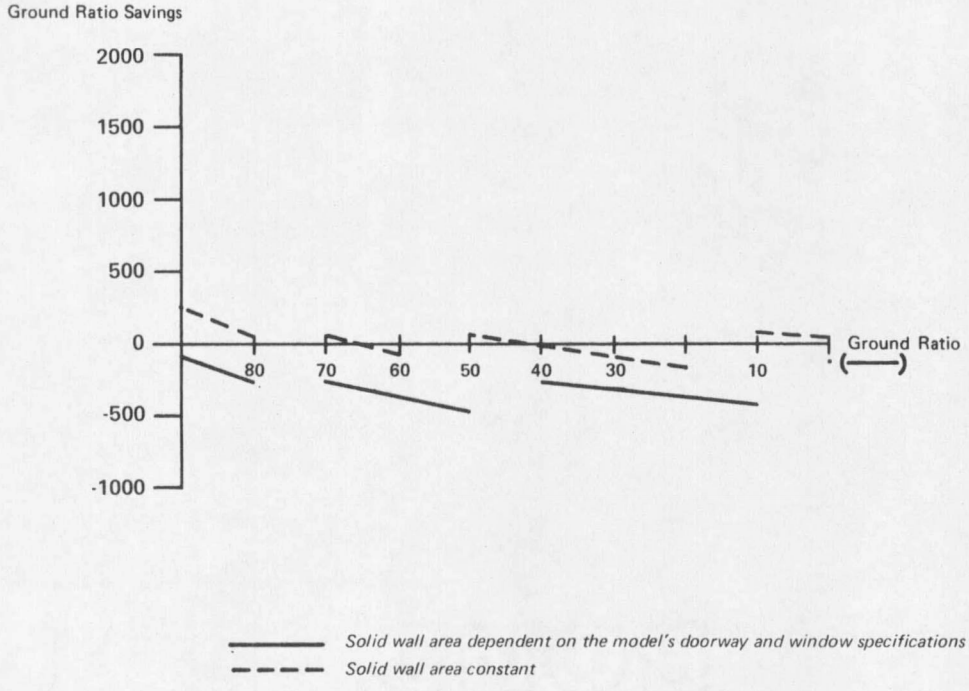

Figure 4.37 Functional Dependency of Ground Ratio Savings on the Ground Ratio and on the Solid Wall Area. (The Fuel Price is $.251/100,000 BTU. Fiberglass Insulation is Used.)

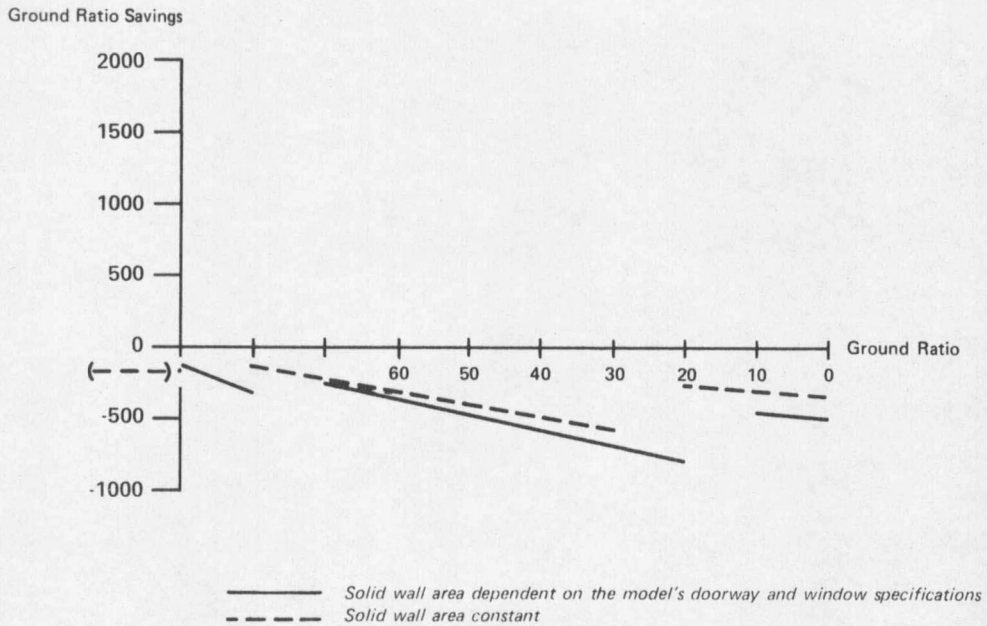

Figure 4.38 Functional Dependency of Ground Ratio Savings on the Ground Ratio and on the Solid Wall Area. (The Fuel Price is $.251/100,000 BTU. Urethane Insulation is Used.)

that case's value from the appropriate dollar value for fuel consumption in the conventional (GR = 100) case. Table 4.18 lists the present dollar values of the total heat flows through the conventional wall design, for the four fuel prices and two insulation types tested.

Table 4.18

Dollar Value of the Lifetime Heat Flow Through the Optimally Insulated Solid Wall Area in the Conventional Case (GR = 100)

Fuel	Insulation	Optimal Insulation R	P.V. Fuel Consumption
.167	f	13	921.30
.251	f	13	1384.68
.334	f	13	1842.61
.501	f	13	2763.91
.167	u	11.12	965.60
.251	u	11.12	1451.27
.334	u	16.68	1565.90
.501	u	16.68	2348.85

Thus, for illustration, the present amount of the dollar value of fuel consumption for the GR = 30 configuration described on line 2 of Table A.43 is \$1384.68 - (-\$304.09) or \$1688.77. This means that the dollar value of the heat flow through the solid wall area in this example increased by (\$304.09)/(\$1384.68) or 21.96 percent when the model home was lowered into the ground so that its component 1 wall height was reduced to only 30 percent of the value it had in the

conventional case.

The result in this example is typical of the findings on fuel consumption for wall configurations of the berm design and suggests that of all optimized wall structures, the conventional design has the lowest fuel costs. There are exceptions to this conclusion. Lines 3 and 4 of Table A.43 describe cases where fuel costs are lower for grounded designs than for their conventional counterparts. Other examples can be found by examining Tables A.1, A.43 - A.46, and A.49 - A.54, and Figures 4.9, 4.22, 4.23, and 4.28 for positive ground ratio savings values which indicate reduced thermal loads. In general, if the grounded wall design is insulated with urethane, and the soil adjacent to its component 3 areas has thermal qualities so unusual that the heat flow through it is only 25 percent to 50 percent of that estimated by standard engineering procedures, fuel usages may result which are lower than those required in the conventional design. (See Tables A.49 and A.50.) When fiberglass is used in the berm wall design, fuel savings beyond the conventional amounts can occur if the heat flow through the soil adjacent to the component 3 walls is 25 percent to 50 percent of ASHRAE estimates or if the fuel price is .334 or higher.

Results such as these are useful to the decision maker whether he is the homeowner or the policy maker who needs to know how fuel usage in the residential sector is a function of wall design.

The final suggested use for the data presented in this section is for comparing the net savings of any wall configuration, with a ground ratio of 90 or less, to the conventional wall under the same conditions, i.e. fuel prices and consumer preferences. To do this, subtract the net savings generated by the conventional wall from that earned by the wall configuration being examined. Before beginning, note that a neutral consumer response to the conventional design is assumed as net excavation and entrance costs are zero for this wall configuration. (See page 8 for a description of these costs.) From such an assumption the excavation (EXR) and entrance (ENR) cost ratios defined for the configuration in question are interpreted as measures of consumer reaction to wall designs having ground ratios different from 100. The following example illustrates how the net savings of two designs are compared when the consumer has an adverse response to the entryway designs required for grounded walls.

From Table A.8, the difference in net savings generated by a wall configuration having urethane insulation and described by GR = 60, EXR = 1, and ENR = 2, when the fuel price is .334, and the net savings resulting from the conventional design having the same insulation type, is -$452.80 - ($20.83) - $473.63. In this example, the consumer's adverse reaction to the entryway design necessitated by the berm wall configuration is depicted by an entryway net cost which is two times the entryway's construction cost. Such a preference in

effect costs the consumer - $315.30 - (-$452.80) or $137.50 more in net savings than a neutral response would. See lines 7 and 11 of Table A.8. (A rational consumer would not choose the GR = 60 configuration, however, and so he would not bear this cost.)

This concludes the interpretations of the ground ratio results. From the data listed in this section and in Appendix A, a wide variety of additional comparisons to match unique sets of fuel prices, insulations, ground ratios, and consumer preferences are possible.

OPTIMAL INSULATION TYPE

Fiberglass and urethane were offered as alternative insulation types in the analysis of cost minimizing wall designs. Fiberglass was used in many of the different walls examined because it is in wide use today in residential construction. Urethane was offered as an alternative insulation because its thermal and structural qualities gave it particular advantages over fiberglass in certain applications. The two qualities or urethane which were found to be particularly useful were its high R-value per unit of thickness which qualified it for use in insulation systems which were less bulky, or thick in the case of walls, and its high resistance to compression which enabled it to be installed without structural supports.[24/] Thus it was considered to

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[24/] The term "structural supports" means studding or furring. In contrast with urethane, fiberglass batts are not free standing so they

be a good substitute for fiberglass in those cases where a significant cost penalty was added to thick wall designs from floor area losses and where the wall structure was conducive to its application.

Material and installation costs for both types of insulations were based on values published in the Building Cost File - 1977 Unit Prices (16) which had been geographically adjusted to reflect local conditions. The values used are listed in Appendix B. Insulation thermal performance was based on specifications supplied by the manufacturer which was Owens/Corning Fiberglas. Thus, when urethane was used, a thermal resistance or R-value of 5.56/inch was specified. This R-value was based on the manufacturer's suggested conductivity of .18 which was recommended as a reasonable level to which urethane not faced with aluminum foil would drift as it aged. (29) The resistance to heat flow of each fiberglass batt used was considered to be equal to its advertised R-value. A comparison of the performance of urethane and fiberglass insulations in the thermal wall designs examined in the analysis is given below.

1. Net Savings (from insulation only)

Tables 4.13 and 4.14 summarize the net savings generated from optimal applications of insulation in each wall design, subject

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24/ continued
must be installed between structural members. For detail on the design of the urethane insulated concrete wall, see pages 13 and 32.

to the constraint that HUD Minimum Property Standards for thermal performance are met. Savings shown are for those levels of insulation which exceed the HUD requirement but are a part of the optimal solutions. The results show that fiberglass will consistently yield greater net savings than urethane at all fuel prices tested. Fuel prices were examined which ranged from .167 to .501. For more information see pages 66 - 94. A good description of how net savings from insulation are added subject to the HUD constraint is given on page 154.

2. Net Savings

In the preceding discussion only those savings which were produced by the insulation's resistance to heat flow were considered. The remainder of this discussion examines the (total) net savings generated by each wall design. On pages 45 - 52, and 105 - 176, costs and savings realized from the utilization of the ground as a thermal barrier are discussed and evaluated. From these sections it is clear that the type of insulation used in a berm wall design affects not only the net savings derivable from the insulation but also the savings and costs associated with the grounding. The suitability of both insulation types, based on the net savings generated by wall designs using each type, is discussed next.

2.1 Fuel Price Sensitivity

At the fuel prices of .167, .251, and .334, the net savings generated by wall configurations employing optimal levels of urethane exceed those from comparable configurations insulated with optimal levels of fiberglass in all grounded designs, i.e. designs having ground ratios of 90 to 0. The difference in savings, in favor of urethane range from approximately $50 to $500. Fiberglass insulated wall designs generate net savings which are $40 to $540 greater when the fuel price is .501. Fiberglass is also the optimal choice in the above ground wall design at all fuel prices from .167 to .501. More detail is given in Figures 4.12 and 4.13, and in Tables A.3 and A.4.

2.2 Reduced Ground Heat Flows

When the thermal balance on the berm wall configuration is altered by reducing the calculated heat flow through the below ground walls, a condition is defined which simulated wall performance in soils having lower thermal conductivities. The range of ground heat flows tested extends from the ASHRAE estimated level (1, p. 378) to 25 percent of that level. At all heat flow levels tested, urethane insulated wall designs produced greater net savings than similar designs insulated with fiberglass when the fuel price is .251. This information is summarized in Figures 4.20 and 4.21.

For additional comparisons of the net savings generated by the insulated walls, see Tables A.9 - A.16.

2.3 No HUD Minimum Property Requirements for Thermal Response

The constraint that fiberglass and urethane insulated wall designs must meet the minimum thermal requirements set forth in the HUD Minimum Property Standards (32) results in suboptimal solutions when the optimal insulation levels are lower than those recommended by HUD. When this constraint is dropped and the net savings from all insulation levels is included in the net savings function generated by each wall design, the total savings generated by all thermal modifications to the wall design can be determined. When this was done, at the fuel prices of .167, .251, and .334, fiberglass insulated wall configurations outperformed those insulated with urethane when the wall designs were above ground or only slightly buried, i.e. when the ground ratio equaled 100, 90, or 80. (At the .334 fuel price, the fully buried, GR = 0, fiberglass design was also shown to generate greater net savings than its urethane counterpart.) When the fuel price was .501 fiberglass insulated configurations covering the full range of possibilities from the above ground to the fully buried design produced the greater net savings. See Figures 4.31 and 4.32 and Tables A.17 and A.21 for additional information.

3. Fuel Usage

Wall configurations utilizing optimal amounts of fiberglass insulation usually generate greater fuel savings than is possible from the same configurations optimally insulated with urethane. In minimum fuel usage configurations, the additional present value lifetime fuel savings which they generate over comparable urethane designs, runs from $44.30 to $1220.45. This result is true at all fuel prices and ground heat flow levels tested, with one exception: when the soil conductivity is 100 percent of the amount estimated by ASHRAE and the fuel price is .334, the optimal urethane design from the standpoint of fuel usage, will require $93.29 less fuel than its fiberglass alternative. More detail is given on page 168. Additional data can be found in Tables A.1 and 4.20 and in Figures 4.8 - 4.11. Tables A.43 - A.54 provide further information on fuel usage when soil conductivities are reduced and when the HUD Minimum Property Standard constraint is dropped.

In conclusion, the characteristics of each insulation type were considered in the analysis. The results presented conformed to a principle which showed how the compactness and high physical strength of the urethane could be exchanged for the lower cost of the fiberglass in a cost minimizing design. Thus, in cases where the thickness and

physical strength of the insulation was not as important as its cost, fiberglass was often selected because its lower cost/unit of thermal resistance would more than offset urethane's advantege of higher resistance/inch of thickness and greater rigidity. Urethane was frequently the insulation choice for thick wall designs because floor area losses added a significant cost penalty to the broader wall cavities that were required for comparable levels of fiberglass.

OPTIMAL FRAME WALL TYPE

Component 1 (frame) walls are broken into two categories called type 1 and type 2 according to their basic structure. (See the definitions and illustrations on page 11. Type 1 walls are patterned after common framing practices and have a single row of studs. Depending on the required thickness of the walls, these studs can range from 2 x 4's to 2 x 12's which makes the overall thickness of the type 1 wall, in inches: 4.5, 6.5, 8.25, 10.25, and 12.25. Type 2 walls have a double row of 2 x 4 studs, one against the exterior sheathing and one against the interior wallboard. The spacing between the rows of studs determines the thicknesses of these walls. For uniformity, where there is overlap, type 2 walls are defined at the same thicknesses as their type 1 counterparts. Thus, their thicknesses are, in inches: 6.5, 8.25, 10.25, 12.25, 14.25, 16.25, 18.25, and 20.25. (See Figures 1.2 and 1.3.) In the area of overlap, which is

the four wall thicknesses: 6.5, 8.25, 10.25, and 12.25, a choice of wall type had to be made. In each case the design was selected which maximized (wall R)/(wall cost).

According to this method of selection the results show that type 2 walls are always optimal for either insulation type when wall thicknesses were 10.25 and 12.25 inches. The reason is that each square foot of 2 x 10 and 2 x 12 studding costs more than twice as much as a square foot of 2 x 4 studding, both installed, while the resistance of the type 1 wall over the entire range of overlap is less than its type 2 counterpart.

When fiberglass insulation is specified, the cost minimizing frame wall is the type 1 design for insulation levels up to and including the fourth increment which is R-22. At all higher levels of insulation, the type 2 design is optimal. Thus for component 1 wall areas insulated with fiberglass at fuel prices of .167 and .251, 2 x 4 (type 1) framing is the minimum cost choice for all designs ranging from the conventional structure (GR = 100) to the nearly totally buried berm wall defined by a ground ratio of 10. R-13 fiberglass is the recommended insulation level at this fuel price. At the higher fuel price of .334, 2 x 4 framing is recommended for component 1 areas in configurations ranging from the conventional design to the GR = 20 design as R-13 fiberglass is also optimal over that range. A type 2 wall having an overall thickness of 14.25 inches and insulated with

two batts of R-22 fiberglass, the equivalent of 12 increments, is optimal for the component 1 area of the GR = 10 configuration at this fuel price. At the highest fuel price examined, which is .501, R-13 fiberglass placed within 2 x 4 framing is optimal if the wall is of conventional design. Otherwise a 14.25 inch thick type 2 wall is needed for the two layers of R-22 which are optimal in all grounded designs.

For urethane insulated walls the type 1 structure is optimal for insulation layers one through five, while the type 2 structure is the minimum cost choice at higher levels. Thus, the recommended framing for all component 1 areas, insulated with urethane, which are included in designs ranging from the conventional to the deeply submerged GR = 10 style, is type 1 2 x 4's. Depending on the fuel price, the optimal insulation levels in all these wall areas ranged from two to three layers of 1 inch urethane boards each rated at R-5.56.

BIASES RESULTING FROM THE LENGTH, DOORWAY AND FLOOR SPECIFICATIONS OF THE MODEL WALL

The thermal wall model used to generate the results, employs numerous simplifying assumptions such as parallel heat flow paths, constant indoor temperatures, uniform construction practices with repeatability, and uniform homogeneous building materials. These assumptions along with others which are needed to specify a steady

state thermal model are typical of those used in the ASHRAE approach to load calculations. They yield results which are widely accepted throughout the industry as a guideline in determining optimum insulation levels, furnace and air conditioner sizing, and annual fuel use. No measure of the accuracy of these assumptions is made in this report as such an undertaking is beyond the capability of the model. Certain other assumptions are made in the thermal modeling of the walls whose effects can be measured. They will be examined here.

The first assumption made involves wall lengths. Thirty-five foot walls having one doorway are used in the modeling calculations where the per square foot wall area costs are found. This wall length is used in place of the 30 foot and 40 foot lengths which corresponded to the model home's dimensions in order to simplify the model and to cut the number of computer operations in the cost calculations by one-half. Since the 35 foot length is but an approximation of the true lengths, its use introduces some bias into the per square foot costs. An investigation revealed that net savings from insulation calculated using this 35 foot model wall assumption will generally be biased downward by an amount which is less than 1 percent.

The second assumption that is made about the 35 foot model wall which was used in the calculations, is that it has one entrance doorway. This doorway specification is used to define per square foot wall area costs of all four walls of the 30 x 40 model residence. It

is made in place of a double specification which would require two 35 foot model walls, one with and one without an entrance doorway. The primary reason for implementing this assumption is that it simplifies the model and that it also reduces the number of computer operations in the wall cost calculations by one-half. The trouble with such an assumption is that it introduces bias into the results because the wall costs for all four walls of the model home have to be determined from the same 35 foot single doorway wall while only two walls of the model home are defined as having doorways.

This doorway specification has a limited effect on the calculated values for insulation net savings. In two circumstances there will be no bias in these savings:

1. The optimal level of insulation equals that recommended in the HUD Minimum Property Standards.
2. The optimal level of insulation is low enough so that no thick wall costs are involved.[25/]

Because of these cases, the biases resulting from the doorway assumption are not as extensive as they could be. No biases result for the component 1 wall areas of a conventionally constructed home (GR = 100),

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[25/] Model wall length and doorway specifications affect net savings from insulation through the thick wall portion of the wall cost formula. (See the definitions on page 5.)

equipped with either insulation type, at any of the fuel prices tested. Likewise, biases in the component 1 wall areas of the half buried wall structure (GR = 50) appear only for the highest fuel price and then only if the wall is insulated with fiberglass. On the other hand, numerous biases occur in the insulation net savings calculated for the component 2 and 3 wall areas because the optimal insulation levels in so many of the cases involve thick wall costs and exceed the HUD MPS recommendations. The effect of the biases is to decrease the calculated savings relative to more realistic results. Their magnitude is under 10 percent.

To this point, length and doorway assumptions to the model wall have been evaluated independently. Such a treatment is not complete, however, because of cross effects which make the savings available from applications of insulation dependent not only on the doorway specification of the model wall but also on its length. The results of an investigation into these cross effects suggests that insulation net savings are more influenced by the doorway specification in the model wall than they are by the length assumption or by the cross effects. Thus, the results which apply only to the doorway specification biases can be used as estimators of the total bias expected at different fuel prices.

Biases in the per square foot wall area costs, resulting from the length and doorway assumptions about the model wall, affect more than

just the net savings from insulation. They also influence the ground ratio costs which result when the wall configuration is changed. In all cases examined, these biases depress net savings generated by the wall designs approximately $100 to $300. This means the net savings curves derived on pages 123 - 167, such as those illustrated in Figures 4.12 and 4.13, are shifted downward from their unbiases counterparts by the amount of the bias for each wall configuration. Fuel usage for the different configurations is practically never affected by these biases.

The biases from the length and doorway assumptions have a negligible effect on the conclusions given in the first five sections of this chapter. They do demonstrate, however, that the method by which the model wall is specified will affect net savings. Two other specifications of the model home which also influence the results, involve the manner in which costs and benefits attributable to grounding are defined. They are discussed next:

In order to isolate the savings resulting from grounding from the savings traceable to other sources, the placement of the wall in relation to the ground level must be examined holding all other structural aspects of the building constant. In the strictest sense, this is violated in the specifications of the conventional, i.e. above ground, wall. The misspecification involves the floor types and affects excavation costs. In the conventional case, the floor type is

wood so the excavation for the floor includes a crawl space. On the other hand all berm designs have concrete floors which require excavation only as deep as the placement of the floor. This change in floor specification which results as the building is grounded biases the net excavation costs of all berm designs so that they no longer reflect only costs due to grounding but also costs resulting from the change in floor type. To remove the effect on the net savings traceable to changes in floor type, subtract the expenditures required to dig the crawl space in the conventional design from the net savings values for the configuration in question. In cases where the excavation cost ratio equals 1, this correction amounts to $97.24.[26/] Thus, when the effects of grounding are examined holding all other structural specifications of the model residence constant, the attractiveness of the conventional (GR = 100) design relative to all "buried" designs is $97.24 greater than shown in the "Net Savings" Appendix Tables.

When the excavation cost ratio is 2, the bias correction to the net savings for ground ratios of 90 - 0 is $194.48. No correction is needed in cases where the excavation cost ratio is 0. These changes

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[26/] The correction is subtracted from the net savings values of GR = 90 to 0 designs because in the net excavation cost relationships, crawl space excavation costs are credited to net savings for all berm designs. This credit is the major reason why the net excavation costs are positive for ground ratios of 90, 80, and 70, in Figure 4.16. It is also the primary source of the twist in the net savings curves shown in Figures 4.14 and 4.15.

shift the GR = 90 - 0 portion of the net savings curves illustrated in this chapter downward by the amount of the bias in net savings resulting from the floor specifications.

The last specification of the model to be examined involves perimeter insulation. As was discussed on page 60, all berm designs employ this type of insulation to reduce "edge" loss along the lower portions of the component 3 walls and along the outside edge of the concrete slab floor. Costs for perimeter insulation are added to berm wall costs because this type of insulation is necessitated by the grounding. Benefits from this thermal barrier, on the other hand, are realized for both the floor and the wall areas of the residence. The failure to capture the entire benefit from perimeter insulation results in a downward bias in the net savings drivable from each grounded configuration. An objective measure of the additional benefits from savings through floor areas cannot be made, however, as heat losses along the edge of floor slabs are not differentiated into wall and floor portions (1, p. 378). This bias and the floor specification bias have the opposite sign. Thus, their influence on the net savings is counterbalancing so that total error is reduced.

This concludes the analysis. The findings in this section do not nullify the results listed in the previous sections. Rather they serve to discourage improper use of those results. The leading objective of this study was to examine the response of optimal structural design to

variables such as fuel price, financial conditions, and consumer preferences. Such a goal places more emphasis on relative changes than on absolute levels and is not seriously jeopardized when biases occur which are of the magnitude noted here. A further reason for treating these levels with care comes from the realization that even in the cases where no biases occur, net savings and optimal insulation levels were derived from mathematical formulas which can only predict thermal response.

SUMMARY OF RESULTS

The objective of this study has been to identify energy conserving modifications to a residential wall structure which will minimize costs to the homeowner and to calculate the resulting net savings to the homeowner that such modifications will yield over their lifetime. Cost minimization criterion outlined on page 15 was employed in the search over a wide range of wall designs for those whose thermal modifications minimized costs. The findings were presented in this chapter.

Insulation levels and their net savings were examined first. They were found to be sensitive, in varying degrees, to the portion of a wall area which was glazed. Changing the glazed portion of the wall was found to have little effect on the optimal insulation levels for either type of insulation. Increasing the glass areas did lower fiberglass and urethane net savings for the entire wall area of the model

home, however. (These results were presented on pages 66 - 71.)

Net savings from both types of insulation were found to be slightly improved with the addition of an air conditioning load. The change was very slight, however, as the cooling load for the Bozeman, Montana climate was less than $1/65^{th}$ as large as the heating load for all wall designs tested. This slight additional load had no influence on the optimal insulation levels. For climates similar to the one in Bozeman, the results were the same. (See pages 71 - 86, and 96 - 105.)

Optimal fiberglass and urethane insulation levels in concrete walls, i.e. in components 2 and 3, were shown to be sensitive to changes in fuel price with higher levels being frequently recommended at the greater fuel costs. Component 1 (frame wall) fiberglass insulation levels, however, were not influenced by fuel price changes with one exception -- in the GR = 50 case when the fuel price climbed from .334 to .501 the optimal insulation level rose from R-13 to R-44. Optimal urethane levels for frame walls did reflect fuel price variation. (See pages 71 - 78 and 96 - 105.)

The dependence of fiberglass insulation levels and net savings on the expected lifetime of the investment were also studied. As was expected, net savings from insulation increased with the lifetime. The sensitivity of optimal fiberglass levels was also extended to various combinations of consumer real discount rates (D) and rates at which the fuel cost changed with respect to inflation (P). Here again net

savings and component 2 and 3 insulation levels quickly reflected changes in the values of D and P. In four cases described on lines 16, 17, 26, and 27 of Table 4.11, the component 1 insulation level was greater than R-13. In all other cases it was R-13. At higher fuel prices than the one tested, which was $.251/100,000 BTU, insulation levels would be more sensitive to changes in P and D. A complete listing of this analysis is given in Table 4.11.

Payback periods in years, for optimal insulation applications beyond those recommended by the HUD Minimum Property Standards, were listed with the results in several of the tables on pages 69 - 82 as they were considered a useful decision criterion in the determination of net savings for each investment. For example, Table 4.8 provides a convenient listing showing how the payback periods decline reflecting the increasing net savings of the component 1 insulation level, in the GR = 100 configuration, which results as the fuel price rises.

As was outlined on page 182, two types of frame wall construction were considered in the analysis for walls with cavity thicknesses between 5.5 and 11.25 inches. However, as the results showed, the optimal fiberglass and urethane insulation levels never required cavity spaces within this range. For urethane insulated walls, 2 x 4 studs 16 inches on center were optimal, i.e. cost minimizing, for framing at all fuel prices between .167 and .501. When fiberglass was used, 2 x 4 stud walls framed 16 inches on center were optimal in conventional

construction at all fuel prices. In those cases where the wall design was grounded and the fuel price was high enough so that two layers of R-22 fiberglass insulation were optimal, the cost minimizing frame wall was constructed with a double row of 2 x 4 studs in an arrangement where one row was against the exterior sheathing and the other row was against the interior wallboad. The total thickness of this wall was 14.25 inches.

Finally to complete the investigation of thermal modifications to the wall designs, the walls were placed deeper in the ground in ten steps so that the effect on the net savings of the changing thermal balance due to the elevated soil level on the walls could be examined. This approach required a total accounting of all costs and savings realized from the change in the wall configuration due to the grounding. The resulting definition of net savings was: Net savings = (total savings realized from the change in the overall fuel cost load which resulted when the optimally insulated wall configuration, which was required to meet HUD Minimum Property Standards for thermal insulation, was changed due to grounding) - (total wall structure costs imposed by the change in the wall configuration) - (net excavation and entrance costs required by the new configuration) + (net savings from insulation in the new configuration). This approach to calculating net savings for each wall configuration provided a useful decision criterion for appraising designs as each net savings figure showed the present value

to the consumuer of a particular design. For example, line 7 of Table A.3 describes a case where the conventional wall's net savings is $276.00 while that of the deeply buried GR = 20 configuration is -$1239.66. Thus, in this example, if the homeowner was to construct the GR = 20 design in lieu of its GR = 100 counterpart, the present worth of his decision would be -$1239.66 - $276.00 or -$1515.66. This figure can also be viewed as the present value to the consumer of the thermal modifications required in changing the conventional wall structure to the GR = 20 design.

The results of the analysis showed that net savings of optimally insulated grounded wall designs are comparable to net savings of conventional (GR = 100) designs in cases where the amount of wall area buried does not exceed approximately one-quarter of the total area of the living wall. This generalized conclusion is valid for urethane insulated walls meeting HUD Minimum Property Standards for thermal response because over the GR = 100 - 70 range, the variance in net savings at any given fuel price is too small to indicate any overall trend. Necessary simplifications to the model are the reason for this conclusion as they limit the precision by which the model can predict thermal response and describe cost. Thus, only larger changes in net savings can be considered significant. In the case of urethane insulated walls not subject to the HUD constraint and fiberglass insulated designs meeting this constraint, there is a noticable

downward trend in net savings over the GR = 90 - 70 range as the result of grounding. The net savings of these configurations are comparable, though, to that of conventional designs. These findings indicate that a cost minimizing consumer will be indifferent, under the conditions expressed, between a conventional wall design and a partially buried design.

The change in net savings as the result of grounding which is observed in the upper ground ratio range is small relative to the decline in net savings seen at lower ground ratios. In every case examined, below a ground ratio of 60, net savings of the optimally insulated wall designs monotonically decline as the wall is placed deeper within the ground. None of the wall designs in the GR = 50 - 0 range would be chosen by a rational consumer, however, as lower cost designs are available at higher ground ratios.

Three factors, primarily, determine the trend in net savings observed over the GR = 100 - 0 range:

1. Construction Costs

   Of the wall structures considered in the study, the most inexpensive one to build is the GR = 70 style. This configuration is less expensive than the conventional and GR = 90 and 80 designs because, compared to these designs, its wood frame area is smaller and its concrete area is the same size. (See page 48.) It has

lower cost than the more deeply buried designs because greater investments are needed to construct each of these designs as they contain less lower cost wood frame area and more higher cost concrete area. These declining and then mounting costs associated with grounding contribute to the change in slope of the net savings curves shown for the various configurations.

2. Optimal Insulation Levels

The first step performed by the model in the process of determining optimal insulation levels for each wall area is to take each area in its non insulated form and successively add levels of insulation to it, one at a time. The basic non insulated walls considered are the 2 x 4 frame, containing 3.5 inches of cavity space, and the 8 inch concrete structure containing 1 inch of space between the furring strips. When a search is made for the optimal insulation levels for each wall area, the costs and savings associated with each level are considered. (See pages 15, and 27 - 40. Due to lower overall costs because no thickened wall structures were needed until the 3.5 inches of "free" cavity space are used up, optimal insulation levels in the frame structures are always as high or higher than comparable insulation levels in the concrete structures which have only 1 inch of "free" cavity space. Therefore, heat flows through each square foot of optimally insulated concrete wall area frequently exceed the flows through a square

foot of optimally insulated frame wall area. The net result is that the fuel expenditures necessitated by each design usually increase with the amount of grounding.

3. Excavation Work and Entryway Constructions

The dirtwork and entrance stairway structures necessitated by the grounded designs increase in cost with depth.

Variations in net savings are noted, however, due to the sensitivity of the net savings from each wall configuration to variables such as fuel price, consumer preferences, component 3 heat loads, and insulation types. The findings, which are calculated for wall areas which meet the HUD Minimum Property Standards for thermal resistance, are summarized below.

Net savings from the various wall configurations are sensitive to fuel prices. However, no strong overall trend of increasing net savings was evident until the fuel price was increased beyond .334. The overall reduction in net savings resulting from the downward shift of the ground ratio was least at the highest fuel price and greatest at the lowest fuel prices. This suggests that wall configurations designed to use the thermal properties of the soil may become increasingly attractive investments as fuel prices rise. Urethane insulated walls generate greater net savings than their fiberglass counterparts in all grounded designs when the fuel price is .167 - .334. At the

greatest fuel price the situation is reversed with fiberglass components producing greater savings. (See Tables A.3 and A.4, and Figures 4.12 and 4.13.)

When structural modifications resulting from grounding were examined, the wall configurations yielded the greatest net savings when the cost to the consumer for each of the design changes was the lowest. The modifications were the excavation requirements for each configuration and the entryways needed for each configuration. Each modification was appraised at three cost levels ranging from 0 to double its construction cost. The results are listed in Tables A.5 - A.8 and summarized in Figures 4.14, 4.15, 4.17, and 4.18.

Thermal impacts having different balances in their overall above ground and below ground portions were placed on the wall components to simulate conditions that would have been overlooked using typical steady state engineering procedures recommended by ASHRAE. The change in the component heat load balance was made by varying the equivalent temperature difference across the component 3 wall-soil combination. The results showed that those configurations which were optimized for and used with reduced component 3 heat loads had a greater net savings than their counterparts which faced the entire heat load estimated by ASHRAE. However, even at the lowest component 3 heat load tested, where the flows were 25 percent of the levels calculated by common engineering practices, significant losses were realized for all wall configurations

having ground ratios of 40 or less. Such findings suggest that deeply buried wall designs are a costly investment even in locations where the soil has much lower thermal conductivities than are assumed by standard engineering procedures. (See Tables A.9 - A.16 and Figures 4.20 and 4.21.)

To this point in the analysis, the HUD Minimum Property Standards for thermal response were required to be met in all wall designs. The purpose in such an approach was to provide a point of reference typical of modern construction from which net savings generated by the optimal applications of insulation found in this study could be compared. It also provided a basis from which current HUD standards could be critiqued. In the following summary these Federal requirements are dropped and the net savings from all insulation levels is included in the net savings produced by each wall design. This establishes a framework by which the total return of all thermal modifications to the wall structure can be appraised. At all fuel prices tested, the results showed that wall configurations designed to utilize the thermal resistance of the soil do not become more attactive as the fuel price rises. (See the slopes of the net savings curves plotted in Figures 4.31 and 4.32.) A large increase in net savings results with each fuel price rise because all energy conserving resources are optimally allocated and all savings from insulation are accounted for once the

HUD Minimum Property Standard constraint is dropped.[27] Without this restriction, fiberglass insulated wall configurations produce greater net savings if they are above ground or only slightly buried. Urethane designs, on the other hand, out performed them in the more deeply buried cases. These results are for fuel costs of .167 and .334. At the highest fuel price examined (.501) the lower cost of fiberglass per unit of resistance, referenced to urethane, is such a positive factor compared to urethane's advantage of a lower thickness per unit of resistance, that higher levels of insulation are feasible for fiberglass. These greater resistances increase the net savings generated by fiberglass designs and make fiberglass the optimal insulation choice for all configurations from the conventional to the deepest buried design considered. The upward trend in net savings, as a function of fuel price rises, was also noted for reduced component 3 heat loads. In all cases conventional wall construction was found to be the lowest cost investment. (See Tables A.17 - A.24 and Figures 4.26, 4.27, 4.31, and 4.32.)

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[27] Taking fiberglass for an example, when the MPS constraint is dropped, the net savings from all insulation levels, including that from the highly efficient first increment (which is a layer of R-11), are counted. With the imposition of the MPS requirements, installation of the first increment becomes mandatory so net savings are counted starting with the second increment.

Throughout this discussion, the net savings of each wall configuration was the criterion by which different structures were appraised. Such an approach provided a global viewpoint through which the effectiveness of the thermal designs to different thermal stresses, fuel prices, consumer preferences, and Federal Minimum Property Standard regulations, could be appraised. An alternative standard by which wall configurations can be compared is on their simulated fuel usage. When this was indeed investigated, the results were quite conclusive -- other than for a few exceptions which are detailed in Figures 4.9, 4.22, 4.23, and 4.28, and are primarily concerned with reduced soil conductivities, fuel expenditures were shown to increase with each deeper placement of the walls into the ground. Wall configurations optimally insulated with fiberglass frequently produced greater fuel savings than was possible from the same configurations optimally insulated with urethane. These findings are useful not only in helping a prospective homeowner decide on a wall design but they provide data to the policy maker in energy planning who needs to know how fuel usage in the residential sector is a function of wall design.

The findings on cost minimizing wall designs are summarized in Parts I and II below:

I. If net savings is the criterion for selection, the optimal wall design is the above ground, i.e., conventional structure with

2 x 4 framing 16 inches on center and R-13 fiberglass insulation. The total thickness of this wall design is 4.5 inches. Exceptions to this conclusion are listed in Table 4.19.

Table 4.19

Optimal Wall Descriptions on the Basis of Net Savings

Ground Heat Flow	EXR	ENR	Fuel	HUD MPS Constraint	Optimal Wall Description			
					GR	INS	Insulation R Compl	Comp23
100%	2	1	.167	yes	80	u	11.12	5.56
100%	2	1	.501	yes & no	90	f	44	13
100%	1	0	.501	yes & no	90	f	44	13
100%	1	2	.501	yes & no	90	f	44	13
100%	1	1	.501	yes & no	90	f	44	13
75%	1	1	.167	yes	80	u	11.12	5.56
75%	1	1	.501	yes & no	90	f	44	8
50%	1	1	.167	yes	80	u	11.12	5.56
50%	1	1	.251	yes	80	u	11.12	5.56
50%	1	1	.501	yes	80	f	44	13
50%	1	1	.501	no	90	f	44	8
25%	1	1	.167	yes	60	u	11.12	5.56
25%	1	1	.251	yes	60	u	11.12	5.56
25%	1	1	.334	yes	60	u	16.68	5.56
25%	1	1	.501	yes	70	f	44	13
25%	1	1	.501	no	90	f	44	8

II. If fuel consumption is the criterion of selection, the optimal wall design in all but the cases listed in Table 4.20, is the conventional structure described in Part I. (The results in Table 4.20 apply both when the HUD Minimum Property Standard

restrictions for thermal response are imposed and when they are relaxed.)

Table 4.20

Optimal Wall Descriptions On the Basis of Fuel Consumption

		Optimal Wall Description			
				Insulation R	
Ground Heat Flow	Fuel	GR	INS	Comp1	Comp 23
100%	.334	100	u	16.68	
100%	.501	90	f	44	13
75%	.334	10	f	44	26
75%	.501	90	f	44	8
50%	.251	0	f		13
50%	.334	10	f	44	19
50%	.501	90	f	44	8
25%	.167	0	f		8
25%	.251	0	f		8
25%	.334	10	f	44	8
25%	.501	10	f	44	19

The first five lines of Table 4.19 define the optimal wall designs for the standard heat flow case when the thermal loads on the above and below ground portions of the wall configurations are estimated according to ASHRAE procedures. (See page 27.) The remaining lines of the table describe special cases where the heat flow through the below ground wall areas are assumed to be reduced by a given percent from the level estimated by ASHRAE. Standard terminology defined on page

13 is used throughout the table. Table 4.20 is set up in a similar manner. The structural descriptions accompanying particular insulation levels are given below:

Component 1 areas insulated with R-44 fiberglass have a double row of 2 x 4 studs 16 inches on center arranged with the outside row against the exterior sheathing and the inside row against the interior wallboard and spaced wide enough apart to permit the insertion of 2 layers of R-22 insulation. The total thickness of the resulting wall design is 14.25 inches of which 13.25 inches are cavity space.

Component 1 areas insulated with R-11.12 urethane are constructed with a single row of 2 x 4 studs 16 inches on center and are filled with 2 one-inch thick layers of R-5.56 insulation. The thickness of this wall structure is 4.5 inches.

Component 1 areas insulated with R-16.68 urethane have 2 x 4 framing 16 inches on center. Their thermal resistance comes from 3 one-inch thick layers of R-5.56 insulation. Their total thickness is 4.5 inches.

Component 2 and 3 areas insulated with R-8 fiberglass have a 2.5 inch cavity supported by 2 x 3 furring 16 inches on center and are filled with a layer of R-8 insulation. Their total thickness including concrete and interior wallboard is 10.75 inches. (The concrete wall is 8 inches thick.)

Component 2 and 3 areas insulated with R-13 fiberglass are 11.75 inches thick, having 3.5 inches of cavity space between the concrete and the interior wallboard, and contain 1 layer of R-13 insulation. Framing is by 2 x 4's 16 inches on center.

Component 2 and 3 areas insulated with R-19 fiberglass have an interior wall construction framed with 2 x 4's 16 inches on center and described by Figure 1.4. They have a cavity space of 5.5 inches within their total thickness of 13.75 inches. R-19 is their insulation requirement.

Component 2 and 3 areas insulated with R-26 fiberglass have a 7.25 inch cavity supported by 2 x 4's in the manner illustrated in Figure 1.4. They contain 2 layers of R-13 insulation and have a total thickness of 15.5 inches.

Component 2 and 3 areas insulated with R-5.56 urethane are constructed after the plan shown in Figure 1.4. They are 9.25 inches thick, have a 1 inch cavity, and are insulated with one layer of R-5.56.

In the findings summarized in Parts I and II, the effects of grounding on net savings and fuel consumption are determined by shifting the placement of the model wall in relation to the ground level. Floor structures are not held constant during this grounding process as the conventional design is defined with wooden floors and a crawl space while all berm configurations are specified with concrete

slab floors which rest on the ground. The change in floor type which results from grounding biases the net excavation costs required for each configuration so that costs resulting from the change in floor type are included in the wall costs resulting from grounding. To remove the effect of this floor specification on the net savings listed in Tables A.3 - A.24, subtract the net excavation cost for the crawl space, which is $97.24 if EXR = 1 or $194.48 is EXR = 2, from the net savings shown for all berm (GR = 90 - 0) configurations. (See page 188.) In cases where the excavation cost ratio is 1 or 2, this correction increases the attractiveness of the conventional design relative to all grounded designs. Its effect on the findings summarized in Part I is to reduce to six the number of cases where a grounded wall structure is the optimal configuration. Thus, when the floor type of the model home is held constant during grounding, the net savings maximizing wall design is, in all but six combinations of fuel price, below grade heat flow, consumer preferences, and government thermal standards, the conventional structure with 2 x 4 framing and R-13 fiberglass insulation. Lines 8, 10, and 12-15 of Table 4.19 list the exceptions where grounded configurations are optimal. The floor specification has no effect on the optimal wall designs chosen on the basis of fuel consumption.

The structural designs presented here are optimized for the Bozeman, Montana climate which is described by the following

parameters:[28]

Degree days = 8343

Heating days = 334

Cooling hours = 225

Design equivalent temperature difference for frame walls = 13.6°F

Design equivalent temperature difference for masonry walls = 6.3°F

Basement wall equivalent temperature difference, for heating days = 61°F

The methods used by the model for converting this weather data into heating and cooling loads faced by the wall components, are consistent with accepted steady state engineering practices. Following is a discussion of the applicability of the findings to other climates.

As the results showed, when wall designs were optimized on the basis of their net savings, one configuration was the overwhelming choice. This design was the all component 1, (frame) structure insulated with R-13 fiberglass. Other climates in which this wall specification would likely be the choice on the basis of cost minimizing criteria are described as having low cooling loads like Bozeman and falling within the approximate heating degree day range

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[28] Complete weather data was not available for Bozeman. In cases where no figure could be found, the values used were based on measurements made in nearby Montana cities.

of 3100 to 10,500.[29/] (This conclusion presumes a fuel price which falls within the range tested in the model.) Thus, whenever local fuel prices fall within the $.167/100,000 BTU to $.501/100,000 BTU category, this wall design is frequently the optimal choice on the basis of net savings for a broad cross section of the nation. If fuel consumption is the basis for selection of the optimal design, this same configuration will be chosen if the climate fits within the broad range described above and if the situation is not described by any of the cases summarized in Table 4.20.

No attempt was made to extend the climatic range over which the configurations described in Tables 4.19 and 4.20 would be optimal, because their specifications are quite sensitive to small climatic changes. Thus, those cases can be considered as applicable only to the local Bozeman, Montana climate.

Construction costs, for both labor and materials, were typcial of those in the Bozeman, Montana area during mid 1977. These costs can be changed with varying impact on the different optimal designs. The design that would be stable under a large increase in labor and materials price, is the all component 1 wall with R-13 insulation.

[29/] Low air conditioning loads are recommended over this expanded climatic range because significant increases in these loads would alter the thermal balance faced by the above and below ground areas of the grounded walls and raise the net savings of configurations having lower ground ratios.

This wall can be erected at up to 2.7 times the cost used in the analysis and still be the optimal choice of above ground designs -- from the viewpoint of net savings and fuel consumption. (Berm walls with ground ratios of 90, 80, and 70, become more attractive relative to this configuration, however, as construction costs rise.) The other designs, which are listed in Tables 4.19 and 4.20, are highly cost sensitive and consequently their specifications are dependent on the current Bozeman, Montana construction market.

The results summarized here are for a model home which is a 40 foot long and 30 foot wide rectangular single story structure having 8 foot high walls. The findings are not confined to this type of structure, however. A most useful extension of the results is to 2 story structures of the same width and length. When this is done and an all-above-ground 2 story residence is compared to one having a single story above ground and a full basement that is heated living space, the results are very conclusive: The net savings maximizing wall design for the entire range of fuel price levels, consumer preferences, soil thermal stresses, and insulation, is the 2 story all-above-ground structure with 2 x 4 framing and R-13 fiberglass. Its relative advantage over the single story design with a heated basement ranges from approximately $1400 to $6700. Certain designs, though, with daylight basements having a basement ground ratio no lower than 60, have net savings which are reasonably comparable to the 2 story all-above-ground

structure described above. The compare net savings of different 2 story configurations, where one has a heated basement, subtract the appropriate net savings amount for the heated basement from that generated by the fiberglass insulated one story above ground design. Thus, from line 2 of Table A.9, the optimally insulated walls of a 2 story all-above-ground structure have a net savings that is \$119.18 - (-\$3599.40) = \$3718.62 greater than the comparable net savings realized from the optimally insulated walls of a single story building with a heated basement, whose walls are also optimally insulated. The fuel price is \$.251/100,000 BTU in this example. By the same procedure relative fuel usages of 2 story designs can be compared. Other comparisons to match unique sets of wall designs, including insulation and ground ratios; consumer preferences; fuel prices; and below grade heat flows are also possible.

Chapter 5

DISCUSSION OF MINIMUM PROPERTY STANDARDS

The specifications set forth in Revision No. 1 to "Minimum Property Standards for One and Two-Family Dwellings," defined the maximum coefficient of transmittance for all wall designs simulated in the model that were specified as meeting the HUD Standards.[30/] For each design, a particular level was referenced as providing the minimum thermal protection set by these government standards. For fiberglass insulated frame wall construction, this level was R-11 and the resulting "U" value, not adjusted for framing, was .069. When urethane was specified for frame walls, two one inch layers, each rated at R-5.56 were referenced as meeting these standards. The corresponding "U" value for these areas insulated with urethane was also .069. (The requirements set forth in Revision No. 1 called for a maximum "U" of .08 for frame walls. See Table 6-7.1 in Reference 32.) When the wall structure was concrete, the government standards

30/ This revision of the HUD Standards, dated November 1974, was used in place of the most current revision, which is No. 4 (March 1976) because the latter version required an accounting of heat loss through windows and doors as well as through the solid wall area. Such a calculation was impossible in this study as the model simulated only solid wall areas. Thus, upon consultation with the HUD office in Helena, Montana, it was concluded that Revision No. 1 did provide a suitable guideline as to current HUD policy on minimum thermal standards for the solid portions of wall structures in housing approved for mortage insurance as well as for low rent public housing.

set forth in Table 6-7.3 of Reference 32 were used as they defined the maximum "U" values of the foundation wall sections of a heated basement. The approximate "U" value for the climatic range applicable to Bozeman was .17. To comply with this standard, R-8 fiberglass was used resulting in thermal conductivities (coefficients of transmission) of .101 for the above ground portions of the wall which was exposed to the outside air, and .102 for the below ground portions.[31] (The differences in these values is due to the surface film resistance of the air on the exposed wall portions.) When urethane insulation was provided as an alternative to fiberglass in concrete wall constructions, a 1 inch layer rated at R-5.56 was used. This application resulted in respective thermal conductivities of .133 and .136 for the above and below ground wall sections. All the insulation levels that were defined here were used as points of reference from which net savings were calculated.

Throughout the study, optimal insulation levels were selected by cost minimizing procedures developed in microeconomic theory. By this criterion each wall structure was examined and the insulation level was identified which yielded the greatest net savings. Net savings

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[31] Following the example set by HUD, these "U" values are not adjusted for furring. The thermal conductivity of the soil is not included in the "U" value for the below ground portion of the wall.

from insulation were accounted in the following manner:

1. When the optimal insulation level was lower than that referenced as meeting HUD Standards, net savings from insulation were calculated using the following formula: net savings from insulation = (the present value of the stream of savings generated from the levels of insulation which exceeded the optimal level but were required by the HUD Standard) - (the cost incurred from the installation of those levels). These net savings are negative.

2. When the optimal insulation level equals that set by HUD in its Minimum Property Standards, net savings from insulation equal 0.

3. When the optimal insulation level exceeds that established by the HUD Standards, net savings from insulation = (the present value of the stream of savings generated from the levels of insulation which exceeded the HUD requirement but which were included in the optimal solution) - (the cost incurred from the installation of these levels). The net savings calculated in this circumstance are positive.

Thus from the sign and magnitude of the insulation net savings calculated for each wall structure, the effectiveness of the HUD Standards as an allocator of insulation resources can be appraised. If the calculated net savings are positive the MPS recommendation is a lower

level of insulation than is optimal. Hence the resources are not optimally allocated and the magnitude of the net savings indicates the present value of the additional stream of savings minus cost, which would be generated over the lifetime of the model home if the additional amount of insulation which would make the total investment optimal had been installed. A zero net savings means that the HUD recommendation and the optimal level coincide. Losses indicate that resources are not optimally allocated as more insulation has been installed in meeting the Minimum Property Standards than is optimal. The amount of the loss is a present value measure of the cost of over-insulating the walls of the model home. Calculated net savings from insulation for a wide variety of fuel prices, construction costs, and financial parameters are listed in many of the tables contained in Chapter 4.[32/]

The objectives of the U.S. Department of Housing and Urban Development in establishing minimum thermal requirements for residential walls dictates how these standards must be evaluated. The following quotes taken from the introductory statement and the statement of purpose of

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[32/] Construction costs include both the physical cost of the walls put in place and the measures of the homeowner's preferences or aversions to 1) living in a home having a partially buried wall, and 2) using the entryway necessitated by each wall design. See pages 49 - 57 for explanations of the definition and function of the costs associated with consumer preferences and aversions and Chapter 4 for examples of their use.

the HUD Minimum Property Standards (32) and (33), are considered to be representative of HUD policy for drafting these standards.

> "As a general policy, development of all properties must be consistent with the national program for conservation of energy and other natural resources, and care must be exercised to avoid air, water, land and noise pollution and other hazards to the environment..... The Standards describe those characteristics in a property which will provide present and continuing utility, durability, desirability, economy of maintenance, and a safe and healthful environment."

The standards were developed "to provide improved design and construction standards based more on performance than has been true in the past, with appropriate flexibility to meet local conditions," and "to encourage design innovations and improved building technologies giving promise of increased quality and reduced costs." Thus, from these statements of HUD, the objectives of the Federal Government in drafting minimum thermal standards for residential walls appear to be open to some interpretation as the purposes for the standards were defined only by broad guidelines.

The usefulness of these physical standards for housing must be evaluated from the intent of those who drafted them. The criterion used in this report to appraise these standards assumed the objectives of the HUD policy makers were consistent with cost minimization criteria achievable through the optimal allocation of resources. Such an interpretation is consistent with the HUD goals outlined above which called for the conservation of energy and resources in new construction

of low rent public housing insured for mortgage financing. The cost minimizing approach also helps assure a balance among present and continuing utility and reduced costs which are other government goals. Following is an appraisal of certain specifications for thermal wall performance which are set forth in Revision No. 1 to "Minimum Property Standards for One and Two-Family Dwellings."

When frame walls were examined in the model, fiberglass insulation in the commonly manufactured resistances of R-11, 13, 19, and 22 was used along with 1 inch boards of rigid urethane rated at R-5.56 in the optimization process. The cost minimizing design was found to have R-13 insulation placed between 2 x 4 wood studding 16 inches on center. Its overall coefficient to heat transmission, not adjusted for framing, was .061. This finding is applicable over the approximate winter degree day range of 3100 to 10,500 for heating fuel prices between $.167/100,000 BTU and $.501/100,000 BTU and construction costs from .8 to 2.7 times the representative values for Bozeman, Montana, in mid 1977. Thus, if HUD goals are consistent with cost minimizing policies, the standards set forth in Table 6-7.1 for maximum "U" values for frame walls should be upgraded from .08 to about .065 for climates where winter degree days exceed approximately 3100. In locations where the heating fuel prices exceed the range tested, higher insulation levels than R-13 are sometimes optimal for frame wall construction. The same applies for climates having much higher cooling hour requirements than the 225

which were tested by the model. Thus, R-13 is truly a minimum optimal insulation level in the winter degree day range specified.[33/]

An upgrading of the recommended minimum thermal standards for frame walls such as is suggested here is consistent with the HUD purpose, "to encourage design innovations and improved building technologies giving promise of increased quality and reduced costs." It is also consistent with the national program for conservation of energy. For example, a change from R-11 to R-13 in the frame wall sections of the single story 30 x 40 model home used in the calculations will mean a present value fuel savings to the homeowner over the lifetime of the building of $157,44 when the heating fuel is priced at $.251/100,000 BTU. (These fuel savings amount to 66 MCF of natural gas.) This assumes the house is located in the Bozeman, Montana climate described by 8343 degree days and is not refrigeration air conditioned.

Both urethane and fiberglass insulation were also examined in the optimum heated basement designs (which correspond to components 2

33/ The Minimum Property Standards approved by HUD recommend a wall insulation level which is lower than optimal. This disparity between the minimum and what is optimal, does not necessarily imply a policy change for the Federal Government, though, as minimum standards define merely the lowest thermal resistance of residential wall structures which are approved for mortgage insurance or as low rent public housing. A rational homebuilder will select an optimally insulated wall design over one just meeting current HUD minimal thermal standards as he realizes greatest net savings from optimally insulated structures.

and 3 in the model.) The findings demonstrated that the optimal amounts of both types of insulation are highly dependent on the fuel price and the portion of the total concrete wall area which was above ground level. Thus, no recommendations are given for upgrading the "U" values of the foundation wall sections of heated basements which are given in Table 6-7.3 of Revision No. 1 other than to suggest that future standards for these areas should reflect local heating and cooling fuel prices and the percentage of the total concrete wall area which is exposed to the outside air. This does not conclude the matter, however, as the approach used in the report has ramifications on the methods used by HUD in drafting the Minimum Property Standards for wall insulation. Two considerations are discussed in the following paragraphs.

The model used in this optimization study included the thermal qualities of the soil in its heat load calculations. In contrast, the HUD approach made no distinction between walls exposed to outside air and those beneath the surface of the ground. Such a method is easier but if a goal of cost minimization is to be followed, all energy conserving resources, including the soil, must be accounted for in the optimization process.

Net savings from a layer of insulation are defined as the present value of the stream of savings generated by the layer minus its total cost. The way in which these savings and costs are specified will have

considerable bearing on the optimal solution. Engineering standards accepted by HUD were complied with in the model for calculating the savings resulting from each layer of insulation. The references followed were the 1972 American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Handbook of Fundamentals, and the National Association of Homebuilders Research Foundation, Inc. (NAHB) Insulation Manual for Homes and Apartments (1), (18). Costs specified in the model may have varied widely from their counterparts defined in the HUD approach, however. In the following discussion no attempt is made to critique possible government goals; instead the discussion concentrates on the usefulness to HUD of the approach used in the model.

The type of costs which are the topic here are those arising from changes in wall structures necessitated by thermal modifications. Three such costs were defined in the model but only thick wall costs, which reflect changes in door jam and window sill construction and include the marginal cost of floor area losses in such designs, are relevant to the HUD insulation standards.[34/] The manner in which these

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[34/] This discussion of costs does not involve the proposed standard for frame walls which was recommended above because the installation of the optimal insulation level (R-13) required no physical alteration to the basic 2 x 4 wall structure. If the optimal level had been R-19, this discussion of costs would have applied as a thicker wall would have been required.

costs are defined should reflect the priorities of the homeowner, the government policy maker, or any other party in the matter. This is an important consideration as the accuracy by which resource costs can be defined determines how optimally they can be allocated. The model based all thick wall costs on the physical amounts required to make the changes in the wall structure. This approach reflected the viewpoint of the homeowner who must pay the construction costs. Such a specification may not reflect the priorities of HUD and so a minimization of costs based on such values would lead to suboptimal results from the viewpoint of that department. The federal government's goal, for example, may be to define standards which minimize fuel use. subject to certain constraints.

If the objective of the HUD organization is to encourage the widest possible voluntary compliance with these construction standards, outside its range of jurisdiction, it should consider drafting standards which will allocate the energy conserving resources of the homeowner in an optimal fashion, i.e. its MPS requirements for housing should reflect the priorities of the user of the building. Such an approach will capitalize on the cost minimizing incentive of the consumer as he will view the MPS requirements as construction guidelines which, if followed, will result in the lowest overall cost. If the objectives used in this study are any indication of the direction which future HUD

policy will take, coming standards will be the outgrowth of a well defined policy.

Chapter 6

RECOMMENDATIONS FOR FUTURE RESEARCH

This study appraised the net savings of certain thermal modifications to a basic 2 x 4 frame residential wall structure by simulating through a mathematical model the wall's response under heat loads representative of the local Bozeman, Montana climate. The thermal characteristics of the climate were expressed in the steady state terms of degree days, cooling hours, ground water temperatures, and equivalent temperature differences. Costs were minimized from the viewpoint of the homeowner so an emphasis was placed on defining consumer response to the structural modifications in a usable cost oriented manner. Materials and labor costs for the physical wall structure were based on typical prices encountered in the Bozeman area in mid 1977. Marginal analysis was used to compare the costs and savings associated with each insulation change and to identify optimum levels in an approach similar to that used by Steve Petersen in his National Bureau of Standards publication, "Retrofitting Existing Housing for Energy Conservation: An Economic Analysis" (24). When ground ratios were varied, the optimal wall configurations were selected on the basis of their net savings.

Three refinements seem evident if the model introduced in this study is to be extended for future research:

1. Windows and doors should be added to the living wall units so that

the net savings from these areas can be combined with the net savings from the solid wall areas calculated in this study. The end result would express more thoroughly the performance of each configuration.

2. Weather inputs need to be upgraded so that they can more precisely reflect actual annual loads faced by walls. This change is necessary if wall orientations and glass areas are to be included in the modeling calculations. Severe restrictions are imposed, however, on the type of weather data which can be used because of the large number of repetitive calculations required in computerized marginal analysis techniques. For this reason hourly and daily observations of drybulb temperatures and solar intensities are out of the question unless they are processed in some manner to extend the time period and to account for heat storage effects, time lags in heat transfer, solar azimuths, and surface effects (1, p. 386). A weather variable which does combine many of the factors mentioned here into one equivalent value is the sol-air temperature. This figure is the theoretical temperature of the outdoor air which through convection and conduction results in the same rate of heat entry into a wall surface as exists from the combined effects of the outside drybulb temperature, the incident solar radiation, and the various radiant energy

exchanges between the outside surface of the building and the sky and other surroundings. One drawback from using such figures to simulate yearly weather loads is that annual hours of cloud cover are not taken into account. Sol-air temperatures also are an hourly value so they could not efficiently be used unless a method of integration were employed to reduce their number and extend their period of coverage. A search of other methods to describe the climate is recommended.

3. The length, doorway and floor specifications of the model wall, which were the source of the measured bias discussed in this report, need to be refined. The entire benefit from perimeter insulation should also be computed.

Other possibilities include the addition of more cost ratios or the refinement of the present ones so the party for whom the design is maximized can make more concise definitions of his preferences. This current study was done from the viewpoint of the homeowner. Maximized wall designs reflecting the policies of fuel companies, or the Federal Government could be found through appropriate redefinition of costs.

Future research is needed in the following three areas:

1. Wood Foundation Systems. The analytical tools developed in this

study of grounded residential wall designs are suitable for appraising the merits of wood foundation systems. These structures incorporate relatively new technology and offer promise of reduced construction costs and greater fuel savings over concrete walls in optimally insulated grounded designs. Especially attractive are their large wall cavities, which are suitable for insulation, and the reduced labor and material expenditures and time inolved in their construction.

2. Total House Designs. The optimization of the entire thermal envelope of a residential building following the procedures introduced in this study is needed. The inclusion of windows and doors in the living wall units is the first step towards this goal. Once this has been done, only the floor and ceiling-roof zones are needed to complete the analysis.

3. Optimized Thickness of Insulation Batts. Many commercially manufactured insulation types are produced in several thicknesses, some of which are not optimal from a cost minimizing point of view for installation in walls, ceilings, and floors of residential buildings. For example, in the analysis, R-11 fiberglass was never selected over R-13 in optimized frame wall structures. The higher resistance R-13 batts were always chosen because they more completely utilized the available cavity space in 2 x 4 structures.

(Their cost/unit of resistance was comparable to R-11 batts.) A study is needed to review the present selection of insulation thicknesses available to the home construction industry and to recommend ones which are cost minimizing subject to constraints imposed by the Federal Government for thermal and structural design and by current technology in wall construction methods. The potential exists for reduced manufacturing and marketing costs in the insulation industry if the number of thicknesses of each insulation type are reduced.[35/] Greater savings to the homeowner may also result from the use of optimized resistances in the thermal envelope of his residence.

35/ A reduction in the number of insulation thicknesses manufactured would not necessarily lead to a suboptimal choice of levels available for residential applications. Going back to the example of the fiberglass batts, if R-11 was not manufactured, R-13 would be the cost minimizing insulation thickness over the climatic range defined by 970 to 10,500 degree days.

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APPENDICES

APPENDIX A

Table A.1

Functional Dependency of Ground Ratio Savings on Air Conditioning, Fuel Price, and Insulation Type

EXR	ENR	IN	FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	-57.51	-168.55	-279.59	-390.63	-305.59	-377.84	-450.09	-522.34	-274.22	-311.41
1	1	F	.167	YES	-56.97	-166.88	-276.79	-386.70	-300.33	-371.45	-442.57	-513.68	-264.27	-300.26
1	1	F	.251	NO	-86.43	-253.33	-242.12	-350.71	-459.30	-249.46	-304.09	-358.72	-412.15	-105.45
1	1	F	.251	YES	-85.63	-250.82	-237.63	-344.52	-451.42	-239.66	-292.59	-345.52	-397.22	-88.63
1	1	F	.334	NO	-115.02	-177.68	-322.18	-186.56	-259.25	-331.95	-73.38	-96.77	12.53	183.42
1	1	F	.334	YES	-113.94	-173.96	-316.20	-178.03	-248.46	-318.89	-57.91	-79.05	34.20	205.94
1	1	F	.501	NO	1635.51	1233.24	1143.44	1123.94	903.33	998.16	833.37	668.58	502.87	331.83
1	1	F	.501	YES	1658.58	1257.41	1169.13	1150.94	931.42	1027.49	863.79	700.10	535.51	365.62
1	1	U	.167	NO	-80.40	-209.45	-338.50	-467.54	-596.59	-725.64	-854.69	-524.23	-597.36	-672.66
1	1	U	.167	YES	-79.94	-207.80	-335.66	-463.52	-591.38	-719.24	-847.10	-515.15	-587.07	-661.12
1	1	U	.251	NO	-120.84	-314.80	-240.47	-349.96	-459.45	-568.94	-678.43	-787.92	-447.43	-507.69
1	1	U	.251	YES	-120.14	-312.32	-235.75	-343.46	-451.17	-558.87	-666.58	-774.29	-431.80	-490.18
1	1	U	.334	NO	-197.03	-246.74	-428.66	-350.22	-464.76	-579.29	-693.83	-808.37	-922.60	-1040.84
1	1	U	.334	YES	-196.54	-243.72	-423.71	-343.10	-455.71	-568.32	-680.94	-793.55	-905.82	-1022.04
1	1	U	.501	NO	-97.23	-181.71	-353.52	-525.33	-377.40	-481.79	-586.19	-690.58	-792.82	-899.79
1	1	U	.501	YES	-95.59	-176.80	-345.72	-514.64	-363.63	-465.13	-566.64	-668.14	-767.43	-871.37

Table A.2

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.1

	INCREMENT NO.	
GR	COMP1	COMP23
90	2	2
90	2	2
90	2	2
90	2	2
0		10
0		10
90	12	4
90	12	4
90	2	1
90	2	1
90	2	1
90	2	1
90	3	1
90	3	1
90	3	2
90	3	2

Table A.3

Functional Dependency of Net Savings from Insulation and the Ground Ratio on Air Conditioning and Fuel Price (Fiberglass Insulation is Used.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	66.48	-235.04	-182.86	-386.35	-590.18	-1086.16	-1869.91	-2383.95	-2898.17	-3389.77	-3856.10
1	1	F	.167	YES	67.78	-232.74	-180.15	-382.63	-585.45	-1080.02	-1862.77	-2375.79	-2889.01	-3379.27	-3844.55
1	1	F	.251	NO	119.18	-158.41	-225.40	-449.15	-633.52	-1113.73	-1835.23	-2284.77	-2734.46	-3182.35	-3599.44
1	1	F	.251	YES	121.12	-154.96	-221.33	-442.96	-625.82	-1104.52	-1824.05	-2272.07	-2720.27	-3166.61	-3581.86
1	1	F	.334	NO	171.24	-135.53	-227.59	-432.92	-588.62	-968.24	-1673.38	-2042.32	-2411.69	-2757.70	-3088.43
1	1	F	.334	YES	173.84	-132.11	-221.37	-424.67	-577.74	-955.34	-1658.47	-2025.09	-2392.45	-2733.18	-3064.81
1	1	F	.501	NO	276.00	320.37	234.67	89.88	51.85	-216.45	-760.64	-999.53	-1239.66	-1473.48	-1812.84
1	1	F	.501	YES	279.89	368.44	281.21	135.76	96.64	-173.25	-718.71	-959.18	-1200.91	-1436.37	-1777.39

Table A.4

Functional Dependency of Net Savings from Insulation and the Ground Ratio on Air Conditioning and Fuel Price (Urethane Insulation is Used.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	.00	-14.16	37.72	-102.82	-243.56	-679.98	-1441.81	-1933.95	-2417.23	-2885.43	-3356.73
1	1	U	.167	YES	.00	-13.69	39.37	-99.98	-239.53	-674.76	-1435.40	-1926.35	-2407.77	-2874.76	-3344.81
1	1	U	.251	NO	.00	-54.60	-67.64	-209.78	-333.11	-752.31	-1497.09	-1972.28	-2447.51	-2919.93	-3373.40
1	1	U	.251	YES	.00	-53.90	-65.16	-204.51	-326.05	-743.46	-1486.45	-1959.86	-2433.31	-2903.48	-3355.09
1	1	U	.334	NO	20.83	-77.86	-55.78	-190.30	-315.30	-689.12	-1388.63	-1818.48	-2248.55	-2675.90	-3106.89
1	1	U	.334	YES	25.36	-73.29	-48.40	-181.43	-304.40	-676.75	-1374.76	-1803.13	-2231.72	-2657.57	-3087.00
1	1	U	.501	NO	203.47	82.26	113.27	51.87	-11.10	-319.81	-946.96	-1304.53	-1662.44	-2013.15	-2366.98
1	1	U	.501	YES	210.27	91.00	125.13	65.98	5.25	-300.79	-925.72	-1281.06	-1636.75	-1985.19	-2336.69

Table A.5

Functional Dependency of Net Savings from Insulation and the Ground Ratio on the Excavation Cost Ratio and Fuel Price (Fiberglass Insulation is Used.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
0	1	F	.167	NO	66.48	-332.29	-293.20	-417.56	-562.36	-968.20	-1661.81	-2085.72	-2509.80	-2911.27	-3287.47
0	1	F	.251	NO	119.18	-255.65	-335.74	-480.36	-605.69	-995.77	-1627.13	-1986.54	-2346.09	-2703.85	-3030.81
0	1	F	.334	NO	171.24	-232.77	-337.93	-464.13	-560.80	-850.28	-1465.28	-1744.10	-2023.33	-2279.21	-2519.80
0	1	F	.501	NO	276.00	223.12	124.32	58.67	79.68	-98.49	-552.54	-701.31	-851.30	-994.98	-1244.22
1	1	F	.167	NO	66.48	-235.04	-182.86	-386.35	-590.18	-1086.16	-1869.91	-2383.95	-2898.17	-3389.77	-3856.10
1	1	F	.251	NO	119.18	-158.41	-225.40	-449.15	-633.52	-1113.73	-1835.23	-2284.77	-2734.46	-3182.35	-3599.44
1	1	F	.334	NO	171.24	-135.53	-227.59	-432.92	-588.62	-968.24	-1673.38	-2042.32	-2411.69	-2757.70	-3088.43
1	1	F	.501	NO	276.00	320.37	234.67	89.88	51.85	-216.45	-760.64	-999.53	-1239.66	-1473.48	-1812.84
2	1	F	.167	NO	66.48	-137.80	-72.52	-355.14	-618.01	-1204.11	-2078.00	-2682.17	-3286.53	-3868.26	-4424.72
2	1	F	.251	NO	119.18	-61.17	-115.06	-417.93	-661.35	-1231.69	-2043.33	-2582.99	-3122.83	-3660.85	-4168.06
2	1	F	.334	NO	171.24	-38.29	-117.25	-401.71	-616.45	-1086.19	-1881.48	-2340.55	-2800.06	-3236.20	-3657.06
2	1	F	.501	NO	276.00	417.61	345.01	121.10	24.02	-334.41	-968.74	-1297.76	-1628.03	-1951.97	-2381.47

Table A.6

Functional Dependency of Net Savings from Insulation and the Ground Ratio on the Excavation Cost Ratio and Fuel Price (Urethane Insulation is Used.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
0	1	U	.167	NO	.00	-111.40	-72.63	-134.04	-215.73	-562.02	-1233.71	-1635.72	-2028.87	-2406.94	-2788.11
0	1	U	.251	NO	.00	-151.84	-177.98	-241.00	-305.29	-634.36	-1288.99	-1674.05	-2059.14	-2441.43	-2804.77
0	1	U	.334	NO	20.83	-175.10	-166.12	-221.51	-287.47	-571.17	-1180.53	-1520.25	-1860.19	-2197.40	-2538.26
0	1	U	.501	NO	203.47	-14.99	2.93	20.66	16.73	-201.85	-738.86	-1006.30	-1274.07	-1534.66	-1798.35
1	1	U	.167	NO	.00	-14.16	37.72	-102.82	-243.56	-679.98	-1441.81	-1933.95	-2417.23	-2885.43	-3356.73
1	1	U	.251	NO	.00	-54.60	-67.64	-209.78	-333.11	-752.31	-1497.09	-1972.28	-2447.51	-2919.93	-3373.40
1	1	U	.334	NO	20.83	-77.86	-55.78	-190.30	-315.30	-689.12	-1388.63	-1818.48	-2248.55	-2675.90	-3106.89
1	1	U	.501	NO	203.47	82.26	113.27	51.87	-11.10	-319.81	-946.96	-1304.53	-1662.44	-2013.15	-2366.98
2	1	U	.167	NO	.00	83.08	148.06	-71.61	-271.39	-797.93	-1649.90	-2232.17	-2805.60	-3363.93	-3925.36
2	1	U	.251	NO	.00	42.64	42.71	-178.57	-360.94	-870.27	-1705.19	-2270.50	-2835.88	-3398.43	-3942.03
2	1	U	.334	NO	20.83	19.39	54.57	-159.09	-343.13	-807.08	-1596.72	-2116.71	-2636.92	-3154.39	-3675.51
2	1	U	.501	NO	203.47	179.50	223.62	83.08	-38.92	-437.76	-1155.05	-1602.76	-2050.80	-2491.65	-2935.61

Table A.7

Functional Dependency of Net Savings from Insulation and the Ground Ratio on the Entrance Cost Ratio and Fuel Price (Fiberglass Insulation is Used.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	0	F	.167	NO	66.48	-235.04	-182.86	-286.35	-452.68	-828.66	-1492.41	-1886.45	-2280.67	-2652.27	-2998.60
1	0	F	.251	NO	119.18	-158.41	-225.40	-349.15	-496.02	-856.23	-1457.73	-1787.27	-2116.96	-2444.85	-2741.94
1	0	F	.334	NO	171.24	-135.53	-227.59	-332.92	-451.12	-710.74	-1295.88	-1544.82	-1794.19	-2020.20	-2230.93
1	0	F	.501	NO	276.00	320.37	234.67	189.88	189.35	41.05	-383.14	-502.03	-622.16	-735.98	-955.34
1	1	F	.167	NO	66.48	-235.04	-182.86	-386.35	-590.18	-1086.16	-1869.91	-2383.95	-2898.17	-3389.77	-3856.10
1	1	F	.251	NO	119.18	-158.41	-225.40	-449.15	-633.52	-1113.73	-1835.23	-2284.77	-2734.46	-3182.35	-3599.44
1	1	F	.334	NO	171.24	-135.53	-227.59	-432.92	-588.62	-968.24	-1673.38	-2042.32	-2411.69	-2757.70	-3088.43
1	1	F	.501	NO	276.00	320.37	234.67	89.88	51.85	-216.45	-760.64	-999.53	-1239.66	-1473.48	-1812.84
1	2	F	.167	NO	66.48	-235.04	-182.86	-486.35	-727.68	-1343.66	-2247.41	-2881.45	-3515.67	-4127.27	-4713.59
1	2	F	.251	NO	119.18	-158.41	-225.40	-549.15	-771.02	-1371.23	-2212.73	-2782.27	-3351.96	-3919.85	-4456.93
1	2	F	.334	NO	171.24	-135.53	-227.59	-532.92	-726.12	-1225.74	-2050.88	-2539.82	-3029.19	-3495.20	-3945.93
1	2	F	.501	NO	276.00	320.37	234.67	-10.12	-85.65	-473.95	-1138.14	-1497.03	-1857.16	-2210.98	-2670.34

Table A.8

Functional Dependency of Net Savings from Insulation and the Ground Ratio on the Entrance Cost Ratio and Fuel Price (Urethane Insulation is Used.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	0	U	.167	NO	.00	-14.16	37.72	-2.82	-106.06	-422.48	-1064.31	-1436.45	-1799.73	-2147.93	-2499.23
1	0	U	.251	NO	.00	-54.60	-67.64	-109.78	-195.61	-494.81	-1119.59	-1474.78	-1830.01	-2182.43	-2515.90
1	0	U	.334	NO	20.83	-77.86	-55.78	-90.30	-177.80	-431.62	-1011.13	-1320.98	-1631.05	-1938.40	-2249.39
1	0	U	.501	NO	203.47	82.26	113.27	151.87	126.40	-62.31	-569.46	-807.03	-1044.94	-1275.65	-1509.48
1	1	U	.167	NO	.00	-14.16	37.72	-102.82	-243.56	-679.98	-1441.81	-1933.95	-2417.23	-2885.43	-3356.73
1	1	U	.251	NO	.00	-54.60	-67.64	-209.78	-333.11	-752.31	-1497.09	-1972.28	-2447.51	-2919.93	-3373.40
1	1	U	.334	NO	20.83	-77.86	-55.78	-190.30	-315.30	-689.12	-1388.63	-1818.48	-2248.55	-2675.90	-3106.89
1	1	U	.501	NO	203.47	82.26	113.27	51.87	-11.10	-319.81	-946.96	-1304.53	-1662.44	-2013.15	-2366.98
1	2	U	.167	NO	.00	-14.16	37.72	-202.82	-381.06	-937.48	-1819.31	-2431.45	-3034.73	-3622.93	-4214.23
1	2	U	.251	NO	.00	-54.60	-67.64	-309.78	-470.61	-1009.81	-1874.59	-2469.78	-3065.01	-3657.43	-4230.90
1	2	U	.334	NO	20.83	-77.86	-55.78	-290.30	-452.80	-946.62	-1766.13	-2315.98	-2866.05	-3413.40	-3964.39
1	2	U	.501	NO	203.47	82.26	113.27	-48.13	-148.60	-577.31	-1324.46	-1802.03	-2279.94	-2750.65	-3224.48

Table A.9

Functional Dependency of Net Savings from Fiberglass Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 100% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	66.48	-235.04	-182.86	-386.35	-590.18	-1086.16	-1869.91	-2383.95	-2898.17	-3389.77	-3856.10
1	1	F	.251	NO	119.18	-158.41	-225.40	-449.15	-633.52	-1113.73	-1835.23	-2284.77	-2734.46	-3182.35	-3599.44
1	1	F	.334	NO	171.24	-135.53	-227.59	-432.92	-588.62	-968.24	-1673.38	-2042.32	-2411.69	-2757.70	-3088.43
1	1	F	.501	NO	276.00	320.37	234.67	89.88	51.85	-216.45	-760.64	-999.53	-1239.66	-1473.48	-1812.84

Table A.10

Functional Dependency of Net Savings from Fiberglass Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 75% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	66.48	-226.81	-138.36	-273.76	-427.00	-875.89	-1650.27	-2155.00	-2659.74	-3157.31	-3645.69
1	1	F	.251	NO	119.18	-146.02	-132.24	-320.76	-480.37	-913.58	-1672.40	-2156.73	-2586.45	-3015.13	-3445.66
1	1	F	.334	NO	171.24	-112.76	-143.46	-291.72	-435.21	-851.15	-1529.62	-1938.62	-2347.81	-2736.43	-3116.86
1	1	F	.501	NO	276.00	353.85	352.23	185.07	137.54	-194.49	-785.60	-1107.43	-1408.27	-1669.44	-2034.98

Table A.11

Functional Dependency of Net Savings from Fiberglass Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 50% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	66.48	-218.56	-95.12	-170.55	-263.81	-662.11	-1385.88	-1840.01	-2294.15	-2753.52	-3213.23
1	1	F	.251	NO	119.18	-133.63	-39.07	-151.54	-264.34	-672.81	-1406.77	-1867.47	-2309.86	-2755.59	-3201.55
1	1	F	.334	NO	171.24	-89.99	-19.49	-142.01	-231.41	-608.31	-1310.87	-1743.78	-2150.84	-2515.19	-2913.59
1	1	F	.501	NO	276.00	388.01	469.79	376.85	282.41	-30.86	-660.78	-1021.63	-1383.57	-1721.11	-2146.18

Table A.12

Functional Dependency of Net Savings from Fiberglass Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 25% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	66.48	-210.32	-51.89	-93.03	-136.09	-475.47	-1140.66	-1536.42	-1932.22	-2337.33	-2744.43
1	1	F	.251	NO	119.18	-121.24	54.09	17.67	-19.08	-351.49	-1009.39	-1397.64	-1785.91	-2180.55	-2571.76
1	1	F	.334	NO	171.24	-67.22	104.48	83.16	61.51	-255.83	-898.63	-1271.79	-1644.96	-2008.46	-2401.13
1	1	F	.501	NO	276.00	422.16	587.35	588.64	588.11	291.18	-331.74	-685.39	-1040.13	-1416.58	-1846.04

Table A.13

Functional Dependency of Net Savings from Urethane Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 100% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	.00	-14.16	37.72	-102.82	-243.56	-679.98	-1441.81	-1933.95	-2417.23	-2885.43	-3356.73
1	1	U	.251	NO	.00	-54.60	-67.64	-209.78	-333.11	-752.31	-1497.09	-1972.28	-2447.51	-2919.93	-3373.40
1	1	U	.334	NO	20.83	-77.86	-55.78	-190.30	-315.30	-689.12	-1388.63	-1818.48	-2248.55	-2675.90	-3106.89
1	1	U	.501	NO	203.47	82.26	113.27	51.87	-11.10	-319.81	-946.96	-1304.53	-1662.44	-2013.15	-2366.98

Table A.14

Functional Dependency of Net Savings from Urethane Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 75% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	.00	-1.51	106.56	22.22	-62.31	-442.53	-1148.16	-1584.10	-2020.04	-2460.51	-2901.95
1	1	U	.251	NO	.00	-35.59	35.84	-85.14	-194.15	-570.98	-1273.44	-1706.33	-2139.28	-2573.39	-3009.06
1	1	U	.334	NO	20.83	-52.57	15.86	-61.88	-140.96	-516.09	-1216.90	-1648.16	-2079.34	-2485.32	-2892.93
1	1	U	.501	NO	203.47	102.76	200.09	135.10	106.59	-218.34	-869.15	-1250.42	-1632.00	-2002.50	-2356.31

Table A.15

Functional Dependency of Net Savings from Urethane Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 50% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	.00	11.13	175.40	147.26	118.93	-205.09	-854.52	-1234.26	-1614.00	-1998.27	-2381.27
1	1	U	.251	NO	.00	-16.59	139.31	102.80	66.09	-266.31	-924.11	-1312.22	-1700.34	-2094.43	-2486.13
1	1	U	.334	NO	20.83	-27.28	116.21	66.54	43.95	-274.80	-919.29	-1294.27	-1669.35	-2045.97	-2421.21
1	1	U	.501	NO	203.47	123.26	307.54	291.16	272.52	-42.53	-683.21	-1030.52	-1378.18	-1724.57	-2069.48

Table A.16

Functional Dependency of Net Savings from Urethane Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 25% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	.00	23.78	244.25	272.31	300.17	32.35	-560.88	-884.42	-1207.96	-1536.03	-1860.60
1	1	U	.251	NO	.00	2.42	242.78	290.74	338.49	90.57	-482.77	-786.41	-1090.06	-1399.68	-1703.56
1	1	U	.334	NO	20.83	-1.99	253.90	317.39	380.67	148.26	-409.54	-697.67	-985.78	-1281.45	-1569.22
1	1	U	.501	NO	203.47	143.77	414.99	483.79	549.89	319.39	-237.04	-524.09	-811.31	-1101.79	-1385.46

Table A.17

Functional Dependency of Net Savings from Fiberglass Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 100% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	1827.95	1595.85	1378.53	1086.23	790.99	202.52	-674.25	-1281.63	-1889.30	-2476.48	-3039.76
1	1	F	.251	NO	2867.71	2511.56	2310.13	1954.99	1635.35	1018.31	159.20	-428.42	-1016.40	-1606.18	-2167.34
1	1	F	.334	NO	3895.10	3515.36	3270.48	2891.68	2557.40	1997.13	1110.31	559.07	7.12	-526.53	-1047.91
1	1	F	.501	NO	5962.24	5982.56	5669.39	5266.48	4962.71	4425.59	3611.06	3100.93	2589.07	2075.58	1451.84

Table A.18

Functional Dependency of Net Savings from Fiberglass Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 75% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	1827.95	1609.17	1456.71	1143.60	872.99	305.55	-587.98	-1212.20	-1836.57	-2456.63	-3069.23
1	1	F	.251	NO	2867.71	2531.59	2358.90	2000.38	1666.50	1057.27	121.57	-540.15	-1147.49	-1758.49	-2374.11
1	1	F	.334	NO	3895.10	3528.24	3295.54	2922.43	2548.45	1899.73	987.32	343.72	-300.40	-930.46	-1556.12
1	1	F	.501	NO	5962.24	6001.21	5698.35	5196.02	4804.87	4125.83	3185.99	2514.44	1863.38	1241.82	510.06

Table A.19

Functional Dependency of Net Savings from Fiberglass Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 50% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

					NET SAVINGS FROM INSULATION AND GROUND RATIO									
EXR	ENR	IN	FUEL	AIR	100	90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	1827.95	1622.51	1528.32	1234.74	955.01	412.08	-456.96	-1056.73	-1656.68	-2265.44	-2876.66
1	1	F	.251	NO	2867.71	2551.62	2407.68	2086.61	1760.52	1136.85	186.75	-490.65	-1150.01	-1818.49	-2490.55
1	1	F	.334	NO	3895.10	3541.11	3360.44	2961.71	2589.90	1928.07	939.33	219.51	-474.83	-1134.41	-1832.61
1	1	F	.501	NO	5962.24	6020.52	5727.32	5222.15	4706.21	3967.71	2910.71	2121.68	1330.97	552.36	-320.80

Table A.20

Functional Dependency of Net Savings from Fiberglass Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 25% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

					NET SAVINGS FROM INSULATION AND GROUND RATIO									
EXR	ENR	IN	FUEL	AIR	100	90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	1827.95	1635.83	1599.93	1364.23	1126.49	592.33	-267.61	-858.07	-1448.65	-2061.84	-2647.74
1	1	F	.251	NO	2867.71	2571.65	2456.45	2172.83	1883.77	1296.98	383.67	-260.59	-905.16	-1562.98	-2221.30
1	1	F	.334	NO	3895.10	3553.99	3425.34	3076.45	2720.46	2066.07	1084.84	372.45	-340.35	-1052.88	-1799.92
1	1	F	.501	NO	5962.24	6039.84	5756.28	5268.28	4768.39	3968.02	2839.63	1979.34	1117.31	219.08	-740.33

Table A.21

Functional Dependency of Net Savings from Urethane Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 100% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

					NET SAVINGS FROM INSULATION AND GROUND RATIO										
EXR	ENR	IN	FUEL	AIR	100	90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	1276.57	1351.55	1373.53	1193.65	1011.22	532.16	-272.78	-808.30	-1335.13	-1848.21	-2365.24
1	1	U	.251	NO	2294.05	2336.20	2241.00	2002.51	1779.30	1258.79	411.98	-165.64	-743.55	-1321.89	-1883.19
1	1	U	.334	NO	3320.26	3325.84	3214.12	2926.92	2644.53	2111.41	1251.68	661.06	69.89	-523.72	-1123.90
1	1	U	.501	NO	5525.75	5523.93	5317.24	4989.83	4653.76	4069.12	3164.62	2528.89	1892.32	1253.99	607.49

Table A.22

Functional Dependency of Net Savings from Urethane Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 75% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

					NET SAVINGS FROM INSULATION AND GROUND RATIO										
EXR	ENR	IN	FUEL	AIR	100	90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	1276.57	1360.31	1419.14	1275.26	1128.61	685.25	-84.04	-583.93	-1084.01	-1590.51	-2099.14
1	1	U	.251	NO	2294.05	2349.35	2309.57	2061.88	1822.28	1313.33	477.96	-88.28	-654.85	-1226.69	-1802.45
1	1	U	.334	NO	3320.26	3343.34	3239.30	2968.48	2691.16	2115.74	1213.60	580.43	-53.03	-667.58	-1287.31
1	1	U	.501	NO	5525.75	5532.76	5334.37	4942.75	4579.90	3917.53	2927.73	2206.58	1484.58	762.99	52.12

Table A.23

Functional Dependency of Net Savings from Urethane Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 50% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	1276.57	1369.05	1464.75	1356.87	1246.01	838.34	104.70	-359.56	-824.03	-1295.49	-1767.14
1	1	U	.251	NO	2294.05	2362.52	2378.13	2184.54	1986.56	1491.21	669.62	117.25	-435.44	-999.05	-1563.10
1	1	U	.334	NO	3320.26	3360.85	3293.19	3010.03	2748.37	2188.32	1301.41	683.37	64.83	-562.67	-1192.96
1	1	U	.501	NO	5525.75	5541.59	5372.13	4968.52	4554.27	3840.26	2798.94	2050.04	1300.20	539.26	-227.10

Table A.24

Functional Dependency of Net Savings from Urethane Insulation and the Ground Ratio on the Fuel Price (The Component 3 Heat Load is 25% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

EXR	ENR	IN	FUEL	AIR	NET SAVINGS FROM INSULATION AND GROUND RATIO 100	90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	1276.57	1377.81	1510.37	1438.49	1363.40	991.42	293.44	-135.20	-564.05	-1000.48	-1435.16
1	1	U	.251	NO	2294.05	2375.68	2446.68	2307.20	2162.99	1721.31	953.30	454.47	-44.69	-555.64	-1064.12
1	1	U	.334	NO	3320.26	3378.36	3384.42	3174.01	2957.39	2442.67	1601.35	1029.02	456.27	-132.59	-718.34
1	1	U	.501	NO	5525.75	5550.42	5409.89	5030.85	4640.09	3949.13	2930.42	2180.06	1428.89	660.37	-109.14

Table A.25

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.3

	INCREMENT NO.	
GR	COMP1	COMP23
100	2	
100	2	
100	2	
100	2	
100	2	
100	2	
90	12	4
90	12	4

Table A.26

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.4

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	1
80	2	1
100	2	
100	2	
100	3	
100	3	
100	3	
100	3	

Table A.27

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.5

GR	INCREMENT NO. COMP1	COMP23
100	2	
100	2	
100	2	
100	2	
100	2	
100	2	
100	2	
90	12	4
100	2	
100	2	
100	2	
90	12	4

Table A.28

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.6

GR	INCREMENT NO. COMP1	COMP23
100	2	
100	2	
100	3	
100	3	
80	2	1
100	2	
100	3	
100	3	
80	2	1
80	2	1
80	3	2
80	3	3

Table A.29

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.7

	INCREMENT NO.	
GR	COMP1	COMP23
100	2	
100	2	
100	2	
90	12	4
100	2	
100	2	
100	2	
90	12	4
100	2	
100	2	
100	2	
90	12	4

Table A.30

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.8

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	1
100	2	
100	3	
100	3	
80	2	1
100	2	
100	3	
100	3	
80	2	1
100	2	
100	3	
100	3	

Table A.31

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Tables A.9 and A.17

	INCREMENT NO.	
GR	COMP1	COMP23
100	2	
100	2	
100	2	
90	12	4

Table A.32

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Tables A.10 and A.18 - A.20

	INCREMENT NO.	
GR	COMP1	COMP23
100	2	
100	2	
100	2	
90	12	2

Table A.33

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.11

	INCREMENT NO.	
GR	COMP1	COMP23
100	2	
100	2	
100	2	
80	12	4

Table A.34

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.12

	INCREMENT NO.	
GR	COMP1	COMP23
100	2	
100	2	
100	2	
70	12	4

Table A.35

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.13

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	1
100	2	
100	3	
100	3	

Table A.36

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.14

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	1
80	2	1
100	3	
100	3	

Table A.37

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.15

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	1
80	2	1
80	3	1
80	3	2

Table A.38

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.16

	INCREMENT NO.	
GR	COMP1	COMP23
60	2	1
60	2	1
60	3	1
60	3	2

Table A.39

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.21

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	1
90	2	1
90	3	1
100	3	

Table A.40

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.22

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	1
90	2	1
90	3	1
90	3	2

Table A.41

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.23

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	1
80	2	1
90	3	1
90	3	2

Table A.42

Insulation and Ground Ratio Specifications for the Optimal Net Savings Cases in Table A.24

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	1
80	2	1
80	3	1
90	3	2

Table A.43

Functional Dependency of Ground Ratio Savings on the Fuel Price (Fiberglass Insulation is Used. The Component 3 Heat Load is 100% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	-57.51	-168.55	-279.59	-390.63	-305.59	-377.84	-450.09	-522.34	-274.22	-311.41
1	1	F	.251	NO	-86.43	-253.33	-242.12	-350.71	-459.30	-249.46	-304.09	-358.72	-412.15	-105.45
1	1	F	.334	NO	-115.02	-177.68	-322.18	-186.56	-259.25	-331.95	-73.38	-96.77	12.53	183.42
1	1	F	.501	NO	1635.51	1233.24	1143.44	1123.94	903.33	998.16	833.37	668.58	502.87	331.83

Table A.44

Functional Dependency of Ground Ratio Savings on the Fuel Price (Fiberglass Insulation is Used. The Component 3 Heat Load is 75% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	-46.12	-106.56	-167.01	-227.45	-287.89	-348.33	-408.77	-469.22	-258.55	-290.73
1	1	F	.251	NO	-69.32	-160.17	-251.01	-152.45	-199.56	-246.68	-5.38	-12.02	-17.47	-23.47
1	1	F	.334	NO	-92.25	-213.13	-140.16	-202.86	10.52	1.69	-7.16	-16.00	436.36	337.09
1	1	F	.501	NO	1546.91	1383.56	1356.55	1157.77	1229.89	1086.57	943.25	1126.19	1023.82	918.63

Table A.45

Functional Dependency of Ground Ratio Savings on the Fuel Price (Fiberglass Insulation is Used. The Component 3 Heat Load is 50% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	-34.74	-44.58	-54.42	-64.26	-74.10	-83.94	-93.79	-103.63	-115.41	-125.50
1	1	F	.251	NO	-52.21	-67.00	-81.80	-96.59	-111.38	-126.17	88.89	103.25	117.04	132.59
1	1	F	.334	NO	-69.48	-89.16	-108.84	60.96	80.07	99.18	118.29	445.34	631.88	560.35
1	1	F	.501	NO	1581.06	1533.87	1377.02	1220.16	1363.66	1260.66	1157.65	1054.65	1290.28	1221.73

Table A.46

Functional Dependency of Ground Ratio Savings on the Fuel Price (Fiberglass Insulation is Used. The Component 3 Heat Load is 25% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	F	.167	NO	-23.35	17.41	58.16	98.92	139.68	180.44	221.20	261.96	300.78	343.30
1	1	F	.251	NO	-35.10	26.16	87.42	148.68	209.94	271.20	332.46	393.72	452.07	515.98
1	1	F	.334	NO	-46.71	34.81	116.33	197.85	279.36	360.88	442.40	523.92	731.50	686.60
1	1	F	.501	NO	1615.22	1684.19	1650.04	1615.89	1581.74	1547.59	1513.45	1479.30	1735.60	1727.90

Table A.47

Functional Dependency of Ground Ratio Savings on the Fuel Price (Urethane Insulation is Used. The Component 3 Heat Load is 100% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	-80.40	-209.45	-338.50	-467.54	-596.59	-725.64	-854.69	-524.23	-597.36	-672.66
1	1	U	.251	NO	-120.84	-314.80	-240.47	-349.96	-459.45	-568.94	-678.43	-787.92	-447.43	-507.69
1	1	U	.334	NO	-197.03	-246.74	-428.66	-350.22	-464.76	-579.29	-693.83	-808.37	-922.60	-1040.84
1	1	U	.501	NO	-97.23	-181.71	-353.52	-525.33	-377.40	-481.79	-586.19	-690.58	-792.82	-899.79

Table A.48

Functional Dependency of Ground Ratio Savings on the Fuel Price (Urethane Insulation is Used. The Component 3 Heat Load is 75% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	-67.76	-140.60	-213.45	-286.30	-359.15	-432.00	-504.84	-577.69	-653.41	-729.14
1	1	U	.251	NO	-101.84	-211.33	-320.82	-145.65	-191.79	-237.93	-284.07	-330.21	-376.77	-424.07
1	1	U	.334	NO	-171.74	-143.47	-241.09	-338.71	-436.33	-533.95	-631.57	-321.01	-367.79	-415.89
1	1	U	.501	NO	-68.78	-215.21	-128.39	-199.01	-269.64	-340.27	-410.89	-481.52	-99.22	-118.52

Table A.49

Functional Dependency of Ground Ratio Savings on the Fuel Price (Urethane Insulation is Used. The Component 3 Heat Load is 50% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	-55.11	-71.76	-88.41	-105.06	-121.71	-138.35	-155.00	-171.65	-191.17	-208.47
1	1	U	.251	NO	-82.83	-107.85	-132.88	-157.90	-182.92	-207.94	-232.97	-257.99	-287.32	-313.32
1	1	U	.334	NO	-146.45	-215.97	-53.53	-66.84	-80.17	-93.48	-106.80	-120.12	-135.22	-148.57
1	1	U	.501	NO	-40.33	-60.31	-80.29	-100.27	-120.25	188.41	218.96	249.52	280.54	313.59

Table A.50

Functional Dependency of Ground Ratio Savings on the Fuel Price (Urethane Insulation is Used. The Component 3 Heat Load is 25% of Engineering Standards.)

EXR	ENR	IN	FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	U	.167	NO	-42.47	-2.92	36.64	76.19	115.74	155.29	194.84	234.39	271.08	312.21
1	1	U	.251	NO	-63.83	-4.38	55.06	114.51	173.95	233.40	292.85	352.29	407.43	469.25
1	1	U	.334	NO	-121.16	-78.28	-35.40	7.48	50.36	93.24	136.12	179.00	214.94	259.14
1	1	U	.501	NO	-11.88	94.59	201.06	307.53	414.00	520.47	626.94	733.41	837.22	948.67

Table A.51

Functional Dependency of Ground Ratio Savings on the Fuel Price
(The Component 3 Heat Load is 100% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

EXR	ENR	IN FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	F .167	NO	-169.66	-168.55	-279.59	-390.63	-305.59	-377.84	-450.09	-522.34	-274.22	-311.41
1	1	F .251	NO	-255.00	-253.33	-242.12	-350.71	-459.30	-249.46	-304.09	-358.72	-412.15	-105.45
1	1	F .334	NO	-115.02	-177.68	-322.18	-186.56	-259.25	-331.95	-73.38	-96.77	12.53	183.42
1	1	F .501	NO	1635.51	1233.24	1143.44	1123.94	903.33	998.16	833.37	668.58	502.87	331.83

Table A.52

Functional Dependency of Ground Ratio Savings on the Fuel Price
(The Component 3 Heat Load is 75% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

EXR	ENR	IN FUEL	AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	F .167	NO	-154.53	-264.94	-167.01	-227.45	-287.89	-348.33	-408.77	-469.22	-258.55	-290.73
1	1	F .251	NO	-232.25	-160.17	-251.01	-152.45	-199.56	-246.68	-5.38	-12.02	-17.47	-23.47
1	1	F .334	NO	-92.25	-213.13	-140.16	-202.86	10.52	1.69	-7.16	-16.00	436.36	337.09
1	1	F .501	NO	1546.91	1383.56	1356.55	1157.77	1229.89	1086.57	943.25	1126.19	1023.82	918.63

Table A.53

Functional Dependency of Ground Ratio Savings on the Fuel Price
(The Component 3 Heat Load is 50% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

EXR	ENR	IN FUEL AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	F .167 NO	-139.39	-182.55	-225.71	-64.26	-74.10	-83.94	-93.79	-103.63	-115.41	-125.50
1	1	F .251 NO	-209.51	-67.00	-81.80	-96.59	-111.38	-126.17	88.89	103.25	117.04	132.59
1	1	F .334 NO	-69.48	-89.16	-108.84	60.96	80.07	99.18	118.29	445.34	631.88	560.35
1	1	F .501 NO	1581.06	1533.87	1377.02	1220.16	1363.66	1260.66	1157.65	1054.65	1290.28	1221.73

Table A.54

Functional Dependency of Ground Ratio Savings on the Fuel Price
(The Component 3 Heat Load is 25% of Engineering Standards. No Minimum Property Standard Requirements are Imposed for Thermal Response.)

EXR	ENR	IN FUEL AIR	TOTAL SAVINGS FROM GROUND RATIO 90	80	70	60	50	40	30	20	10	0
1	1	F .167 NO	-124.26	-100.16	-76.06	-51.96	-27.85	-3.75	20.35	44.45	300.78	343.30
1	1	F .251 NO	-186.76	26.16	87.42	148.68	209.94	271.20	332.46	393.72	452.07	515.98
1	1	F .334 NO	-46.71	34.81	116.33	197.85	279.36	360.88	442.40	523.92	731.50	686.60
1	1	F .501 NO	1615.22	1684.19	1650.04	1615.89	1581.74	1547.59	1513.45	1479.30	1735.60	1727.90

Table A.55

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.43

	INCREMENT NO.	
GR	COMP1	COMP23
90	2	2
90	2	2
0		10
90	12	4

Table A.56

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.44

	INCREMENT NO.	
GR	COMP1	COMP23
90	2	2
30	2	5
10	12	8
90	12	2

Table A.57

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.45

	INCREMENT NO.	
GR	COMP1	COMP23
90	2	2
0		4
10	12	5
90	12	2

Table A.58

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Tables A.46 and A.54

	INCREMENT NO.	
GR	COMP1	COMP23
0		2
0		2
10	12	2
10	12	5

Table A.59

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.47

	INCREMENT NO.	
GR	COMP1	COMP23
90	2	1
90	2	1
90	3	1
90	3	2

Table A.60

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.48

	INCREMENT NO.	
GR	COMP1	COMP23
90	2	1
90	2	1
80	3	2
90	3	2

Table A.61

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.49

	INCREMENT NO.	
GR	COMP1	COMP23
90	2	1
90	2	1
70	3	2
0		3

Table A.62

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.50

	INCREMENT NO.	
GR	COMP1	COMP23
0		1
0		1
0		1
0		2

Table A.63

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.51

	INCREMENT NO.	
GR	COMP1	COMP23
80	2	2
0		8
0		10
90	12	4

Table A.64

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.52

	INCREMENT NO.	
GR	COMP1	COMP23
90	2	1
30	2	5
10	12	8
90	12	2

Table A.65

Insulation and Ground Ratio Specifications for the Optimal Ground Ratio Savings Cases in Table A.53

	INCREMENT NO.	
GR	COMP1	COMP23
60	2	2
0		4
10	12	5
90	12	2

APPENDIX B

Appendix B

Data Used in the Thermal Wall Model

I. Insulation Costs (Dollars/sq.ft.)[36/]

A. Fiberglass plain unbacked batts

Resistance	Materials	Labor	Total	Bozeman
R-3	.05	.12	.17	.14
R-8	.08	.13	.21	.18
R-11	.11	.14	.25	.21
R-13	.12	.17	.29	.25
R-19	.18	.23	.41	.35
R-22	.20	.24	.44	.37

B. One-inch urethane boards

					Each Additional Board		
Resistance	Materials	Labor	Total	Bozeman	Labor	Total	Bozeman
R-5.56	.30	.19	.49	.42	.13	.43	.36

C. Perimeter insulation[37/]

The materials and labor cost to install 2 inch by 24 inch styrofoam perimeter insulation around the outside edge of the below ground walls is $.60/sq.ft.

II. Construction Costs (Labor + Materials in Dollars/sq.ft.)

A. Marginal floor cost along exterior walls = 8.00

36/ Insulation costs were based on values published in Reference 16 which had been geographically adjusted to reflect local conditions.

37/ Perimeter insulation costs and construction costs were provided by a private estimator (14).

B. Wall studding 16 inches on center

2 x 4	2 x 6	2 x 8	2 x 10	2 x 12
.52	.77	.91	1.10	1.32

C. Wall furring 16 inches on center

1 x 2	2 x 3
.42	.42

D. Wallboard

Interior sheetrock including tape and 3 coats of paint = .50

One-half inch ply exterior sheathing plus T-111 siding = 1.27

The following costs are per unit indicated:

E. Thick window sills and door jams

Sill costs = $35. per window for walls up to 10 inches thick,

and $40. per window for thicker walls.

Jam costs = $50. per door for walls up to 10 inches thick, and

$60. per door for thicker walls.

F. Concrete in place

Walls 8 inches thick and up to 4 feet high = $100./yd. or $2.47/sq.ft.

Walls 8 inches thick and greater than 4 feet but not more than 8 feet high = $121./yd. or $2.99/sq. ft.

G. Concrete stairs and landings

Steps up to the doorway in a conventional wall = $100.

Steps down to the doorway in a berm wall;

If the descent is 1.33 feet or less = $100.

If the descent is from 1.33 to 2.33 feet = $150.

If the descent is more than 2.33 feet = $150. + $75. per foot below 2.33 feet.

H. Dirt work

Crawler excavation and backfill = $2.00/yd.

Backhoe excavation = $1.50/yd.

Crawler backfill = $.75/yd.

III. Climate[38/]

Heating days = 334 (31, p. 317)

Degree days = 8343 (Montana Power Company records)

Cooling hours = 225 (18, p. 30)

Design equivalent temperature difference: (1, p. 441)

for frame walls = 13.6°F

for masonry walls above ground = 6.3°F

for masonry walls below ground = 61°F[39/] (1, p. 378)

[38/] Complete weather data was not available for Bozeman, Montana. In cases where no figure was available, values were based on measurements made in nearby Montana cities.

[39/] This figure was calculated from a measured ground water temperature

Inside design drybulb temperature = $75^{o}F$[40]

IV. Fuel Costs and Heating and Cooling Efficiencies

Heating fuel cost (natural gas) = \$.167/100,000 BTU[41]

Cooling fuel cost (electricity) = \$.454/100,000 BTU[42]

Burning efficiency factor for natural gas = .70 (2, p. 79), (34, p. 29)

39/continued
in the Bozeman, Montana area of $42^{o}F$. The measurement was done in compliance with the recommendations set forth in the Soil Conservation Service Agricultural Handbook No. 436, which states, "If the water table stands between 9 and 18 m and water is drawn from the well frequently, the temperature of water in the well, which is in equilibrium with the soil temperature, gives the mean annual soil temperature with an error of less than $1^{o}C$" (30, p. 62). An alternate estimator of the mean annual soil temperature in a locale is the mean annual drybulb temperature. For Bozeman, Montana, this mean for the 30 year period from 1940 through 1969 is $43.1^{o}F$ (7).

40/An obvious approach to energy saving not considered in this report is to adjust the inside temperature of the dwelling downward during periods of heating and upward during periods of cooling. Such a practice is becoming commonplace so the ASHRAE design indoor air temperature of 75^{o} for both winter and summer may not be as representative of actual conditions within residential buildings today as it was in 1972 when the standards were made (1, p. 667).

41/Natural gas costs are taken from the Montana Public Service Commission Schedule GSG-72 Supplement No. 10, issued 12/31/75, which establishes a base rate of \$1.582/MCF for a residential monthly use of 2 to 100 MCF. A conversion factor of 950,000 BTU/MCF is used.

42/Electricity costs are taken from the Montana Public Service Commission Schedule R-72, issued 9/5/72, which defines a rate of 1.55¢/Kwh for a residential monthly use of 201 Kwh or more. The conversion factor used is 3412 BTU/Kwh. Heating and cooling fuel costs based on other rate schedules are listed in Tables 4.5 and 4.6.

Coefficient of performance (COP) for electric air conditioning

= 2.345[43/] (2, p. 85), (34, p. 29)

[43/] The ratio of useful cooling to the energy required to produce that cooling is called the coefficient of performance. In the study, the coefficient of performance was calculated from a BTU removal performance of 8000 BTU/Kwh. Thus the coefficient of performance is (8000 BTU/Kwh)/(3412 BTU/Kwh).

APPENDIX C

Appendix C

Technique Used for Calculating Annual Heat Losses and Heat Gains Through the Solid Wall Areas of the Residential Wall Structure

Heating and cooling loads for the various wall areas of the model home were determined by the steady state procedure outlined here. The notation listed below was used in the mathematical relationships to determine annual heat flows:

$U_n(I)$ = thermal conductance of wall component n containing I increments of insulation

$R_f(I)$ = thermal resistance of I increments of fiberglass studding insulation

$R_u(I)$ = thermal resistance of I increments of urethane sheet insulation

$R_t(I)$ = thermal resistance of that portion of I layers of insulation which exceed the stud thickness

R_s = thermal resistance of stud; R_s = 1.25/inch of thickness

R_b = thermal resistance of basic wall not adjusted for studding, air space, or outside film resistance; R_b = 3.26 for component 1 walls, 1.77 for component 2 walls, and 11.13 for component 3 walls, which includes the thermal resistance of the soil

R_w = outside surface resistance of wall; R_w = .17 (Wind speed - 15 m.p.h.)

R_a = thermal resistance of wall cavity air space; R_a = 0 when the

air space is less than or equal to .75 inches thick and .97 in all other cases; R_a doubles as a compression factor assuming the value of -1.00 whenever the fiberglass layer within the wall cavity is compressed more than .75 inches

DD = degree days; DD = 8343

HD = heating days; HD = 334

CH = cooling hours over 80°F; CH = 225

TEQ = design equivalent temperature difference for walls; TEQ = 13.6°F for frame walls and 6.3°F for above ground masonry walls

TBSMT = equivalent ground temperature during the heating season; TBSMT = 14°F

Thermal conductivity of the wall components was calculated from the following formulas:

For component 1 (type 1) fiberglass insulated walls --

$U_1(I) = .906/(R_b + R_w + R_a + R_f(I)) + .094/(R_b + R_w + R_s)$

where .906 and .094 are the respective weights for the non-stud and stud portions of the wall

For component 1 (type 2) fiberglass insulated walls --

$U_1(I) = .812/(R_b + R_w + R_a + R_f(I)) + .188/(R_b + R_w + R_s + R_a + R_t$ (I)) where .812 and .188 are weights for the non-stud and stud portions of the wall, respectively

To derive the formulas for the thermal conductivity of component 1 urethane insulated walls, substitute the variable $R_u(I)$ for $R_f(I)$ in the above relationships.

For component 2 and 3 fiberglass insulated walls --

$U_n(I) = .906/(R_b + R_w + R_a + R_f(I)) + .094/(R_b + R_w + R_s + R_a + R_t(I))$ where .906 and .094 are the respective weights for the non-stud and stud portions of the wall

For component 2 and 3 urethane insulated walls --

$U_n(I) = 1/(R_b + R_w + R_a + R_u(I))$

The annual heat flow (H) through a square foot of any wall component is derived from its thermal conductivity and the appropriate climate factors:

$H_n(I) = U_n(I) \cdot (T_w + T_s)$

Where T_w = the winter climate factor; for components 1 and 2, $T_w = 24 \cdot DD$; for component 3, $T_w = (75 - TBSMT) \cdot 24 \cdot HD$

T_s = the summer climate factor; $T_s = TEQ \cdot CH$

Annual heat flow reductions resulting from the addition of the I^{th} increment of insulation are calculated from consecutive heat flow values: $\Delta H_n(I) = H_n(I-1) - H_n(I)$

APPENDIX D

Appendix D

The Computer Programs for the Thermal Wall Model

Three Fortran language computer programs were written to perform the insulation calculations required by the model. Two of these programs, called "W1" for "Wall 1" and "W23" for "Walls 2 and 3", physically modeled the wall components. They calculated the cost and transmittance resulting from the increased levels of insulation in each wall section. W1 dealt with component 1 walls while W23 was concerned with the component 2 and 3 wall sections. The third program, called "MA" which is short for "Marginal Analysis", interfaced with W1 and W23. From weather, fuel price data, and financial factors, it converted the transmittances calculated by the wall programs into marginal savings. Then from the marginal cost data which also came from W1 and W23, it determined the globally optimal levels of insulation.

When net savings from insulation and the ground ratio were optimized, a modified version of the setup described here was used. Central to this analysis was a provision in the model which placed the walls deeper in the ground in steps of 10 percent of the living wall height (i.e. 9.6 inches). Such an approach defined a systematic manner for examining the use of the ground as a thermal barrier. In this study, four Fortran programs were employed. W1 and W23 were again used to mathematically describe each wall component's cost and thermal

response. Insulation levels were optimized and their respective net savings were calculated by a program called "M", which performed a similar function to the MA program. The fourth program, called "G" for "Ground Ratio", interfaced with W1, W23, and M. Subject to the homeowner's utility preferences, it combined the construction costs arising from the different wall configurations with the thermal savings resulting from the structural variations. For each case examined, it listed the combined net savings from insulation and the ground ratio for all eleven configurations. It also displayed the structural parameters for the optimal configuration. Three small Fortran programs called "Companion", "Savings", and "Profit", were used to print the headings on the various tables which were generated by G.

Below is a device assignment listing for the two setups described above. The language is Xerox Extended Fortran-IV (35).

I. Insulation Optimization

Command	Explanation
SET F:1/OPTIONS;IN	OPTIONS is the input file through which control is passed
SET F:3/AW1;IN	AW1 is an input file for MA
SET F:4/AW23;IN	AW23 is an input file for MA
SET F:5/WALL1DATA;IN	WALL1DATA is an input file for W1
SET F:6 L1	L1 is the output device for the results

SET F:7/AW1;OUT	AW1 is the output file for W1
SET F:8/WALL23DATA;IN	WALL23DATA is an input file for W23
SET F:9/AW23;OUT	AW23 is the output file for W23

II. Combined Insulation and Ground Ratio Optimization

Command	Explanation
SET F:1/OPTIONS;IN	OPTIONS is the input file through which control is passed
SET F:2 L1	L1 is an output device for the results
SET F:3/AW1;IN	AW1 is an input file for M and G
SET F:4/AW23;IN	AW23 is an input file for M and G
SET F:5/WALL1DATA;IN	WALL1DATA is an input file for W1 and G
SET F:7/AW1;OUT	AW1 is the output file for W1
SET F:8/WALL23DATA;IN	WALL23DATA is an input file for W23
SET F:9/AW23;OUT	AW23 is the output file for W23
SET F:10 L2	L2 is an output device for the results
SET F:11/AM;OUT	AM is the output file for M
SET F:12/AM;IN	AM is an input file for G

Figures D.1 and D.2 describe the program flow diagrams for the two setups described here. In each figure the input and output streams are numbered according to the above listing.

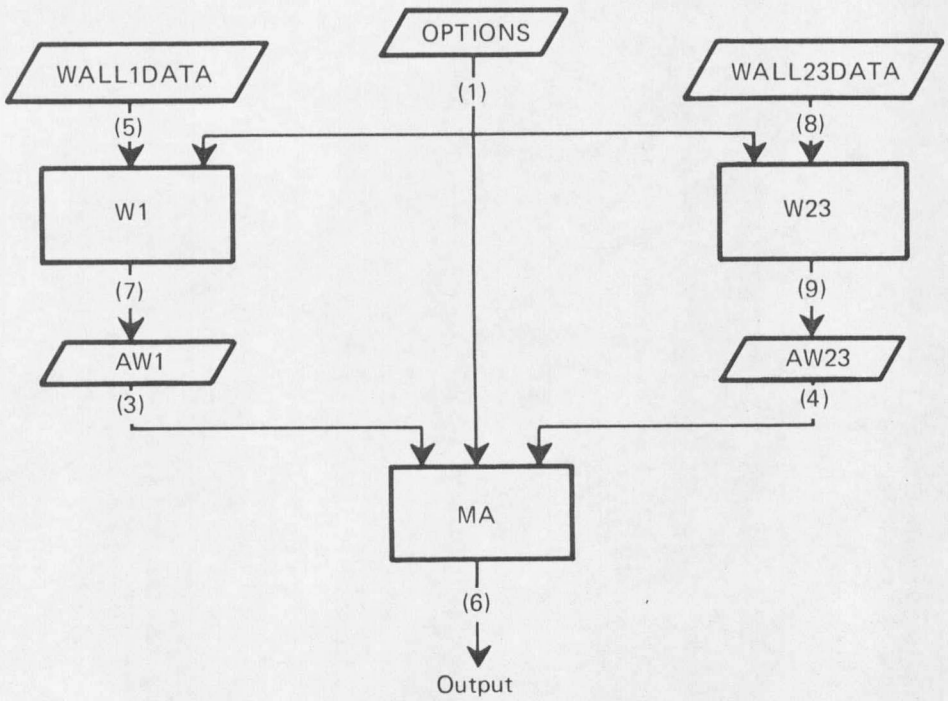

Figure D.1 Program Flow Diagram for Insulation Optimization

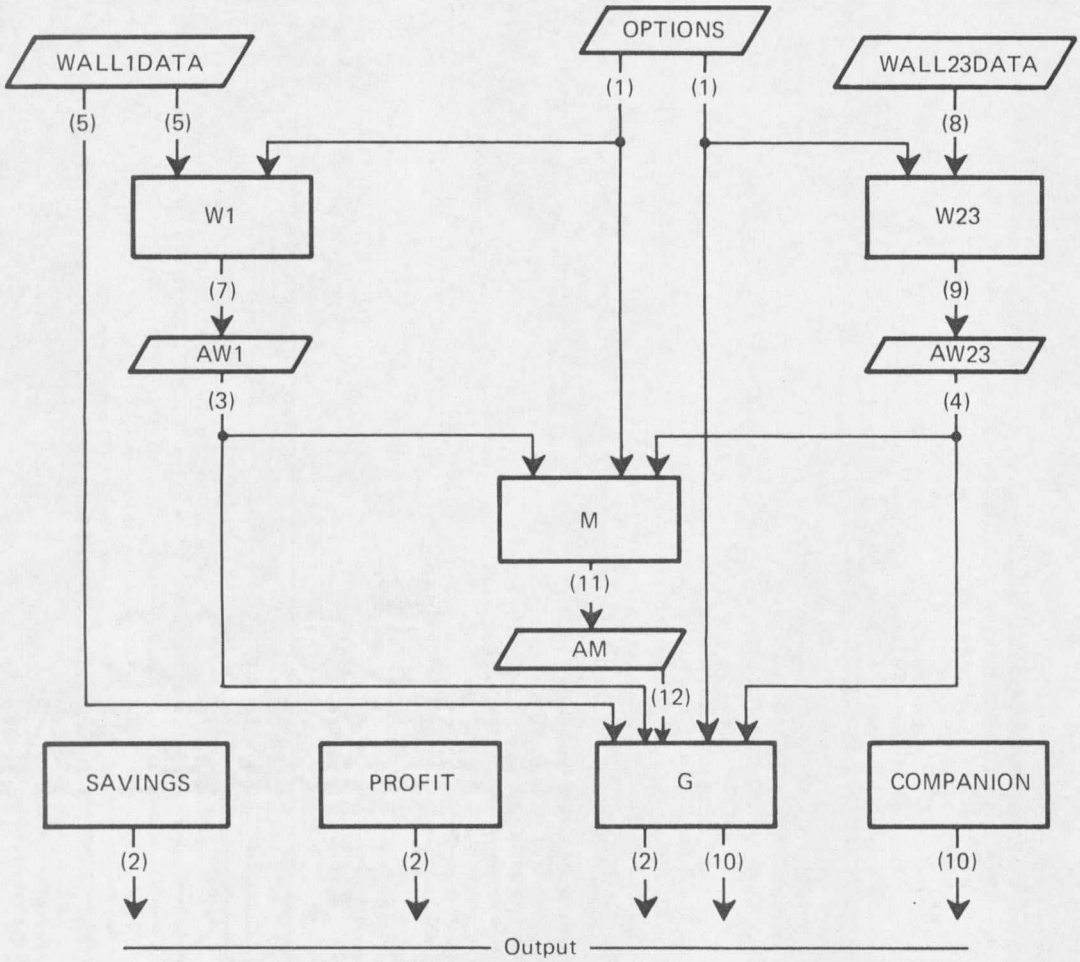

Figure D.2 Program Flow Diagram for Combined Insulation and Ground Ratio Optimization

APPENDIX E

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1 -    1.000 ****************************************** OPTIONS ******************************************
2 -    2.000 35.  35.                    Y W LENGTH WIDTH
3 -    3.000   100    0                  IP1U IP1L UPPER AND LOWER RANGE OF IP1
4 -    4.000 7.75                        P2 COMPONENT 2 PERCENTAGE
5 -    5.000 8.                          H HEIGHT OF WALL
6 -    6.000 1    OPTION1: TO USE URETHANE INSULATION IN WALL COMPONENTS 2 AND 3   1=YES 0=NO
7 -    7.000 0    OPTION2: TO AIR CONDITION IN SUMMERTIME   1=YES 0=NO
8 -    8.000  .11  .11  .20  .40    PGL1(K) GLAZING FRACTIONS   COMPONENT 1
9 -    9.000  .20  .20  .40  .60    PGL2(K) GLAZING FRACTIONS   COMPONENT 2
10 -  10.000  3.   6.67               D(K) DOOR WIDTH AND HEIGHT
11 -  11.000  1                       KK NO. OF GLAZING FRACTIONS CONSIDERED
12 -  12.000  8.                      CSF FLOOR SQ.FT. COST
13 -  13.000 1.0                      CUSF123 FLOOR SQ.FT. COST CONSTRAINT RATIO
14 -  14.000 1.0    1.0               ECSF123 ENSF123 EXCAVATION & ENTRANCE SQ.FT. COST CONSTRAINT RATIOS
15 -  15.000  .01   .01  30.          D P XL DISCOUNT RATE, REAL RATE OF FUEL PRICE INCREASE, LIFETIME
16 -  16.000 .167  .454               HFUEL CFUEL HEATING-COOLING FUEL COST/100,000 BTU
17 -  17.000 1.0                      CC MARGINAL ANALYSIS CONSTANT   CC=MARG SAVINGS/MARG COST
18 -  18.000  334.   8343.  225.      HD DD CH HEATING DAYS, DEGREE DAYS, COOLING HOURS
19 -  19.000  14.                     TBSMT  DESIGN TEMP FOR BELOW GROUND CONCRETE WALLS
20 -  20.000  13.6 6.3  0.            TEQ(N)  EQUIVALENT TEMPERATURE DIFFERENCE FOR EACH COMPONENT
21 -  21.000   2 3                    NPS(1,N) NPS INCREMENT NO. FOR EACH UNIT-FIBERGLASS INS.
22 -  22.000   3 2                    NPS(2,N) NPS INCREMENT NO. FOR EACH UNIT-URETHANE INS.
23 -  23.000 .70   2.345               HE CE EFFICIENCY FACTOR-GAS HEATING ELECTRIC COOLING
24 -  24.000 1    OPTION3: SELECTION OF OUTPUT   1=TOTAL PROFIT  0=GROUND RATIO SAVINGS
```

```
 1 -    1.000 ******************************** WALL1DATA ********************************
 2 -    2.000  1.25,.97                                  RJ RAIR
 3 -    3.000 3.5    5.5    7.25  9.25  11.25           THJ(IN)
 4 -    4.000 66.                                       RM
 5 -    5.000 105.7                                     RM1
 6 -    6.000    19                                     NI
 7 -    7.000    19                                     NI1
 8 -    8.000 11,2,6,3,2,2,4,3,2,3,3,3,5,3,3,2,3,3,3                        P(I)
 9 -    9.000 556,556,556,556,556,556,556,556,556,556,556,                  P1(I)
10 -   10.000 556,556,556,556,556,556,556,556,556,
11 -   11.000 .094 .094 .094                           WJ1 WJ2 WJ3
12 -   12.000 3.26                                     RB
13 -   13.000 21,04,10,02,09,04,06,02,04,08,02,02,17,02,02,10,02,02,02,    CI(I)
14 -   14.000 42,36,36,36,36,36,36,36,36,36,36,36,36,36,36,36,36,36,36,    CI1(I)
15 -   15.000   .52  .77  .91 1.10 1.32               CW(IN)
16 -   16.000  10.85 19.46                             RTHJ RTHJU
17 -   17.000 35.  40.  50.  60.                       SILL1 SILL2 JAM1 JAM2
18 -   18.000 .50    1.27   100.                       CIBOARD COBOARD ENTRANCE1
19 -   19.000  2.00  1.50  .75                         CAT BACK CATB
20 -   20.000  .17                                     RWIND
21 -   21.000  2.47                                    CONCRETE
```

```
 1 -    1.000 ******************************** WALL23DATA ********************************
 2 -    2.000  1.25,.97                                    RJ RAIR
 3 -    3.000 1.0   2.5   3.5                              THJ(IN)
 4 -    4.000 66.                                          RM
 5 -    5.000 142.                                         RM1
 6 -    6.000    21                                        NI
 7 -    7.000    20                                        NI1
 8 -    8.000 3,5,3,2,6,3,2,2,4,3,2,3,3,3,5,3,3,2,3,3,3                          P(I)
 9 -    9.000 556,556,556,556,556,556,556,556,556,556,                           P1(I)
10 -   10.000 556,556,556,556,556,556,556,556,556,556,
11 -   11.000 .094                                        WJ3
12 -   12.000 1.77                                        RB
13 -   13.000 11.13                                       R8G
14 -   14.000 14,04,03,04,10,02,09,04,06,02,04,08,02,02,17,02,02,10,02,02,02,  CI(I)
15 -   15.000 42,36,36,36,36,36,36,36,36,36,36,36,36,36,36,36,36,36,36,36,      CI1(I)
16 -   16.000   .42  .42  .52                            CW(IN)
17 -   17.000  10.85                                      RTHJ
18 -   18.000 35.  40.  50.  60.                         SILL1 SILL2 JAM1 JAM2
19 -   19.000  2.00  1.50  .75                           CAT BACK CATB
20 -   20.000 .52   .60   2.47  .50                      HIWALL PERI CONCRETE CIBOARD
21 -   21.000  .17                                       RWIND
```

```
C********************************** W1 ************************************
      DIMENSION RJT(12),THJ(12),CFM1(20,4),PGL2(4),CF1(20,4),P(20),
     2RIJ(20),WJO(2),U4(3),U5(20),PGL1(4),U1(20),U2(20),TYPE(20,4,11),
     3CA(20,4),CB(20,4),CI(20),C(20),A1(4,20),D(2),Z(4),CW(20),R(20),
     4RUJ(20),R1(20),P1(20),C1(20),CI1(20),CRA(20,4),CRB(20,4),UU4(4),
     5UU5(20),UU2(20),UU1(20),CU1(20,4),CUM1(20,4),TYPU(20,4,11)
      READ(5,131)
  131 FORMAT()
      READ(5,1)RJ,RAIR
    1 FORMAT(X,2F5.2)
      READ(5,2)(THJ(IN),IN=4,12,2)
    2 FORMAT(5F6.2)
      READ(5,3)RM
      READ(5,3)RM1
      READ(5,54)NI
      READ(5,54)NI1
    3 FORMAT(F5.2)
   54 FORMAT(I5)
      READ(5,5)(P(I),I=2,NI+1)
      READ(5,203)(P1(I),I=2,11)
      READ(5,204)(P1(I),I=12,NI1+1)
    5 FORMAT(19F.0)
  203 FORMAT(10F.2)
  204 FORMAT(9F.2)
      READ(5,7)WJ1,WJ2,WJ3
    7 FORMAT(3F5.3)
      READ(5,8)RB
    8 FORMAT(F5.2)
      READ(5,33)(CI(I),I=2,NI+1)
      READ(5,33)(CI1(I),I=2,NI1+1)
   33 FORMAT(19F4.2)
      READ(5,36)(CW(IN),IN=4,12,2)
   36 FORMAT(5F5.2)
      READ(5,75)RTHJ,RTHJU
   75 FORMAT(X,2F6.2)
      READ(5,105)SILL1,SILL2,JAM1,JAM2
  105 FORMAT(4F5.1)
```

```
38 -    38.000       READ(5,144)CIBOARD,COBOARD
39 -    39.000   144 FORMAT(2F7.2)
40 -    40.000       READ(5,164)CAT,BACK,CATB
41 -    41.000   164 FORMAT(X,3F6.2)
42 -    42.000       READ(5,178)RWIND
43 -    43.000   178 FORMAT(F4.2)
44 -    44.000       READ(1,130)
45 -    45.000   130 FORMAT()
46 -    46.000       READ(1,9)Y,W
47 -    47.000     9 FORMAT(2F5.1)
48 -    48.000       READ(1,99)IP1U,IP1L
49 -    49.000    99 FORMAT(2I5)
50 -    50.000       READ(1,100)P2
51 -    51.000   100 FORMAT(F5.2)
52 -    52.000       READ(1,31)H
53 -    53.000    31 FORMAT(F5.2)
54 -    54.000       READ(1,35)
55 -    55.000    35 FORMAT(/)
56 -    56.000       READ(1,63)(PGL1(K),K=1,4)
57 -    57.000    63 FORMAT(4F5.2)
58 -    58.000       READ(1,132)(PGL2(K),K=1,4)
59 -    59.000   132 FORMAT(4F5.2)
60 -    60.000       READ(1,143)(D(K),K=1,2)
61 -    61.000   143 FORMAT(2F5.2)
62 -    62.000       READ(1,64)KK
63 -    63.000    64 FORMAT(1X,I1)
64 -    64.000       READ(1,65)CSF
65 -    65.000    65 FORMAT(F5.1)
66 -    66.000       READ(1,150)CUSF123
67 -    67.000   150 FORMAT(F7.4)
68 -    68.000 C CUSF=USABLE SQ.FT. COSTS FOR RESIDENCE WITH 4.5 IN. WALLS
69 -    69.000       CUSF=(W*Y*CSF)/((W-.75)*(Y-.75))
70 -    70.000       CUSF=CUSF*CUSF123
71 -    71.000       IF(IP1L.EQ.0)IP1L=IP1L+10
72 -    72.000       J=0
73 -    73.000       DO 98 IP1=IP1U,IP1L,-10
74 -    74.000       J=J+1
75 -    75.000       H1=H*IP1*.01
76 -    76.000       P3=(100.-IP1-P2)
77 -    77.000       H3=H*P3*.01
78 -    78.000       H23=H*(P2+P3)*.01
```

```
 79 -    79.000         H2=(H23-H3)
 80 -    80.000         IF(IP1.EQ.100)GO TO 148
 81 -    81.000    163  HD=D(2)-(H-H1)
 82 -    82.000         GO TO 149
 83 -    83.000    148  H1=H
 84 -    84.000         HD=D(2)
 85 -    85.000    149  DO 42 K=1,KK
 86 -    86.000         IF(K.EQ.1.OR.K.EQ.3)Z(K)=W;GO TO 146
 87 -    87.000         Z(K)=Y
 88 -    88.000    146  DO 110 IN=4,20,2
 89 -    89.000         IF(IP1.EQ.100)GO TO 29
 90 -    90.000     77  IF(IN.EQ.4)Y1=0;Z1=0;GO TO 109
 91 -    91.000         IF(IN.LE.10)Y1=SILL1;Z1=JAM1;GO TO 109
 92 -    92.000         IF(IN.GT.10)Y1=SILL2;Z1=JAM2;GO TO 109
 93 -    93.000 C  A1=THICK WALL COST
 94 -    94.000    109  A1(K,IN)=(((PGL1(K)*H1*Z(K)*Y1)/12)+((HD
 95 -    95.000        2*D(1)*Z1)/(D(2)*3.0)))/(H1*Z(K)*(1-PGL1(K))-HD*D(1))
 96 -    96.000         GO TO 110
 97 -    97.000     29  IF(IN.EQ.4)X=0;Y1=0;Z1=0;GO TO 96
 98 -    98.000         IF(IN.EQ.6)X=2;Y1=SILL1;Z1=JAM1;GO TO 96
 99 -    99.000         IF(IN.LE.10)X=IN-4.25;Y1=SILL1;Z1=JAM1;GO TO 96
100 -   100.000         IF(IN.GT.10)X=IN-4.25;Y1=SILL2;Z1=JAM2;GO TO 96
101 -   101.000     96  A1(K,IN)=(((X/12)*Z(K)*CUSF)+((PGL1(K)*H1*Z(K)*Y1)/12)+((HD
102 -   102.000        2*D(1)*Z1)/(D(2)*3.0)))/(H1*Z(K)*(1-PGL1(K))-HD*D(1))
103 -   103.000    110  CONTINUE
104 -   104.000 C  RJT=TOTAL THERMAL RESISTANCE OF STUD
105 -   105.000         DO 12 IN=4,12,2
106 -   106.000     12  RJT(IN)=RJ*THJ(IN)
107 -   107.000         R(1)=0
108 -   108.000         NA=1
109 -   109.000         DO 14 I=2,NI+1
110 -   110.000         NA=NA+1
111 -   111.000 C  R=THERMAL RESISTANCE OF I INCREMENTS OF FIBERGLASS INSULATION
112 -   112.000 C  RTHJ=THERMAL RESISTANCE OF FIBERGLASS INS. AS THICK AS A 2X4 STUD
113 -   113.000         R(I)=R(I-1)+P(I)
114 -   114.000         IF(R(I).LE.RTHJ)GO TO 14
115 -   115.000 C  RIJ=THERMAL RESISTANCE ON TOP OF STUDS
116 -   116.000         RIJ(I)=R(I)-RTHJ
117 -   117.000         IF(R(I).GT.RM)GO TO 15
118 -   118.000     14  CONTINUE
119 -   119.000         GO TO 16
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120 -  120.000     15 NA=NA-1
121 -  121.000     16 NAZ=NA
122 -  122.000 C C=COST FOR I INCREMENTS OF FIBERGLASS INSULATION
123 -  123.000        C(1)=0
124 -  124.000        DO 41 I=2,NA
125 -  125.000     41 C(I)=C(I-1)+CI(I)
126 -  126.000        CI(1)=0
127 -  127.000        DO 188 I=1,NA
128 -  128.000        IF(I-3)43,43,44
129 -  129.000 C CA AND CB ARE TOTAL COSTS OF WALL TYPES 1 AND 2 RESPECTIVELY
130 -  130.000     43 CA(I,K)=C(I)+A1(K,4)+CW(4)+CIBOARD+COBOARD
131 -  131.000        CB(I,K)=77.77
132 -  132.000        GO TO 188
133 -  133.000     44 IN=IWALLTHICKNESS(I)
134 -  134.000        IF(IN.GT.12)GO TO 87
135 -  135.000        CA(I,K)=C(I)+A1(K,IN)+CW(IN)+CIBOARD+COBOARD
136 -  136.000     87 CB(I,K)=C(I)+A1(K,IN)+CW(4)+CW(4)+CIBOARD+COBOARD
137 -  137.000    188 CONTINUE
138 -  138.000        R1(1)=0
139 -  139.000        NB=1
140 -  140.000        DO 180 I=2,NI1+1
141 -  141.000 C R1=THERMAL RESISTANCE FOR I INCREMENTS OF URETHANE INSULATION
142 -  142.000        R1(I)=R1(I-1)+P1(I)
143 -  143.000 C NB=MAXIMUM INCREMENT NUMBER FOR URETHANE INSULATION
144 -  144.000        NB=NB+1
145 -  145.000 C RTHJU=THERMAL RESISTANCE OF URETHANE INS. AS THICK AS A 2X4 STUD
146 -  146.000        IF(R1(I).LE.RTHJU)GO TO 180
147 -  147.000 C RUJ=THERMAL RESISTANCE ON TOP OF STUDS
148 -  148.000        RUJ(I)=R1(I)-RTHJU
149 -  149.000        IF(R1(I).GT.RM1)GO TO 181
150 -  150.000    180 CONTINUE
151 -  151.000        GO TO 182
152 -  152.000    181 NB=NB-1
153 -  153.000    182 NBZ=NB
154 -  154.000 C C1=COST FOR I INCREMENTS OF URETHANE INSULATION
155 -  155.000        C1(1)=0
156 -  156.000        DO 183 I=2,NB
157 -  157.000    183 C1(I)=C1(I-1)+CI1(I)
158 -  158.000        CI1(1)=0
159 -  159.000        DO 42 I=1,NB
160 -  160.000        IF(I-4)185,185,186
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161 -   161.000 C CRA=TOTAL COST FOR URETHANE INSULATED TYPE 1 WALL
162 -   162.000 C CRB=TOTAL COST FOR URETHANE INSULATED TYPE 2 WALL
163 -   163.000   185 CRA(I,K)=C1(I)+A1(K,4)+CW(4)+CIBOARD+COBOARD
164 -   164.000       CRB(I,K)=77.77
165 -   165.000       GO TO 42
166 -   166.000   186 IN=ITHICKNESS(I)
167 -   167.000       IF(IN.GT.12)GO TO 187
168 -   168.000       CRA(I,K)=C1(I)+A1(K,IN)+CW(IN)+CIBOARD+COBOARD
169 -   169.000   187 CRB(I,K)=C1(I)+A1(K,IN)+CW(4)+CW(4)+CIBOARD+COBOARD
170 -   170.000    42 CONTINUE
171 -   171.000       DO 23 K=1,KK
172 -   172.000 C WJ0(1)=WEIGHT NON STUD AREA TYPE 1 WALL
173 -   173.000       WJ0(1)=1-WJ1
174 -   174.000 C WJ0(2)=WEIGHT NON STUD AREA TYPE 2 WALL
175 -   175.000       WJ0(2)=1-(WJ2+WJ3)
176 -   176.000       RAIRZ=RAIR
177 -   177.000    17 DO 20 I=1,3
178 -   178.000       IF(R(I).LT.11)GO TO 20
179 -   179.000    18 RAIR=0.
180 -   180.000 C U4=THERMAL CONDUCTANCE OF 4IN. FIBERGLASS TYPE 1 WALLS
181 -   181.000    20 U4(I)=WJ0(1)/(RB+RWIND+RAIR+R(I))+WJ1/(RB+RWIND+RJT(4))
182 -   182.000       RAIR=RAIRZ
183 -   183.000 C NAZ=MAXIMUM INCREMENT NO. FOR TYPE 2 WALLS.  NA=MAXIMUM INCREMENT
184 -   184.000 C NO.FOR TYPE 1 WALLS.  (THE INCREMENT NO. IS ONE HIGHER THAN THE NO.
185 -   185.000 C OF INCREMENTS, SO 2 IS THE INCREMENT NO. FOR THE FIRST INCREMENT
186 -   186.000 C OF INSULATION.)
187 -   187.000       IF(NA.GT.11)NA=11
188 -   188.000       DO 21 I=4,NA
189 -   189.000       IN=IWALLTHICKNESS(I)
190 -   190.000 C WHEN THE AIR SPACE IS LESS THAN OR EQUAL TO .75 IN. THICK, ASSIGN
191 -   191.000 C RAIR=0.  WHEN THE FIBERGLASS IS COMPRESSED MORE THAN .75 IN., ASSIGN
192 -   192.000 C RAIR=-1 AS A COMPRESSION FACTOR.
193 -   193.000       IF(I.EQ.10)RAIR=-1.;GO TO 21
194 -   194.000       RAIR=0
195 -   195.000 C U5=THERMAL CONDUCTANCE OF THICK FIBERGLASS TYPE 1 WALLS
196 -   196.000    21 U5(I)=WJ0(1)/(RB+RWIND+RAIR+R(I))+WJ1/(RB+RWIND+RJT(IN))
197 -   197.000       RAIR=RAIRZ
198 -   198.000    19 DO 24 I=4,NAZ
199 -   199.000       IF(I.EQ.10)RAIR=-1;GO TO 24
200 -   200.000       RAIR=0
201 -   201.000 C U2=THERMAL CONDUCTANCE OF FIBERGLASS TYPE 2 WALLS (2X4 STUDDING INSIDE
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202 -  202.000 C AND OUT)
203 -  203.000    24 U2(I)=WJ0(2)/(RB+RAIR+RWIND+R(I))+(WJ2+WJ3)/(RB+RWIND+RAIR+RJT(4)
204 -  204.000      2+RIJ(I))
205 -  205.000       RAIR=RAIRZ
206 -  206.000 C THE DETERMINATION OF THE MOST EFFICIENT WALL TYPE IS DONE BY
207 -  207.000 C MAXIMIZING (WALL R/WALL COST).
208 -  208.000       DO 78 I=1,3
209 -  209.000       U1(I)=U4(I)
210 -  210.000       CF1(I,K)=CA(I,K)
211 -  211.000       CFM1(I,K)=CI(I)
212 -  212.000    78 TYPE(I,K,J)=1
213 -  213.000       DO 27 I=4,NA
214 -  214.000       IF(1/(U5(I)*CA(I,K))-1/(U2(I)*CB(I,K)))25,28,28
215 -  215.000    28 U1(I)=U5(I)
216 -  216.000       CF1(I,K)=CA(I,K)
217 -  217.000       CFM1(I,K)=CA(I,K)-CA(I-1,K)
218 -  218.000       TYPE(I,K,J)=1
219 -  219.000       IF(TYPE(I,K,J)-TYPE(I-1,K,J))138,27,138
220 -  220.000   138 CFM1(I,K)=CA(I,K)-CB(I-1,K)
221 -  221.000       GO TO 27
222 -  222.000    25 U1(I)=U2(I)
223 -  223.000       CF1(I,K)=CB(I,K)
224 -  224.000       CFM1(I,K)=CB(I,K)-CB(I-1,K)
225 -  225.000       TYPE(I,K,J)=2
226 -  226.000       IF(TYPE(I,K,J)-TYPE(I-1,K,J))140,27,140
227 -  227.000   140 CFM1(I,K)=CB(I,K)-CA(I-1,K)
228 -  228.000    27 CONTINUE
229 -  229.000       IF(NA.EQ.NAZ)GO TO 189
230 -  230.000       DO 189 I=NA+1,NAZ
231 -  231.000       U1(I)=U2(I)
232 -  232.000       CF1(I,K)=CB(I,K)
233 -  233.000       CFM1(I,K)=CB(I,K)-CB(I-1,K)
234 -  234.000       TYPE(I,K,J)=2
235 -  235.000       IF(TYPE(I,K,J)-TYPE(I-1,K,J))141,189,141
236 -  236.000   141 CFM1(I,K)=CB(I,K)-CA(I-1,K)
237 -  237.000   189 CONTINUE
238 -  238.000       RAIR=RAIRZ
239 -  239.000       DO 190 I=1,4
240 -  240.000       IF(I.LT.4)GO TO 190
241 -  241.000       RAIR=0
242 -  242.000 C UU4=THERMAL CONDUCTANCE OF 4 IN. URETHANE TYPE 1 WALLS
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243 -  243.000   190 UU4(I)=WJ0(1)/(RB+RWIND+RAIR+R1(I))+WJ1/(RB+RWIND+RJT(4))
244 -  244.000       RAIR=RAIRZ
245 -  245.000 C NBZ=MAXIMUM INCREMENT NO. FOR TYPE 2 WALLS.  NB=MAXIMUM INCREMENT
246 -  246.000 C NO. FOR TYPE 1 WALLS.
247 -  247.000       IF(NB.GT.12)NB=12
248 -  248.000       DO 191 I=5,NB
249 -  249.000       IN=ITHICKNESS(I)
250 -  250.000       M1=I/2
251 -  251.000       M2=(I+1)/2
252 -  252.000       IF(M1.LT.M2)GO TO 193
253 -  253.000       RAIR=0
254 -  254.000 C UU5=THERMAL CONDUCTANCE OF THICK URETHANE TYPE 1 WALLS
255 -  255.000   193 UU5(I)=WJ0(1)/(RB+RWIND+RAIR+R1(I))+WJ1/(RB+RWIND+RJT(IN))
256 -  256.000   191 RAIR=RAIRZ
257 -  257.000       DO 192 I=5,NBZ
258 -  258.000       M3=I/2
259 -  259.000       M4=(I+1)/2
260 -  260.000       IF(M1.LT.M2)GO TO 194
261 -  261.000       RAIR=0
262 -  262.000 C UU2=THERMAL CONDUCTANCE OF URETHANE TYPE 2 WALLS
263 -  263.000   194 UU2(I)=WJ0(2)/(RB+RAIR+RWIND+R1(I))+(WJ2+WJ3)/(RB+RWIND+RAIR+
264 -  264.000      2RJT(4)+RUJ(I))
265 -  265.000   192 RAIR=RAIRZ
266 -  266.000       DO 195 I=1,4
267 -  267.000       UU1(I)=UU4(I)
268 -  268.000       CU1(I,K)=CRA(I,K)
269 -  269.000       CUM1(I,K)=CI1(I)
270 -  270.000   195 TYPU(I,K,J)=1
271 -  271.000       DO 196 I=5,NB
272 -  272.000       IF(1/(UU5(I)*CRA(I,K))-1/(UU2(I)*CRB(I,K)))197,198,198
273 -  273.000   198 UU1(I)=UU5(I)
274 -  274.000       CU1(I,K)=CRA(I,K)
275 -  275.000       CUM1(I,K)=CRA(I,K)-CRA(I-1,K)
276 -  276.000       TYPU(I,K,J)=1
277 -  277.000       IF(TYPU(I,K,J)-TYPU(I-1,K,J))199,196,199
278 -  278.000   199 CUM1(I,K)=CRA(I,K)-CRB(I-1,K)
279 -  279.000       GO TO 196
280 -  280.000   197 UU1(I)=UU2(I)
281 -  281.000       CU1(I,K)=CRB(I,K)
282 -  282.000       CUM1(I,K)=CRB(I,K)-CRB(I-1,K)
283 -  283.000       TYPU(I,K,J)=2
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284 -  284.000       IF(TYPU(I,K,J)-TYPU(I-1,K,J))201,196,201
285 -  285.000   201 CUM1(I,K)=CRB(I,K)-CRA(I-1,K)
286 -  286.000   196 CONTINUE
287 -  287.000       IF(NB.EQ.NBZ)GO TO 23
288 -  288.000       DO 23 I=NB+1,NBZ
289 -  289.000       UU1(I)=UU2(I)
290 -  290.000       CU1(I,K)=CRB(I,K)
291 -  291.000       CUM1(I,K)=CRB(I,K)-CRB(I-1,K)
292 -  292.000       TYPU(I,K,J)=2
293 -  293.000       IF(TYPU(I,K,J)-TYPU(I-1,K,J))202,23,202
294 -  294.000   202 CUM1(I,K)=CRB(I,K)-CRA(I-1,K)
295 -  295.000    23 CONTINUE
296 -  296.000       WRITE(7,58)H1
297 -  297.000       WRITE(7,179)NAZ,NBZ
298 -  298.000   179 FORMAT(2I3)
299 -  299.000    58 FORMAT(X,F6.4)
300 -  300.000       WRITE(7,59)((TYPE(I,K,J),I=1,NAZ),K=1,KK)
301 -  301.000       WRITE(7,59)((TYPU(I,K,J),I=1,NBZ),K=1,KK)
302 -  302.000    59 FORMAT(55I2)
303 -  303.000       WRITE(7,61)(U1(I),I=1,NAZ)
304 -  304.000       WRITE(7,61)(UU1(I),I=1,NBZ)
305 -  305.000    61 FORMAT(15F7.5)
306 -  306.000       WRITE(7,94)((CF1(I,K),I=1,NAZ),K=1,KK)
307 -  307.000    94 FORMAT(X,13F8.4)
308 -  308.000       WRITE(7,94)((CFM1(I,K),I=1,NAZ),K=1,KK)
309 -  309.000       WRITE(7,94)((CU1(I,K),I=1,NBZ),K=1,KK)
310 -  310.000       WRITE(7,94)((CUM1(I,K),I=1,NBZ),K=1,KK)
311 -  311.000    98 CONTINUE
312 -  312.000       STOP
313 -  313.000       END
314 -  314.000       FUNCTION IWALLTHICKNESS(I)
315 -  315.000 C IWALLTHICKNESS(I) REPRESENTS THE WALL CAVITY THICKNESS REQUIRED FOR
316 -  316.000 C THE ITH INCREMENT OF FIBERGLASS INS.  THE THICKNESSES ARE ROUNDED
317 -  317.000 C UP TO THE NEAREST INCH.  THUS THE IWALLTHICKNESS NUMBER FOR A
318 -  318.000 C 2X4 STUD WALL=4 WHILE THE ACTUAL THICKNESS OF THE CAVITY IS 3.5 IN.
319 -  319.000       IF(I.LT.4)IWALLTHICKNESS=4;RETURN
320 -  320.000       IF(I.EQ.4)IWALLTHICKNESS=6;RETURN
321 -  321.000       IF(I.LT.8)IWALLTHICKNESS=8;RETURN
322 -  322.000       IF(I.LT.11)IWALLTHICKNESS=10;RETURN
323 -  323.000       IF(I.EQ.11)IWALLTHICKNESS=12;RETURN
324 -  324.000       IF(I.LT.14)IWALLTHICKNESS=14;RETURN
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325 -   325.000        IF(I.LT.16)IWALLTHICKNESS=16;RETURN
326 -   326.000        IF(I.LT.18)IWALLTHICKNESS=18;RETURN
327 -   327.000        IF(I.GT.17)IWALLTHICKNESS=20;RETURN
328 -   328.000        END
329 -   329.000        FUNCTION ITHICKNESS(I)
330 -   330.000 C ITHICKNESS(I) REPRESENTS THE WALL CAVITY THICKNESS REQUIRED FOR THE
331 -   331.000 C ITH INCREMENT IF URETHANE INSULATION.
332 -   332.000        IF(I.LT.5)ITHICKNESS=4;RETURN
333 -   333.000        IF(I.LT.7)ITHICKNESS=6;RETURN
334 -   334.000        IF(I.LT.9)ITHICKNESS=8;RETURN
335 -   335.000        IF(I.LT.11)ITHICKNESS=10;RETURN
336 -   336.000        IF(I.LT.13)ITHICKNESS=12;RETURN
337 -   337.000        IF(I.LT.15)ITHICKNESS=14;RETURN
338 -   338.000        IF(I.LT.17)ITHICKNESS=16;RETURN
339 -   339.000        IF(I.LT.19)ITHICKNESS=18;RETURN
340 -   340.000        IF(I.LT.21)ITHICKNESS=20;RETURN
341 -   341.000        END
```

```
C********************************* W23 ************************************
      DIMENSION THJ(4),RJT(4),PGL2(4),D(2),R(22),P(22),R1(21),P1(21),
     2RIJ(22),U4(22,2),U5(22,2),U2(22,2),U3(22,2),Z(4),A3(4,20),C(22),
     3CI(22),CW(20),CS(22,4),PGL1(4),CI1(21),CR(21,4),A2(4,20),C1(21),
     4CPERW(4),CSM(22,4),AM3(4,20),CRM(21,4)
      READ(8,58)
   58 FORMAT()
      READ(8,1)RJ,RAIR
    1 FORMAT(X,2F5.2)
      READ(8,2)(THJ(IN),IN=2,4)
    2 FORMAT(4F6.2)
      READ(8,3)RM
      READ(8,3)RM1
    3 FORMAT(F6.1)
      READ(8,4)NI
      READ(8,4)NI1
    4 FORMAT(I5)
      READ(8,5)(P(I),I=2,NI+1)
      READ(8,6)(P1(I),I=2,11)
      READ(8,6)(P1(I),I=12,NI1+1)
    5 FORMAT(21F.0)
    6 FORMAT(10F.2)
      READ(8,9)WJ3
    9 FORMAT(F5.3)
      READ(8,10)RB
      READ(8,10)RBG
   10 FORMAT(F6.2)
      READ(8,55)(CI(I),I=2,NI+1)
      READ(8,56)(CI1(I),I=2,NI1+1)
   55 FORMAT(21F4.2)
   56 FORMAT(20F4.2)
      READ(8,57)(CW(IN),IN=2,4)
   57 FORMAT(4F5.2)
      READ(8,53)RTHJ
   53 FORMAT(X,F6.2)
      READ(8,123)SILL1,SILL2,JAM1,JAM2
  123 FORMAT(4F5.1)
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38 -    38.000       READ(8,153)CAT,BACK,CATB
39 -    39.000   153 FORMAT(X,3F6.2)
40 -    40.000       READ(8,155)HIWALL,PERI,CONCRETE,CIBOARD
41 -    41.000   155 FORMAT(4F6.2)
42 -    42.000       READ(8,184)RWIND
43 -    43.000   184 FORMAT(F4.2)
44 -    44.000       READ(1,121)
45 -    45.000   121 FORMAT()
46 -    46.000       READ(1,54)Y,W
47 -    47.000    54 FORMAT(2F5.1)
48 -    48.000       READ(1,82)IP1U,IP1L
49 -    49.000    82 FORMAT(2I5)
50 -    50.000       READ(1,83)P2
51 -    51.000    83 FORMAT(F5.2)
52 -    52.000       READ(1,85)H
53 -    53.000    85 FORMAT(F5.2)
54 -    54.000       READ(1,89)
55 -    55.000    89 FORMAT(/)
56 -    56.000       READ(1,179)(PGL1(K),K=1,4)
57 -    57.000   179 FORMAT(4F5.2)
58 -    58.000       READ(1,90)(PGL2(K),K=1,4)
59 -    59.000    90 FORMAT(4F5.2)
60 -    60.000       READ(1,163)(D(K),K=1,2)
61 -    61.000   163 FORMAT(2F5.2)
62 -    62.000       READ(1,91)KK
63 -    63.000    91 FORMAT(1X,I1)
64 -    64.000       READ(1,92)CSF
65 -    65.000    92 FORMAT(F5.1)
66 -    66.000       READ(1,166)CUSF123
67 -    67.000   166 FORMAT(F7.4)
68 -    68.000 C...THE FOLLOWING CALCULATIONS ARE FOR STUDDING (OR FURRING) INSULATION:
69 -    69.000 C CUSF=USABLE SQ.FT. COSTS FOR A RESIDENCE WITH 8 INCH CONCRETE WALLS
70 -    70.000 C HAVING WALLBOARD MOUNTED ON 1 INCH FURRING STRIPS SO 1.25 INCHES OF
71 -    71.000 C FLOOR AREA IS LOST ON ALL WALLS.
72 -    72.000 C IP1=PERCENTAGE OF TOTAL LIVING WALL AREA WHICH IS FRAME (COMPONENT 1)
73 -    73.000 C P2=PERCENTAGE OF TOTAL LIVING WALL AREA WHICH IS CONCRETE ABOVE
74 -    74.000 C GROUND (COMPONENT2)
75 -    75.000 C P3=PERCENTAGE OF TOTAL LIVING WALL AREA WHICH IS CONCRETE BELOW
76 -    76.000 C GROUND (COMPONENT3)
77 -    77.000       CUSF=(W*Y*CSF)/((W-1.542)*(Y-1.542))
78 -    78.000       CUSF=CUSF*CUSF123
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 79 -    79.000        IF(IP1U.EQ.100)IP1U=IP1U-10
 80 -    80.000        DO 114 IP1=IP1U,IP1L,-10
 81 -    81.000        P3=(100.-IP1-P2)
 82 -    82.000        H3=H*P3*.01
 83 -    83.000        H23=H*(P2+P3)*.01
 84 -    84.000        H2=(H23-H3)
 85 -    85.000        H1=H*IP1*.01
 86 -    86.000 C CAT$=CAT EXCAVATION COSTS, INC. BACKFILL          CAT=COST/YD.
 87 -    87.000 C BACK$=BACKHOE EXCAVATION COSTS                    BACK=COST/YD.
 88 -    88.000 C CATB$=CAT BACKFILL COSTS                          CATB=COST/YD.
 89 -    89.000        CATB$=((((W+40)*(Y+40)-(W*Y))*.5)/27)*CATB
 90 -    90.000 C THE BACKHOE IS USED TO DIG FOOTINGS IF THEY ARE 1 FT. OR MORE BELOW
 91 -    91.000 C THE EXCAVATION FOR THE FLOOR.
 92 -    92.000        CAT$=(((W+4)*(Y+4)*(H3-1+.667))/27)*CAT
 93 -    93.000        IF(H3.GT.(1.33))GO TO 145
 94 -    94.000        ENTRANCE23=100
 95 -    95.000        BACK$=((2*(Y+W)*4*(3-(H3+.667)))/27)*BACK
 96 -    96.000        IF(CAT$.LT.CATB$)EC=CATB$+BACK$;GO TO 144
 97 -    97.000        EC=CAT$+BACK$;GO TO 144
 98 -    98.000 C FOR FOOTINGS LESS THAN 1 FT. BELOW THE EXCAVATION OF THE FLOOR, A
 99 -    99.000 C CAT IS USED.  THE YARDS MOVED ARE THE DIFFERENCE BETWEEN DIGGING TO
100 -   100.000 C THE BOTTOM OF THE FOOTINGS AND DIGGING ONLY TO THE FLOOR DEPTH.
101 -   101.000   145 IF(H3.GT.(2.33))GO TO 146
102 -   102.000        ENTRANCE23=150
103 -   103.000        CAT$=(((W+4)*(Y+4)*((H3/2)+.833))/27)*CAT
104 -   104.000        IF(CAT$.LT.CATB$)EC=CATB$;GO TO 144
105 -   105.000        EC=CAT$;GO TO 144
106 -   106.000   146 ENTRANCE23=(H3-2.33)*75+150
107 -   107.000        CAT$=(((W+4)*(Y+4)*(H3-1+.667))/27)*CAT
108 -   108.000        IF(CAT$.LT.CATB$)EC=CATB$;GO TO 144
109 -   109.000        EC=CAT$
110 -   110.000 C ALL COSTS ARE CALCULATED ON A PER SQ.FT.BASIS.
111 -   111.000   144 DO 47 K=1,KK
112 -   112.000 C HIGHWALL=THE ADDITIONAL COST INCURRED IN POURING A WALL GREATER
113 -   113.000 C THAN 4 FEET HIGH
114 -   114.000        HIGHWALL=0
115 -   115.000        IF(H23.GT.4)HIGHWALL=HIWALL
116 -   116.000 C CPERW=PERIMETER INSULATION COSTS
117 -   117.000        IF(H23.GT.(6.67))Z5=6.67;GO TO 177
118 -   118.000        Z5=H23
119 -   119.000   177 CPERW(K)=((2*(W+Y)-2*D(1))*2*PERI)/((2*(W+Y)*(H23-H2*PGL2(K)))
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120 -  120.000       2-2*Z5*D(1))
121 -  121.000        IF(K.EQ.1)Z(K)=W;GO TO 180
122 -  122.000        IF(K.EQ.3)Z(K)=W;GO TO 180
123 -  123.000        Z(K)=Y
124 -  124.000    180 DO 147 IN=2,20
125 -  125.000    107 IF(IN.LT.3)X=0;Y1=SILL1;Z1=JAM1;GO TO 33
126 -  126.000        IF(IN.EQ.3)X=1.5;Y1=SILL2;Z1=JAM2;GO TO 33
127 -  127.000        IF(IN.LT.8)X=IN-1.5;Y1=SILL2;Z1=JAM2;GO TO 33
128 -  128.000        IF(IN.GT.7)X=IN-1.75;Y1=SILL2;Z1=JAM2;GO TO 33
129 -  129.000 C A2=THICK WALL COST
130 -  130.000     33 A2(K,IN)=(((X/12)*Z(K)*CUSF)+((PGL2(K)*(H23-H3)*Z(K)*Y1)/12)+((H23
131 -  131.000       2*D(1)*Z1)/(D(2)*3.0)))/(H23*Z(K)-H2*Z(K)*PGL2(K)-Z5*D(1))
132 -  132.000    147 CONTINUE
133 -  133.000        DO 12 IN=2,4
134 -  134.000 C RJT=TOTAL THERMAL RESISTANCE OF STUD
135 -  135.000     12 RJT(IN)=RJ*THJ(IN)
136 -  136.000        R(1)=0
137 -  137.000 C NC=MAXIMUM INCREMENT NO. FOR STUDDING INSULATION.  NI=MAXIMUM
138 -  138.000 C ALLOWABLE NO. OF INCREMENTS.  (NC=2 DEPICTS THE FIRST INCREMENT
139 -  139.000 C OF INSULATION.)
140 -  140.000 C RIJ=THERMAL RESISTANCE ON TOP OF 2X4 STUDS
141 -  141.000 C RTHJ=THERMAL RESISTANCE OF INSULATION AS THICK AS A 2X4 STUD
142 -  142.000 C RM=R MAXIMUM FOR EACH WALL
143 -  143.000        NC=1
144 -  144.000        DO 18 I=2,NI+1
145 -  145.000        NC=NC+1
146 -  146.000        RIJ(I)=0
147 -  147.000        R(I)=R(I-1)+P(I)
148 -  148.000        IF(I.GT.5) RIJ(I)=R(I)-RTHJ
149 -  149.000        IF(R(I).GT.RM)GO TO 15
150 -  150.000     18 CONTINUE
151 -  151.000        GO TO 16
152 -  152.000     15 NC=NC-1
153 -  153.000     16 C(1)=0
154 -  154.000        DO 35 I=2,NC
155 -  155.000 C C=COST FOR I INCREMENTS OF STUDDING INSULATION
156 -  156.000     35 C(I)=C(I-1)+CI(I)
157 -  157.000        CI(1)=0
158 -  158.000        DO 148 I=1,NC
159 -  159.000        IF(I.LT.4)IN=IWALLTHICKNESS(I)+1;GO TO 40
160 -  160.000        IN=IWALLTHICKNESS(I)
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161 -  161.000     40 IF(I-3)36,36,41
162 -  162.000 C CW(IN)=COST OF STUDDING OR FURRING FOR A WALL OF THICKNESS IN
163 -  163.000     41 CW(IN)=CW(4)
164 -  164.000 C CS=TOTAL COST FOR STUD OR FURRING INSULATED WALL
165 -  165.000 C CSM=MARGINAL WALL COST
166 -  166.000     36 CS(I,K)=C(I)+A2(K,IN)+CONCRETE*HIGHWALL*CW(IN)+CIBOARD+CPERW(K)
167 -  167.000        IF(I.EQ.1)CSM(I,K)=0;GO TO 148
168 -  168.000        CSM(I,K)=CS(I,K)-CS(I-1,K)
169 -  169.000    148 CONTINUE
170 -  170.000 C...THE FOLLOWING CALCULATIONS ARE FOR URETHANE INSULATION:
171 -  171.000        DO 149 IN=1,20
172 -  172.000    111 IF(IN.EQ.1)Y1=SILL1;Z1=JAM1;GO TO 124
173 -  173.000        IF(IN.GE.2)Y1=SILL2;Z1=JAM2;GO TO 124
174 -  174.000 C A3=THICK WALL COST
175 -  175.000    124 A3(K,IN)=((((IN-1)/12)*Z(K)*CUSF)+((PGL2(K)*(H23-H3)*Z(K)*Y1)/12)
176 -  176.000       2+((H23*D(1)*Z1)/(D(2)*3.0)))/(H23*Z(K)-H2*Z(K)*PGL2(K)-Z5*D(1))
177 -  177.000    115 IF(IN.EQ.1)AM3(K,IN)=0;GO TO 149
178 -  178.000        AM3(K,IN)=A3(K,IN)-A3(K,IN-1)
179 -  179.000    149 CONTINUE
180 -  180.000        R1(1)=0
181 -  181.000        NB=1
182 -  182.000        DO 28 I=2,NI1+1
183 -  183.000 C R1=THERMAL RESISTANCE FOR I INCREMENTS OF URETHANE INSULATION
184 -  184.000        R1(I)=R1(I-1)+P1(I)
185 -  185.000 C NB=MAXIMUM INCREMENT NO. FOR URETHANE INSULATION
186 -  186.000        NB=NB+1
187 -  187.000        IF(R1(I).GT.RM1)GO TO 29
188 -  188.000     28 CONTINUE
189 -  189.000        GO TO 30
190 -  190.000     29 NB=NB-1
191 -  191.000 C C=COST FOR I INCREMENTS OF URETHANE INSULATION
192 -  192.000     30 C1(1)=0
193 -  193.000        DO 46 I=2,NB
194 -  194.000     46 C1(I)=C1(I-1)+CI1(I)
195 -  195.000        CI1(1)=0
196 -  196.000        DO 47  I=1,NB
197 -  197.000        IF(I-1)48,49,48
198 -  198.000     49 IN=1
199 -  199.000        GO TO 150
200 -  200.000     48 IN=I-1
201 -  201.000 C CR=TOTAL COST FOR URETHANE INSULATED WALL
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202 -  202.000 C CRM=MARGINAL WALL COST
203 -  203.000   150 CW1=0;CW2=0
204 -  204.000       IF(I.EQ.1)CW1=CW(2)
205 -  205.000       IF(I.EQ.2)CW2=-CW(2)
206 -  206.000       CR(I,K)=C1(I)+A3(K,IN)+CONCRETE+HIGHWALL+CW1+CIBOARD+CPERW(K)
207 -  207.000       IF(I.EQ.1)CRM(I,K)=CI1(I);GO TO 47
208 -  208.000       CRM(I,K)=CI1(I)+AM3(K,IN)+CW2
209 -  209.000    47 CONTINUE
210 -  210.000       WRITE(9,178)H2,H3
211 -  211.000   178 FORMAT(X,2F7.3)
212 -  212.000       WRITE(9,125)NC
213 -  213.000       WRITE(9,125)NB
214 -  214.000   125 FORMAT(I3)
215 -  215.000       WRITE(9,116)((CS(I,K),I=1,NC),K=1,KK)
216 -  216.000       WRITE(9,116)((CSM(I,K),I=1,NC),K=1,KK)
217 -  217.000       WRITE(9,116)((CR(I,K),I=1,NB),K=1,KK)
218 -  218.000       WRITE(9,116)((CRM(I,K),I=1,NB),K=1,KK)
219 -  219.000   116 FORMAT(X,12F9.4)
220 -  220.000       WRITE(9,185)EC
221 -  221.000   185 FORMAT(X,F7.2)
222 -  222.000       WRITE(9,185)2*ENTRANCE23
223 -  223.000   114 CONTINUE
224 -  224.000 C WJ0=WEIGHT OF NON STUD OR FURRING AREA
225 -  225.000       WJ0=1-WJ3
226 -  226.000       RBZ=RB
227 -  227.000       RAIRZ=RAIR
228 -  228.000       DO 75 N1=1,2
229 -  229.000 C N1=1=ABOVE GROUND          N1=2=BELOW GROUND
230 -  230.000       IF(N1.EQ.1)GO TO 19
231 -  231.000       RWIND=0
232 -  232.000       RB=RBG
233 -  233.000    19 DO 25 I=1,NC
234 -  234.000       RIJ(1)=0
235 -  235.000       IF(I-1) 24,20,24
236 -  236.000    20 IN=2
237 -  237.000       GO TO 25
238 -  238.000 C WHEN THE AIR SPACE IS LESS THAN OR EQUAL TO .75 IN. THICK, ASSIGN
239 -  239.000 C RAIR=0.  WHEN THE FIBERGLASS IS COMPRESSED MORE THAN .75 IN., ASSIGN
240 -  240.000 C RAIR=-1 AS A COMPRESSION FACTOR.
241 -  241.000    24 RAIR=0
242 -  242.000       IF(I.GE.4)IN=4;GO TO 186
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243 -  243.000        IF(I.LT.4)IN=IWALLTHICKNESS(I)+1
244 -  244.000    186 IF(I.EQ.12)RAIR=-1
245 -  245.000 C U4=THERMAL CONDUCTANCE OF STUD INSULATED WALLS
246 -  246.000     25 U4(I,N1)=WJ0/(RB+RWIND+RAIR+R(I))+WJ3/(RB+RWIND+RJT(IN)+RIJ(I)+
247 -  247.000       2RAIR)
248 -  248.000        RAIR=RAIRZ
249 -  249.000        DO 31 I=1,NB
250 -  250.000        IF(I.GT.1)RAIR=0
251 -  251.000 C U5=THERMAL CONDUCTANCE OF URETHANE INSULATED WALLS
252 -  252.000     31 U5(I,N1)=1/(RB+RWIND+RAIR+R1(I))
253 -  253.000     75 RAIR=RAIRZ
254 -  254.000        U5(1,1)=U4(1,1);U5(1,2)=U4(1,2)
255 -  255.000        RB=RBZ
256 -  256.000        DO 32 I=1,NC
257 -  257.000 C U2 AND U3 ARE SUBSCRIPTED (I,N2) WHERE N2=1 FOR STUDDING INSULATION
258 -  258.000 C AND N2=2 FOR URETHANE
259 -  259.000 C THERMAL CONDUCTANCE OF ABOVE GROUND STUD INSULATED WALLS
260 -  260.000 C (COMPONENT 2):
261 -  261.000        U2(I,1)=U4(I,1)
262 -  262.000 C THERMAL CONDUCTANCE OF BELOW GROUND STUD INSULATED WALLS
263 -  263.000 C (COMPONENT 3):
264 -  264.000     32 U3(I,1)=U4(I,2)
265 -  265.000        DO 23 I=1,NB
266 -  266.000 C THERMAL CONDUCTANCE OF ABOVE GROUND URETHANE INSULATED WALLS
267 -  267.000 C (COMPONENT 2):
268 -  268.000        U2(I,2)=U5(I,1)
269 -  269.000 C THERMAL CONDUCTANCE OF BELOW GROUND URETHANE INSULATED WALLS
270 -  270.000 C (COMPONENT 3):
271 -  271.000        U3(I,2)=U5(I,2)
272 -  272.000     23 CONTINUE
273 -  273.000        WRITE(9,78)((U2(I,1),U3(I,1)),I=1,NC)
274 -  274.000     78 FORMAT(15F7.5)
275 -  275.000        WRITE(9,80)((U2(I,2),U3(I,2)),I=1,NB)
276 -  276.000     80 FORMAT(15F7.5)
277 -  277.000     81 CONTINUE
278 -  278.000        STOP
279 -  279.000        END
280 -  280.000        FUNCTION IWALLTHICKNESS(I)
281 -  281.000 C IWALLTHICKNESS(I) REPRESENTS THE WALL CAVITY THICKNESS REQUIRED
282 -  282.000 C FOR THE ITH INCREMENT OF INSULATION.  THE THICKNESSES ARE ROUNDED
283 -  283.000 C UP TO THE NEAREST INCH.  THUS THE IWALLTHICKNESS NUMBER FOR A
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284 -   284.000 C 2X4 STUD WALL=4 WHILE THE ACTUAL THICKNESS OF THE CAVITY IS 3.5 IN.
285 -   285.000       IF(I.EQ.1)IWALLTHICKNESS=1;RETURN
286 -   286.000       IF(I.EQ.2)IWALLTHICKNESS=1;RETURN
287 -   287.000       IF(I.EQ.3)IWALLTHICKNESS=2;RETURN
288 -   288.000       IF(I.LT.6)IWALLTHICKNESS=4;RETURN
289 -   289.000       IF(I.EQ.6)IWALLTHICKNESS=6;RETURN
290 -   290.000       IF(I.LT.10)IWALLTHICKNESS=8;RETURN
291 -   291.000       IF(I.LT.13)IWALLTHICKNESS=10;RETURN
292 -   292.000       IF(I.EQ.13)IWALLTHICKNESS=12;RETURN
293 -   293.000       IF(I.LT.16)IWALLTHICKNESS=14;RETURN
294 -   294.000       IF(I.LT.18)IWALLTHICKNESS=16;RETURN
295 -   295.000       IF(I.LT.20)IWALLTHICKNESS=18;RETURN
296 -   296.000       IF(I.GT.19)IWALLTHICKNESS=20;RETURN
297 -   297.000       END
```

```
 1 -     1.000 C********************************** MA ************************************
 2 -     2.000       DIMENSION TC(4,21,2),TS(4,21,2),BTU(22,4,3),YLF(2),TS2(4,21,2),
 3 -     3.000      2U(2,22,3),XLF(2),A(2),PA(2),N1(2,3),TEQ(3),IFLAG(3),TC2(4,21,2),
 4 -     4.000      3CM(2,22,4,21,2),MPS(2,3),H(21,3),C(2,22,4,21,2),PGL1(4),PGL2(4),
 5 -     5.000      4TYPE(2,22,4,21,3),R(2,22,3),PLA(2)
 6 -     6.000       READ(1,17)
 7 -     7.000    17 FORMAT(/)
 8 -     8.000       READ(1,1)IP1U,IP1L
 9 -     9.000     1 FORMAT(2I5)
10 -    10.000       READ(1,2)
11 -    11.000     2 FORMAT(/)
12 -    12.000       READ(1,3)OPTION1
13 -    13.000     3 FORMAT(I1)
14 -    14.000       READ(1,3)OPTION2
15 -    15.000       READ(1,5)(PGL1(K),K=1,4)
16 -    16.000       READ(1,5)(PGL2(K),K=1,4)
17 -    17.000     5 FORMAT(4F5.2)
18 -    18.000       READ(1,108)DOOR
19 -    19.000   108 FORMAT(F5.2)
20 -    20.000       READ(1,115)KK
21 -    21.000   115 FORMAT(1X,I1)
22 -    22.000       READ(1,110)CSF
23 -    23.000   110 FORMAT(F5.1)
24 -    24.000       READ(1,111)CUSF123
25 -    25.000   111 FORMAT(F7.4)
26 -    26.000       READ(1,113)ECSF123,ENSF123
27 -    27.000   113 FORMAT(2F7.4)
28 -    28.000       READ(1,7)D,P,XL
29 -    29.000     7 FORMAT(X,3F6.2)
30 -    30.000       READ(1,9)HFUEL,CFUEL
31 -    31.000     9 FORMAT(X,2F6.3)
32 -    32.000       READ(1,11)CC
33 -    33.000    11 FORMAT(X,F4.2)
34 -    34.000       READ(1,12)HD,DD,CH
35 -    35.000    12 FORMAT(X,3F7.0)
36 -    36.000       READ(1,13)TBSMT
37 -    37.000    13 FORMAT(X,F4.1)
```

```
      READ(1,14)(TEQ(N),N=1,3)
   14 FORMAT(X,3F5.1)
      READ(1,15)(MPS(1,N),N=1,2)
      READ(1,15)(MPS(2,N),N=1,2)
   15 FORMAT(X,2I2)
      READ(1,16)HE,CE
   16 FORMAT(2F6.3)
      IF(IP1L.EQ.100)J2=1;GO TO 158
      J1=0
      DO 25 IP1=IP1U,IP1L,-10
   25 J1=J1+1
      IF(IP1U.EQ.100)J2=2;GO TO 159
      J2=1
  159 DO 22 J=J2,J1
      READ(4,34)H(J,2),H(J,3)
   34 FORMAT(X,2F7.3)
      READ(4,20)N1(1,2)
      READ(4,20)N1(2,2)
   20 FORMAT(I3)
      READ(4,21)((C(1,I,K,J,2),I=1,N1(1,2)),K=1,KK)
      READ(4,21)((CM(1,I,K,J,2),I=1,N1(1,2)),K=1,KK)
      READ(4,21)((C(2,I,K,J,2),I=1,N1(2,2)),K=1,KK)
      READ(4,21)((CM(2,I,K,J,2),I=1,N1(2,2)),K=1,KK)
   21 FORMAT(X,12F9.4)
      READ(4,168)
  168 FORMAT(/)
   22 CONTINUE
      READ(4,26)((U(1,I,2),U(1,I,3)),I=1,N1(1,2))
      READ(4,26)((U(2,I,2),U(2,I,3)),I=1,N1(2,2))
   26 FORMAT(15F7.5)
      IF(IP1U.EQ.0)GO TO 27
   18 IF(IP1L.EQ.0)J2=J1-1;GO TO 158
      J2=J1
  158 DO 27 J=1,J2
      READ(3,33)H(J,1)
   33 FORMAT(X,F6.4)
      READ(3,28)N1(1,1),N1(2,1)
   28 FORMAT(2I3)
      READ(3,29)((TYPE(1,I,K,J,1),I=1,N1(1,1)),K=1,KK)
      READ(3,29)((TYPE(2,I,K,J,1),I=1,N1(2,1)),K=1,KK)
   29 FORMAT(55I2)
```

```
 79 -    79.000        READ(3,31)(U(1,I,1),I=1,N1(1,1))
 80 -    80.000        READ(3,31)(U(2,I,1),I=1,N1(2,1))
 81 -    81.000     31 FORMAT(15F7.5)
 82 -    82.000        READ(3,32)(((C(1,I,K,J,1),I=1,N1(1,1)),K=1,KK)
 83 -    83.000        READ(3,32)(((CM(1,I,K,J,1),I=1,N1(1,1)),K=1,KK)
 84 -    84.000        READ(3,32)(((C(2,I,K,J,1),I=1,N1(2,1)),K=1,KK)
 85 -    85.000        READ(3,32)(((CM(2,I,K,J,1),I=1,N1(2,1)),K=1,KK)
 86 -    86.000     32 FORMAT(X,13F8.4)
 87 -    87.000     27 CONTINUE
 88 -    88.000        IF(IP1L.EQ.100)GO TO 165
 89 -    89.000        N1(1,3)=N1(1,2)
 90 -    90.000        N1(2,3)=N1(2,2)
 91 -    91.000        I4=MAX(N1(1,2),N1(2,2))
 92 -    92.000        DO 62 K=1,KK
 93 -    93.000        DO 62 J=1,21
 94 -    94.000        DO 62 I=1,I4
 95 -    95.000        DO 62 L=1,2
 96 -    96.000     62 TYPE(L,I,K,J,2)=3
 97 -    97.000    165 IF(D.EQ.P)PV=XL;GO TO 40
 98 -    98.000        PV=((1+P)/(D-P))*(1-((1+P)/(1+D))**XL)
 99 -    99.000     40 L=1
100 -   100.000        IF(OPTION1.EQ.1)L=2
101 -   101.000        LL=L
102 -   102.000        CH1=CH
103 -   103.000        IF(OPTION2.EQ.0)CH1=0
104 -   104.000        J=0
105 -   105.000        DO 45 IP1=IP1U,IP1L,-10
106 -   106.000        J=J+1
107 -   107.000        IF(IP1.EQ.100)I1=I2=1;GO TO 47
108 -   108.000        IF(IP1.EQ.0)I1=2;I2=3;GO TO 47
109 -   109.000        I1=1;I2=3
110 -   110.000     47 DO 45 K=1,KK
111 -   111.000        DO 119 N=I1,I2
112 -   112.000        L=LL
113 -   113.000        DO 119 I=1,N1(L,N)
114 -   114.000        IF(I.EQ.1)BTU(I,K,N)=0;GO TO 119
115 -   115.000        IF(N.EQ.3)T=((75-TBSMT)*24*HD);GO TO 51
116 -   116.000        T=24*DD
117 -   117.000 C BTU=PRESENT VALUE SAVINGS FROM THE ITH INCREMENT OF INSULATION
118 -   118.000     51 BTU(I,K,N)=(((U(L,I-1,N)-U(L,I,N))*(T*(HFUEL/HE)
119 -   119.000       2+TEQ(N)*CH1*(CFUEL/CE)))/100000)*PV
```

```
120 -  120.000   119 CONTINUE
121 -  121.000       L=LL
122 -  122.000       R(L,1,1)=1.0/U(L,1,1)
123 -  123.000       R(L,1,2)=(H(J,2)/U(L,1,2)+H(J,3)/U(L,1,3))/(H(J,2)+H(J,3))
124 -  124.000       IF(IP1.EQ.100)I3=I4=1;GO TO 117
125 -  125.000       DO 116 I=1,N1(L,2)
126 -  126.000   116 BTU(I,K,2)=(H(J,2)*BTU(I,K,2)+H(J,3)*BTU(I,K,3))/(H(J,2)+H(J,3))
127 -  127.000       IF(IP1.EQ.0)I3=I4=2;GO TO 117
128 -  128.000       I3=1;I4=2
129 -  129.000   117 DO 46 N=I3,I4
130 -  130.000       Z=0
131 -  131.000       IH=IG=IZ=IFLAG(N)=0
132 -  132.000       FLAG=FLAG1=0
133 -  133.000       TS1=TC1=0
134 -  134.000       L=LL
135 -  135.000       DO 79 I=2,N1(L,N)
136 -  136.000       IF(CM(L,I,K,J,N).LE.0)GO TO 128
137 -  137.000       IF((BTU(I,K,N)/(CM(L,I,K,J,N)**CC)).LT.1)Z=1;GO TO 42
138 -  138.000   128 IH=I
139 -  139.000    42 IF(Z.EQ.0)IZ=IH;GO TO 41
140 -  140.000       TS1=TS1+BTU(I,K,N)
141 -  141.000       TC1=TC1+CM(L,I,K,J,N)
142 -  142.000       IF((TS1/(TC1*CC))-1)41,43,43
143 -  143.000    43 IG=I
144 -  144.000       IF(IH.EQ.IG)FLAG=TS1-TC1
145 -  145.000       IF(FLAG.GT.FLAG1)FLAG1=FLAG;IFLAG(N)=I
146 -  146.000    41 IF(N.EQ.1)R(L,I,1)=1.0/U(L,I,1);GO TO 79
147 -  147.000       R(L,I,2)=(H(J,2)/U(L,I,2)+H(J,3)/U(L,I,3))/(H(J,2)+H(J,3))
148 -  148.000    79 CONTINUE
149 -  149.000       IF(IFLAG(N).EQ.0)IFLAG(N)=IZ
150 -  150.000       TS2(K,J,N)=TC2(K,J,N)=0
151 -  151.000       TS(K,J,N)=TC(K,J,N)=0
152 -  152.000       IF(MPS(L,N).GT.IFLAG(N))GO TO 129
153 -  153.000       GO TO 131
154 -  154.000   129 DO 130 I=IFLAG(N)+1,MPS(L,N)
155 -  155.000       TC2(K,J,N)=TC2(K,J,N)+CM(L,I,K,J,N)
156 -  156.000   130 TS2(K,J,N)=TS2(K,J,N)+BTU(I,K,N)
157 -  157.000   131 IF(MPS(L,N).GE.IFLAG(N))YLF(N)=77;GO TO 60
158 -  158.000       DO 44 I=MPS(L,N)+1,IFLAG(N)
159 -  159.000 C TC=TOTAL COST OF THE PRESENT VALUE MAXIMIZING POINT
160 -  160.000       TC(K,J,N)=TC(K,J,N)+CM(L,I,K,J,N)
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161 -   161.000 C TS=TOTAL REVENUE OR SAVINGS OF THE PRESENT VALUE MAXIMIZING POINT
162 -   162.000     44 TS(K,J,N)=TS(K,J,N)+BTU(I,K,N)
163 -   163.000        IF(TC(K,J,N).LE.0)YLF(N)=77;GO TO 60
164 -   164.000        IF(D.EQ.P)YLF(N)=TC(K,J,N)/(TS(K,J,N)/PV);GO TO 60
165 -   165.000        YLF(N)=(LOG(1-((TC(K,J,N)/(TS(K,J,N)/PV))*(D-P)/(1+P))))/
166 -   166.000       2(LOG((1+P)/(1+D)))
167 -   167.000     60 IF(IFLAG(N).EQ.1)XLF(N)=YLF(N)=77;GO TO 49
168 -   168.000        IF(IFLAG(N).LE.MPS(L,N))XLF(N)=YLF(N)=77;GO TO 49
169 -   169.000        IF(CM(L,IFLAG(N),K,J,N).LE.0)XLF(N)=77;GO TO 49
170 -   170.000        IF(D.EQ.P)XLF(N)=CM(L,IFLAG(N),K,J,N)/(BTU(IFLAG(N),K,N)/PV);GO TO
171 -   171.000       2 49
172 -   172.000        XLF(N)=(LOG(1-((CM(L,IFLAG(N),K,J,N)/(BTU(IFLAG(N),K,N)/PV)
173 -   173.000       2)*(D-P)/(1+P))))/(LOG((1+P)/(1+D)))
174 -   174.000     49 IF(H(J,1).EQ.8)X1=6.67;X2=X3=0;GO TO 50
175 -   175.000        IF(H(J,3)+H(J,2).LE.(6.67))X1=(6.67-H(J,3)-H(J,2));X2=H(J,2);
176 -   176.000       2X3=H(J,3);GO TO 50
177 -   177.000        IF(H(J,3).GE.(6.67))X1=0;X2=0;X3=6.67;GO TO 50
178 -   178.000        X1=0;X2=(6.67-H(J,3));X3=H(J,3)
179 -   179.000     50 A(1)=((2*(30+40)*H(J,1)*(1-PGL1(K)))-2*3*X1)
180 -   180.000        A(2)=((2*(30+40)*(H(J,2)*(1-PGL2(K))+H(J,3)))-2*3*X2-2*3*X3)
181 -   181.000 C PLA(N)=PRESENT VALUE LOSS FROM MEETING MPS REQUIREMENTS FOR
182 -   182.000 C WALL AREA A(N)
183 -   183.000        PLA(N)=(TS2(K,J,N)-TC2(K,J,N))*A(N)
184 -   184.000 C PA(N)=PRESENT VALUE MAXIMUM PROFIT FOR WALL AREA A(N)
185 -   185.000     46 PA(N)=(TS(K,J,N)-TC(K,J,N))*A(N)
186 -   186.000        IF(IP1.EQ.100)PA(2)=PLA(2)=0
187 -   187.000        IF(IP1.EQ.0)PA(1)=PLA(1)=0
188 -   188.000        P$=PA(1)+PA(2)+PLA(1)+PLA(2)
189 -   189.000        WRITE(6,114)
190 -   190.000    114 FORMAT(1H1,5X,'CONSTRAINTS PLACED BY HOMEOWNERS:')
191 -   191.000        WRITE(6,82)(KK,(PGL1(K1),K1=1,KK))
192 -   192.000     82 FORMAT(1H ,7X,I1,' GLAZING FRACTIONS ARE CONSIDERED FOR COMPONENT
193 -   193.000       21: PGL1(K)=',4(F3.2,4X))
194 -   194.000        WRITE(6,83)(PGL2(K1),K1=1,KK)
195 -   195.000     83 FORMAT(1H ,42X,'AND COMPONENT 2: PGL2(K)=',4(F3.2,4X))
196 -   196.000        IF(DOOR-0)84,84,85
197 -   197.000     84 WRITE(6,86)
198 -   198.000     86 FORMAT(1H ,7X,'(NO DOOR IS ASSUMED IN THE MODEL WALL)')
199 -   199.000        GO TO 88
200 -   200.000     85 WRITE(6,87)
201 -   201.000     87 FORMAT(1H ,7X,'(ONE DOOR IS ASSUMED IN THE MODEL WALL)')
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202 -  202.000    88 WRITE(6,107)CSF
203 -  203.000   107 FORMAT(1H ,7X,'THE MARGINAL SQ.FT. COSTS OF THE RESIDENCE ARE '
204 -  204.000      2,F4.1)
205 -  205.000       IF(OPTION1-1)57,56,56
206 -  206.000    56 WRITE(6,58)
207 -  207.000       GO TO 76
208 -  208.000    57 WRITE(6,59)
209 -  209.000    58 FORMAT(1H ,7X,'URETHANE INSULATION IS USED THROUGHOUT')
210 -  210.000    59 FORMAT(1H ,7X,'FIBERGLASS STUDDING INSULATION IS USED THROUGHOUT')
211 -  211.000    76 IF(OPTION2-0)89,89,90
212 -  212.000    89 WRITE(6,91)
213 -  213.000    91 FORMAT(1H ,7X,'NO SUMMER AIR CONDITIONING')
214 -  214.000       GO TO 93
215 -  215.000    90 WRITE(6,92)
216 -  216.000    92 FORMAT(1H ,7X,'SUMMER AIR CONDITIONING')
217 -  217.000    93 WRITE(6,94)D,P,XL
218 -  218.000    94 FORMAT(1H ,5X,'DISCOUNT RATE=',F3.2,10X,'REAL RATE OF FUEL PRICE I
219 -  219.000      2NCREASE=',F3.2,10X,'LIFETIME=',F5.2)
220 -  220.000       WRITE(6,167)PV
221 -  221.000   167 FORMAT(1H ,7X,'PRESENT VALUE FACTOR=',F5.2)
222 -  222.000       WRITE(6,95)
223 -  223.000    95 FORMAT(1H ,5X,'WEATHER AND FUEL PRICE DATA:')
224 -  224.000       WRITE(6,96)DD,CH
225 -  225.000    96 FORMAT(1H ,7X,'DEGREE DAYS=',F6.0,10X,'COOLING HOURS=',F5.0)
226 -  226.000       WRITE(6,97)HFUEL,CFUEL
227 -  227.000    97 FORMAT(1H ,7X,'HEATING FUEL COST/100000 BTU =',F5.3,10X,'COOLING F
228 -  228.000      2UEL COST/100000 BTU =',F5.3)
229 -  229.000       WRITE(6,98)P$
230 -  230.000    98 FORMAT(1H ,5X,'PRESENT VALUE MAX NET SAVINGS(+) OR LOSS(-) FOR THE
231 -  231.000      2 TOTAL WALL AREA OF THE MODEL HOME IS',F8.2)
232 -  232.000       WRITE(6,121)
233 -  233.000   121 FORMAT(1H ,5X,'THE SUBSCRIPTS DENOTE FUNCTIONAL DEPENDENCIES:',
234 -  234.000      2/,8X,'L= THE INSULATION TYPE (L=1 FOR FIBERGLASS   L=2 FOR URETHAN
235 -  235.000      3E)',/,8X,'I= THE INSULATION INCREMENT NO.',/,8X,'K= THE GLAZING FR
236 -  236.000      4ACTION NO.',/,8X,'J= THE GROUND RATIO STEP NO. (P1=THE PERCENTAGE
237 -  237.000      5OF THE LIVING WALL AREA WHICH IS COMPONENT 1)',/,8X,'N= THE WALL U
238 -  238.000      6NIT NO.')
239 -  239.000       DO 45 N=I3,I4
240 -  240.000       L=LL
241 -  241.000       IF(N-1)123,123,124
242 -  242.000   123 WRITE(6,125)
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243 -  243.000       GO TO 127
244 -  244.000   124 WRITE(6,126)
245 -  245.000   125 FORMAT(1H0,5X,'THE FOLLOWING LISTING IS FOR A SQ.FT. OF COMPONENT
246 -  246.000      21:')
247 -  247.000   126 FORMAT(1H0,5X,'THE FOLLOWING LISTING IS FOR A SQ.FT. OF COMPONENTS
248 -  248.000      2 2 AND 3:')
249 -  249.000   127 WRITE(6,100)L,K,J,IP1,N
250 -  250.000   100 FORMAT(1H ,7X,'L=',I1,20X,'K=',I1,19X,'J=',I2,1X,'(GR=',I3,')',11X
251 -  251.000      2,'N=',I1)
252 -  252.000       WRITE(6,102)IFLAG(N)-1
253 -  253.000   102 FORMAT(1H ,7X,'THE OPTIMAL INCREMENT NO. IS ',I2)
254 -  254.000       WRITE(6,122)MPS(L,N)-1
255 -  255.000   122 FORMAT(1H ,7X,'(INCREMENT NO. ',I1,' IS REQUIRED TO MEET HUD MINIM
256 -  256.000      2UM PROPERTY STANDARDS (MPS))')
257 -  257.000       IF(XLF(N).EQ.77)GO TO 156
258 -  258.000       WRITE(6,103)XLF(N)
259 -  259.000   103 FORMAT(1H ,7X,'THE YEARS REQUIRED TO PAY BACK THE LAST INCREMENT A
260 -  260.000      2RE',F6.2)
261 -  261.000   156 IF(YLF(N).EQ.77)GO TO 157
262 -  262.000       WRITE(6,145)YLF(N)
263 -  263.000   145 FORMAT(1H ,7X,'THE YEARS REQUIRED TO PAY BACK THE TOTAL INVESTMENT
264 -  264.000      2 BEYOND MPS ARE',F6.2)
265 -  265.000   157 IF(PA(N)-0)146,146,147
266 -  266.000   146 WRITE(6,149)TC2(K,J,N)-TS2(K,J,N),TC2(K,J,N)
267 -  267.000   149 FORMAT(1H ,7X,'TOTAL LOSS MEETING MPS/SQ.FT.=',F7.4,6X,'TOTAL COST
268 -  268.000      2 FROM OPTIMAL PT. TO MPS/SQ.FT.=',F7.4)
269 -  269.000       GO TO 148
270 -  270.000   147 WRITE(6,104)TS(K,J,N),TC(K,J,N)
271 -  271.000   104 FORMAT(1H ,7X,'TOTAL SAVINGS BEYOND MPS/SQ.FT.=',F7.4,10X,'TOTAL C
272 -  272.000      2OST BEYOND MPS/SQ.FT.=',F7.4)
273 -  273.000   148 IF(N-1)132,132,133
274 -  274.000   132 IF(PA(N)-0)134,134,135
275 -  275.000   134 WRITE(6,137)-PLA(N)
276 -  276.000   137 FORMAT(1H ,7X,'PRESENT VALUE LOSS FROM MEETING MPS REQUIREMENTS FO
277 -  277.000      2R THE COMPONENT 1',/,9X,'WALL AREA OF THE MODEL HOME IS',F8.2)
278 -  278.000       GO TO 136
279 -  279.000   135 WRITE(6,138)PA(N)
280 -  280.000   138 FORMAT(1H ,7X,'PRESENT VALUE MAXIMUM NET SAVINGS FOR THE COMPONENT
281 -  281.000      2 1 WALL AREA OF THE MODEL HOME IS',F8.2)
282 -  282.000       GO TO 136
283 -  283.000   133 IF(PA(N)-1)139,139,140
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284 -  284.000    139 WRITE(6,141)-PLA(N)
285 -  285.000    141 FORMAT(1H ,7X,"PRESENT VALUE LOSS FROM MEETING MPS REQUIREMENTS FO
286 -  286.000       2R THE COMPONENT 2",/,9X,"AND 3 WALL AREAS OF THE MODEL HOME IS"
287 -  287.000       3,F8.2)
288 -  288.000        GO TO 136
289 -  289.000    140 WRITE(6,142)PA(N)
290 -  290.000    142 FORMAT(1H ,7X,"PRESENT VALUE MAX NET SAVINGS FOR THE COMPONENT 2 A
291 -  291.000       2ND 3 WALL AREAS OF THE MODEL HOME IS",F8.2)
292 -  292.000    136 IF(N-1)162,162,161
293 -  293.000    161 WRITE(6,105)
294 -  294.000    105 FORMAT(1H ,13X,"THICKNESS",6X,"TYPE(N)",5X,"R(L,I,J,N)",6X,"MS(L,I
295 -  295.000       2,J,N)",4X,"MC(L,I,K,J,N)",4X,"C(L,I,K,J,N)")
296 -  296.000        GO TO 164
297 -  297.000    162 WRITE(6,163)
298 -  298.000    163 FORMAT(1H ,13X,"THICKNESS",4X,"TYPE(I,J,N)",4X,"R(L,I,N)",8X,"MS(L
299 -  299.000       2,I,N)",5X,"MC(L,I,K,J,N)",4X,"C(L,I,K,J,N)")
300 -  300.000    164 DO 45 I=1,N1(L,N)
301 -  301.000        IF(N-1)151,151,152
302 -  302.000    151 IF(L-1)170,170,169
303 -  303.000    170 TH=THICK1(I)
304 -  304.000        GO TO 153
305 -  305.000    169 TH=THICK3(I)
306 -  306.000        GO TO 153
307 -  307.000    152 IF(L-1)154,154,155
308 -  308.000    154 TH=THICK2(I)
309 -  309.000        GO TO 153
310 -  310.000    155 IF(I.EQ.1)TH=9.25;GO TO 153
311 -  311.000        TH=I+7.25
312 -  312.000    153 WRITE(6,106)I-1,TH,TYPE(L,I,K,J,N),R(L,I,N),BTU(I,K,N),CM(L,I,K,J,
313 -  313.000       2N),C(L,I,K,J,N)
314 -  314.000    106 FORMAT(1H ,7X,"I=",I2,4X,F5.2,11X,I1,10X,F6.2,9X,F7.4,9X,F7.4,
315 -  315.000       29X,F8.4)
316 -  316.000     45 CONTINUE
317 -  317.000        STOP
318 -  318.000        END
319 -  319.000        FUNCTION THICK1(I)
320 -  320.000        IF(I.LT.4)THICK1=4.5;RETURN
321 -  321.000        IF(I.EQ.4)THICK1=6.5;RETURN
322 -  322.000        IF(I.LT.8)THICK1=8.25;RETURN
323 -  323.000        IF(I.LT.11)THICK1=10.25;RETURN
324 -  324.000        IF(I.EQ.11)THICK1=12.25;RETURN
```

```
325 -  325.000        IF(I.LT.14)THICK1=14.25;RETURN
326 -  326.000        IF(I.LT.16)THICK1=16.25;RETURN
327 -  327.000        IF(I.LT.18)THICK1=18.25;RETURN
328 -  328.000        IF(I.GT.17)THICK1=20.25;RETURN
329 -  329.000        END
330 -  330.000        FUNCTION THICK2(I)
331 -  331.000        IF(I.LE.2)THICK2=9.25;RETURN
332 -  332.000        IF(I.EQ.3)THICK2=10.75;RETURN
333 -  333.000        IF(I.LT.6)THICK2=11.75;RETURN
334 -  334.000        IF(I.EQ.6)THICK2=13.75;RETURN
335 -  335.000        IF(I.LT.10)THICK2=15.5;RETURN
336 -  336.000        IF(I.LT.13)THICK2=17.5;RETURN
337 -  337.000        IF(I.EQ.13)THICK2=19.5;RETURN
338 -  338.000        IF(I.LT.16)THICK2=21.5;RETURN
339 -  339.000        IF(I.LT.18)THICK2=23.5;RETURN
340 -  340.000        IF(I.LT.20)THICK2=25.5;RETURN
341 -  341.000        IF(I.GT.19)THICK2=27.5;RETURN
342 -  342.000        END
343 -  343.000        FUNCTION THICK3(I)
344 -  344.000        IF(I.LT.5)THICK3=4.5;RETURN
345 -  345.000        IF(I.LT.7)THICK3=6.5;RETURN
346 -  346.000        IF(I.LT.9)THICK3=8.25;RETURN
347 -  347.000        IF(I.LT.11)THICK3=10.25;RETURN
348 -  348.000        IF(I.LT.13)THICK3=12.25;RETURN
349 -  349.000        IF(I.LT.15)THICK3=14.25;RETURN
350 -  350.000        IF(I.LT.17)THICK3=16.25;RETURN
351 -  351.000        IF(I.LT.19)THICK3=18.25;RETURN
352 -  352.000        IF(I.LT.21)THICK3=20.25;RETURN
353 -  353.000        END
```

```
1 -     1.000 C********************************** M ************************************
2 -     2.000       DIMENSION TC(4,21,2),TS(4,21,2),BTU(22,4,3),YLF(2),TS2(4,21,2),
3 -     3.000      2U(2,22,3),XLF(2),A(2),PA(2),N1(2,3),TEQ(3),IFLAG(3),TC2(4,21,2),
4 -     4.000      3CM(2,22,4,21,2),MPS(2,3),H(21,3),C(2,22,4,21,2),PGL1(4),PGL2(4),
5 -     5.000      4TYPE(2,22,4,21,3),R(2,22,3),PLA(2)
6 -     6.000        READ(1,17)
7 -     7.000     17 FORMAT(/)
8 -     8.000        READ(1,1)IP1U,IP1L
9 -     9.000      1 FORMAT(2I5)
10 -   10.000        READ(1,2)
11 -   11.000      2 FORMAT(/)
12 -   12.000        READ(1,3)OPTION1
13 -   13.000      3 FORMAT(I1)
14 -   14.000        READ(1,3)OPTION2
15 -   15.000        READ(1,5)(PGL1(K),K=1,4)
16 -   16.000        READ(1,5)(PGL2(K),K=1,4)
17 -   17.000      5 FORMAT(4F5.2)
18 -   18.000        READ(1,108)DOOR
19 -   19.000    108 FORMAT(F5.2)
20 -   20.000        READ(1,115)KK
21 -   21.000    115 FORMAT(1X,I1)
22 -   22.000        READ(1,110)CSF
23 -   23.000    110 FORMAT(F5.1)
24 -   24.000        READ(1,111)CUSF123
25 -   25.000    111 FORMAT(F7.4)
26 -   26.000        READ(1,113)ECSF123,ENSF123
27 -   27.000    113 FORMAT(2F7.4)
28 -   28.000        READ(1,7)D,P,XL
29 -   29.000      7 FORMAT(X,3F6.2)
30 -   30.000        READ(1,9)HFUEL,CFUEL
31 -   31.000      9 FORMAT(X,2F6.3)
32 -   32.000        READ(1,11)CC
33 -   33.000     11 FORMAT(X,F4.2)
34 -   34.000        READ(1,12)HD,DD,CH
35 -   35.000     12 FORMAT(X,3F7.0)
36 -   36.000        READ(1,13)TBSMT
37 -   37.000     13 FORMAT(X,F5.2)
```

```
38 -    38.000        READ(1,14)(TEQ(N),N=1,3)
39 -    39.000     14 FORMAT(X,3F5.1)
40 -    40.000        READ(1,15)(MPS(1,N),N=1,2)
41 -    41.000        READ(1,15)(MPS(2,N),N=1,2)
42 -    42.000     15 FORMAT(X,2I2)
43 -    43.000        READ(1,16)HE,CE
44 -    44.000     16 FORMAT(2F6.3)
45 -    45.000        IF(IP1L.EQ.100)J2=1;GO TO 158
46 -    46.000        J1=0
47 -    47.000        DO 25 IP1=IP1U,IP1L,-10
48 -    48.000     25 J1=J1+1
49 -    49.000        IF(IP1U.EQ.100)J2=2;GO TO 159
50 -    50.000        J2=1
51 -    51.000    159 DO 22 J=J2,J1
52 -    52.000        READ(4,34)H(J,2),H(J,3)
53 -    53.000     34 FORMAT(X,2F7.3)
54 -    54.000        READ(4,20)N1(1,2)
55 -    55.000        READ(4,20)N1(2,2)
56 -    56.000     20 FORMAT(I3)
57 -    57.000        READ(4,21)((C(1,I,K,J,2),I=1,N1(1,2)),K=1,KK)
58 -    58.000        READ(4,21)((CM(1,I,K,J,2),I=1,N1(1,2)),K=1,KK)
59 -    59.000        READ(4,21)((C(2,I,K,J,2),I=1,N1(2,2)),K=1,KK)
60 -    60.000        READ(4,21)((CM(2,I,K,J,2),I=1,N1(2,2)),K=1,KK)
61 -    61.000     21 FORMAT(X,12F9.4)
62 -    62.000        READ(4,168)
63 -    63.000    168 FORMAT(/)
64 -    64.000     22 CONTINUE
65 -    65.000        READ(4,26)((U(1,I,2),U(1,I,3)),I=1,N1(1,2))
66 -    66.000        READ(4,26)((U(2,I,2),U(2,I,3)),I=1,N1(2,2))
67 -    67.000     26 FORMAT(15F7.5)
68 -    68.000        IF(IP1U.EQ.0)GO TO 27
69 -    69.000     18 IF(IP1L.EQ.0)J2=J1-1;GO TO 158
70 -    70.000        J2=J1
71 -    71.000    158 DO 27 J=1,J2
72 -    72.000        READ(3,33)H(J,1)
73 -    73.000     33 FORMAT(X,F6.4)
74 -    74.000        READ(3,28)N1(1,1),N1(2,1)
75 -    75.000     28 FORMAT(2I3)
76 -    76.000        READ(3,29)((TYPE(1,I,K,J,1),I=1,N1(1,1)),K=1,KK)
77 -    77.000        READ(3,29)((TYPE(2,I,K,J,1),I=1,N1(2,1)),K=1,KK)
78 -    78.000     29 FORMAT(55I2)
```

```
79 -    79.000        READ(3,31)(U(1,I,1),I=1,N1(1,1))
80 -    80.000        READ(3,31)(U(2,I,1),I=1,N1(2,1))
81 -    81.000     31 FORMAT(15F7.5)
82 -    82.000        READ(3,32)(((C(1,I,K,J,1),I=1,N1(1,1)),K=1,KK)
83 -    83.000        READ(3,32)(((CM(1,I,K,J,1),I=1,N1(1,1)),K=1,KK)
84 -    84.000        READ(3,32)(((C(2,I,K,J,1),I=1,N1(2,1)),K=1,KK)
85 -    85.000        READ(3,32)(((CM(2,I,K,J,1),I=1,N1(2,1)),K=1,KK)
86 -    86.000     32 FORMAT(X,13F8.4)
87 -    87.000     27 CONTINUE
88 -    88.000        IF(IP1L.EQ.100)GO TO 165
89 -    89.000        N1(1,3)=N1(1,2)
90 -    90.000        N1(2,3)=N1(2,2)
91 -    91.000        I4=MAX(N1(1,2),N1(2,2))
92 -    92.000        DO 62 K=1,KK
93 -    93.000        DO 62 J=1,21
94 -    94.000        DO 62 I=1,I4
95 -    95.000        DO 62 L=1,2
96 -    96.000     62 TYPE(L,I,K,J,2)=3
97 -    97.000    165 IF(D.EQ.P)PV=XL;GO TO 40
98 -    98.000        PV=((1+P)/(D-P))*(1-((1+P)/(1+D))**XL)
99 -    99.000     40 L=1
100 -  100.000        IF(OPTION1.EQ.1)L=2
101 -  101.000        LL=L
102 -  102.000        CH1=CH
103 -  103.000        IF(OPTION2.EQ.0)CH1=0
104 -  104.000        J=0
105 -  105.000        DO 45 IP1=IP1U,IP1L,-10
106 -  106.000        J=J+1
107 -  107.000        IF(IP1.EQ.100)I1=I2=1;GO TO 47
108 -  108.000        IF(IP1.EQ.0)I1=2;I2=3;GO TO 47
109 -  109.000        I1=1;I2=3
110 -  110.000     47 DO 45 K=1,KK
111 -  111.000        DO 119 N=I1,I2
112 -  112.000        L=LL
113 -  113.000        DO 119 I=1,N1(L,N)
114 -  114.000        IF(I.EQ.1)BTU(I,K,N)=0;GO TO 119
115 -  115.000        IF(N.EQ.3)T=((75-TBSMT)*24*HD);GO TO 51
116 -  116.000        T=24*DD
117 -  117.000 C BTU=PRESENT VALUE SAVINGS FROM THE ITH INCREMENT OF INSULATION
118 -  118.000     51 BTU(I,K,N)=(((U(L,I-1,N)-U(L,I,N))*(T*(HFUEL/HE)
119 -  119.000       2+TEQ(N)*CH1*(CFUEL/CE)))/100000)*PV
```

```
120 -  120.000   119 CONTINUE
121 -  121.000       L=LL
122 -  122.000       R(L,1,1)=1.0/U(L,1,1)
123 -  123.000       R(L,1,2)=(H(J,2)/U(L,1,2)+H(J,3)/U(L,1,3))/(H(J,2)+H(J,3))
124 -  124.000       IF(IP1.EQ.100)I3=I4=1;GO TO 117
125 -  125.000       DO 116 I=1,N1(L,2)
126 -  126.000   116 BTU(I,K,2)=(H(J,2)*BTU(I,K,2)+H(J,3)*BTU(I,K,3))/(H(J,2)+H(J,3))
127 -  127.000       IF(IP1.EQ.0)I3=I4=2;GO TO 117
128 -  128.000       I3=1;I4=2
129 -  129.000   117 DO 46 N=I3,I4
130 -  130.000       Z=0
131 -  131.000       IH=IG=IZ=IFLAG(N)=0
132 -  132.000       FLAG=FLAG1=0
133 -  133.000       TS1=TC1=0
134 -  134.000       L=LL
135 -  135.000       DO 79 I=2,N1(L,N)
136 -  136.000       IF(CM(L,I,K,J,N).LE.0)GO TO 128
137 -  137.000       IF((BTU(I,K,N)/(CM(L,I,K,J,N)**CC)).LT.1)Z=1;GO TO 42
138 -  138.000   128 IH=I
139 -  139.000    42 IF(Z.EQ.0)IZ=IH;GO TO 41
140 -  140.000       TS1=TS1+BTU(I,K,N)
141 -  141.000       TC1=TC1+CM(L,I,K,J,N)
142 -  142.000       IF((TS1/(TC1*CC))-1)41,43,43
143 -  143.000    43 IG=I
144 -  144.000       IF(IH.EQ.IG)FLAG=TS1-TC1
145 -  145.000       IF(FLAG.GT.FLAG1)FLAG1=FLAG;IFLAG(N)=I
146 -  146.000    41 IF(N.EQ.1)R(L,I,1)=1.0/U(L,I,1);GO TO 79
147 -  147.000       R(L,I,2)=(H(J,2)/U(L,I,2)+H(J,3)/U(L,I,3))/(H(J,2)+H(J,3))
148 -  148.000    79 CONTINUE
149 -  149.000       IF(IFLAG(N).EQ.0)IFLAG(N)=IZ
150 -  150.000       TS2(K,J,N)=TC2(K,J,N)=0
151 -  151.000       TS(K,J,N)=TC(K,J,N)=0
152 -  152.000       IF(MPS(L,N).GT.IFLAG(N))GO TO 129
153 -  153.000       GO TO 131
154 -  154.000   129 DO 130 I=IFLAG(N)+1,MPS(L,N)
155 -  155.000       TC2(K,J,N)=TC2(K,J,N)+CM(L,I,K,J,N)
156 -  156.000   130 TS2(K,J,N)=TS2(K,J,N)+BTU(I,K,N)
157 -  157.000   131 IF(MPS(L,N).GE.IFLAG(N))YLF(N)=77;GO TO 60
158 -  158.000       DO 44 I=MPS(L,N)+1,IFLAG(N)
159 -  159.000 C TC=TOTAL COST OF THE PRESENT VALUE MAXIMIZING POINT
160 -  160.000       TC(K,J,N)=TC(K,J,N)+CM(L,I,K,J,N)
```

```
161 -  161.000 C TS=TOTAL REVENUE OR SAVINGS OF THE PRESENT VALUE MAXIMIZING POINT
162 -  162.000     44 TS(K,J,N)=TS(K,J,N)+BTU(I,K,N)
163 -  163.000        IF(TC(K,J,N).LE.0)YLF(N)=77;GO TO 60
164 -  164.000        IF(D.EQ.P)YLF(N)=TC(K,J,N)/(TS(K,J,N)/PV);GO TO 60
165 -  165.000        YLF(N)=(LOG(1-((TC(K,J,N)/(TS(K,J,N)/PV))*(D-P)/(1+P))))/
166 -  166.000       2(LOG((1+P)/(1+D)))
167 -  167.000     60 IF(IFLAG(N).EQ.1)XLF(N)=YLF(N)=77;GO TO 49
168 -  168.000        IF(IFLAG(N).LE.MPS(L,N))XLF(N)=YLF(N)=77;GO TO 49
169 -  169.000        IF(CM(L,IFLAG(N),K,J,N).LE.0)XLF(N)=77;GO TO 49
170 -  170.000        IF(D.EQ.P)XLF(N)=CM(L,IFLAG(N),K,J,N)/(BTU(IFLAG(N),K,N)/PV);GO TO
171 -  171.000       2 49
172 -  172.000        XLF(N)=(LOG(1-((CM(L,IFLAG(N),K,J,N)/(BTU(IFLAG(N),K,N)/PV)
173 -  173.000       2)*(D-P)/(1+P))))/(LOG((1+P)/(1+D)))
174 -  174.000     49 IF(H(J,1).EQ.8)X1=6.67;X2=X3=0;GO TO 50
175 -  175.000        IF(H(J,3)+H(J,2).LE.(6.67))X1=(6.67-H(J,3)-H(J,2));X2=H(J,2);
176 -  176.000       2X3=H(J,3);GO TO 50
177 -  177.000        IF(H(J,3).GE.(6.67))X1=0;X2=0;X3=6.67;GO TO 50
178 -  178.000        X1=0;X2=(6.67-H(J,3));X3=H(J,3)
179 -  179.000     50 A(1)=((2*(30+40)*H(J,1)*(1-PGL1(K)))-2*3*X1)
180 -  180.000        A(2)=((2*(30+40)*(H(J,2)*(1-PGL2(K))+H(J,3)))-2*3*X2-2*3*X3)
181 -  181.000 C PLA(N)=PRESENT VALUE LOSS FROM MEETING MPS REQUIREMENTS FOR
182 -  182.000 C WALL AREA A(N)
183 -  183.000        PLA(N)=(TS2(K,J,N)-TC2(K,J,N))*A(N)
184 -  184.000 C PA(N)=PRESENT VALUE MAXIMUM PROFIT FOR WALL AREA A(N)
185 -  185.000        PA(N)=(TS(K,J,N)-TC(K,J,N))*A(N)
186 -  186.000     46 WRITE(11,169)IFLAG(N)
187 -  187.000    169 FORMAT(X,I2)
188 -  188.000        IF(IP1.EQ.100)PA(2)=PLA(2)=0
189 -  189.000        IF(IP1.EQ.0)PA(1)=PLA(1)=0
190 -  190.000        P$=PA(1)+PA(2)+PLA(1)+PLA(2)
191 -  191.000        WRITE(11,170)P$
192 -  192.000    170 FORMAT(X,F10.2)
193 -  193.000     45 CONTINUE
194 -  194.000        END
```

```
1 -     1.000 C********************************** G **********************************
2 -     2.000       DIMENSION U(2,22,3),N1(2,3),TEQ(3),CM(2,22,4,21,2),MPS(2,3),EC(11)
3 -     3.000      2,H(21,3),C(2,22,4,21,2),PGL1(4),PGL2(4),TYPE(2,22,4,21,3),PR(11,4)
4 -     4.000      3,ENT(11),IFLAG(11,4,2),P$(11,4),A(11,3),A1(11,3),S(11,4,3),
5 -     5.000      4GRS(11,4),CON(11)
6 -     6.000       READ(1,17)
7 -     7.000     17 FORMAT(/)
8 -     8.000       READ(1,1)IP1U,IP1L
9 -     9.000      1 FORMAT(2I5)
10 -   10.000       READ(1,2)
11 -   11.000      2 FORMAT(/)
12 -   12.000       READ(1,3)OPTION1
13 -   13.000      3 FORMAT(I1)
14 -   14.000       READ(1,3)OPTION2
15 -   15.000       READ(1,5)(PGL1(K),K=1,4)
16 -   16.000       READ(1,5)(PGL2(K),K=1,4)
17 -   17.000      5 FORMAT(4F5.2)
18 -   18.000       READ(1,10)
19 -   19.000     10 FORMAT()
20 -   20.000       READ(1,115)KK
21 -   21.000    115 FORMAT(1X,I1)
22 -   22.000       READ(1,6)
23 -   23.000      6 FORMAT()
24 -   24.000       READ(1,8)CUSF123
25 -   25.000      8 FORMAT(F7.4)
26 -   26.000       READ(1,113)ECSF123,ENSF123
27 -   27.000    113 FORMAT(2F7.4)
28 -   28.000       READ(1,7)D,P,XL
29 -   29.000      7 FORMAT(X,3F6.2)
30 -   30.000       READ(1,9)HFUEL,CFUEL
31 -   31.000      9 FORMAT(X,2F6.3)
32 -   32.000       READ(1,11)
33 -   33.000     11 FORMAT()
34 -   34.000       READ(1,12)HD,DD,CH
35 -   35.000     12 FORMAT(X,3F7.0)
36 -   36.000       READ(1,13)TBSMT
37 -   37.000     13 FORMAT(X,F5.2)
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38 -    38.000        READ(1,14)(TEQ(N),N=1,3)
39 -    39.000     14 FORMAT(X,3F5.1)
40 -    40.000        READ(1,15)(MPS(1,N),N=1,2)
41 -    41.000        READ(1,15)(MPS(2,N),N=1,2)
42 -    42.000     15 FORMAT(X,2I2)
43 -    43.000        READ(1,16)HE,CE
44 -    44.000     16 FORMAT(2F6.3)
45 -    45.000        READ(1,4)OPTION3
46 -    46.000      4 FORMAT(I1)
47 -    47.000        IF(IP1L.EQ.100)J2=1;GO TO 158
48 -    48.000        J1=0
49 -    49.000        DO 25 IP1=IP1U,IP1L,-10
50 -    50.000     25 J1=J1+1
51 -    51.000        IF(IP1U.EQ.100)J2=2;GO TO 159
52 -    52.000        J2=1
53 -    53.000    159 DO 22 J=J2,J1
54 -    54.000        READ(4,34)H(J,2),H(J,3)
55 -    55.000     34 FORMAT(X,2F7.3)
56 -    56.000        READ(4,20)N1(1,2)
57 -    57.000        READ(4,20)N1(2,2)
58 -    58.000     20 FORMAT(I3)
59 -    59.000        READ(4,21)(((C(1,I,K,J,2),I=1,N1(1,2)),K=1,KK)
60 -    60.000        READ(4,21)(((CM(1,I,K,J,2),I=1,N1(1,2)),K=1,KK)
61 -    61.000        READ(4,21)(((C(2,I,K,J,2),I=1,N1(2,2)),K=1,KK)
62 -    62.000        READ(4,21)(((CM(2,I,K,J,2),I=1,N1(2,2)),K=1,KK)
63 -    63.000     21 FORMAT(X,12F9.4)
64 -    64.000        READ(4,168)PC(J)
65 -    65.000        READ(4,168)ENT(J)
66 -    66.000    168 FORMAT(X,F7.2)
67 -    67.000     22 CONTINUE
68 -    68.000        READ(4,26)((U(1,I,2),U(1,I,3)),I=1,N1(1,2))
69 -    69.000        READ(4,26)((U(2,I,2),U(2,I,3)),I=1,N1(2,2))
70 -    70.000     26 FORMAT(15F7.5)
71 -    71.000        IF(IP1U.EQ.0)GO TO 27
72 -    72.000     18 IF(IP1L.EQ.0)J2=J1-1;GO TO 158
73 -    73.000        J2=J1
74 -    74.000    158 DO 27 J=1,J2
75 -    75.000        READ(3,33)H(J,1)
76 -    76.000     33 FORMAT(X,F6.4)
77 -    77.000        READ(3,28)N1(1,1),N1(2,1)
78 -    78.000     28 FORMAT(2I3)
```

```
 79 -    79.000        READ(3,29)((TYPE(1,I,K,J,1),I=1,N1(1,1)),K=1,KK)
 80 -    80.000        READ(3,29)((TYPE(2,I,K,J,1),I=1,N1(2,1)),K=1,KK)
 81 -    81.000     29 FORMAT(55I2)
 82 -    82.000        READ(3,31)(U(1,I,1),I=1,N1(1,1))
 83 -    83.000        READ(3,31)(U(2,I,1),I=1,N1(2,1))
 84 -    84.000     31 FORMAT(15F7.5)
 85 -    85.000        READ(3,32)(((C(1,I,K,J,1),I=1,N1(1,1)),K=1,KK)
 86 -    86.000        READ(3,32)(((CM(1,I,K,J,1),I=1,N1(1,1)),K=1,KK)
 87 -    87.000        READ(3,32)(((C(2,I,K,J,1),I=1,N1(2,1)),K=1,KK)
 88 -    88.000        READ(3,32)(((CM(2,I,K,J,1),I=1,N1(2,1)),K=1,KK)
 89 -    89.000     32 FORMAT(X,13F8.4)
 90 -    90.000     27 CONTINUE
 91 -    91.000        READ(5,163)
 92 -    92.000    163 FORMAT(16/)
 93 -    93.000        READ(5,161)ENT(1)
 94 -    94.000    161 FORMAT(14X,F7.2)
 95 -    95.000        READ(5,170)CAT
 96 -    96.000    170 FORMAT(F6.2)
 97 -    97.000        READ(5,172)
 98 -    98.000    172 FORMAT()
 99 -    99.000        READ(5,170)CONCRETE
100 -   100.000        J=0
101 -   101.000        DO 41 IP1=IP1U,IP1L,-10
102 -   102.000        J=J+1
103 -   103.000        IF(IP1.EQ.100)I6=I7=1;GO TO 117
104 -   104.000        IF(IP1.EQ.0)I6=I7=2;GO TO 117
105 -   105.000        I6=1;I7=2
106 -   106.000    117 DO 41 K=1,KK
107 -   107.000        DO 42 N=I6,I7
108 -   108.000     42 READ(12,43)IFLAG(J,K,N)
109 -   109.000     43 FORMAT(X,I2)
110 -   110.000     41 READ(12,44)P$(J,K)
111 -   111.000     44 FORMAT(X,F10.2)
112 -   112.000        H(1,1)=H(1,2)=H(1,3)=0
113 -   113.000        IF(D.EQ.P)PV=XL;GO TO 40
114 -   114.000        PV=((1+P)/(D-P))*(1-((1+P)/(1+D))**XL)
115 -   115.000     40 L=1
116 -   116.000        IF(OPTION1.EQ.1)L=2
117 -   117.000        LL=L
118 -   118.000        CH1=CH
119 -   119.000        IF(OPTION2.EQ.0)CH1=0
```

```
120 -  120.000        DO 110 K=1,KK
121 -  121.000        DO 67 I=1,N1(1,2)
122 -  122.000     67 C(1,I,K,1,2)=0
123 -  123.000        DO 68 I=1,N1(2,2)
124 -  124.000     68 C(2,I,K,1,2)=0
125 -  125.000        DO 69 I=1,N1(1,1)
126 -  126.000     69 C(1,I,K,11,1)=0
127 -  127.000        DO 169 I=1,N1(2,1)
128 -  128.000    169 C(2,I,K,11,1)=0
129 -  129.000        ENT1=2*ENT(1)
130 -  130.000        J=0
131 -  131.000        DO 45 IP1=IP1U,IP1L,-10
132 -  132.000        J=J+1
133 -  133.000        EC(1)=((39*39*2)/27)*CAT;ENT(1)=ENT1
134 -  134.000        EC(J)=(EC(J)-EC(1))*ECSF123
135 -  135.000        ENT(J)=(ENT(J)-ENT(1))*ENSF123
136 -  136.000    162 IF(IP1.EQ.100)I4=I5=1;GO TO 47
137 -  137.000        I4=1;I5=3
138 -  138.000     47 IF(H(J,1).EQ.8)X1=6.67;X2=X3=0;GO TO 50
139 -  139.000        IF(H(J,3)+H(J,2).LE.(6.67))X1=(6.67-H(J,3)-H(J,2));X2=H(J,2);
140 -  140.000       2X3=H(J,3);GO TO 50
141 -  141.000        IF(H(J,3).GE.(6.67))X1=X2=0;X3=6.67;GO TO 50
142 -  142.000        X1=0;X2=(6.67-H(J,3));X3=H(J,3)
143 -  143.000     50 A(J,1)=((2*(30+40)*H(J,1)*(1-PGL1(K)))-2*3*X1)
144 -  144.000        A(J,2)=((2*(30+40)*H(J,2)*(1-PGL2(K)))-2*3*X2)
145 -  145.000        A(J,3)=((2*(30+40)*H(J,3))-2*3*X3)
146 -  146.000        IF(H(J,3)+H(J,2).GT.(2.95))CON(J)=((2*(30+40)*2.33)-2*3*2.33)
147 -  147.000       2*A(2,2);GO TO 171
148 -  148.000        CON(J)=A(J,2)+A(J,3)
149 -  149.000    171 S(J,K,1)=S(J,K,2)=S(J,K,3)=0
150 -  150.000        DO 73 N=I4,I5
151 -  151.000        A1(J,N)=A(1,N)-A(J,N)
152 -  152.000        IF(IP1U.EQ.100)A1(1,1)=A1(1,2)=A1(1,3)=0
153 -  153.000        L=LL
154 -  154.000        IF(N.EQ.3)T=((75-TBSMT)*24*HD);GO TO 52
155 -  155.000        T=24*DD
156 -  156.000     52 IF(N.EQ.1)GO TO 72
157 -  157.000        I=MAX(IFLAG(J,K,2),MPS(L,2))
158 -  158.000        S(J,K,N)=((U(L,I,N)*A1(J,N)*(T*(HFUEL/HE)+TEQ(N)*CH1*(CFUEL/CE))
159 -  159.000       2)/100000)*PV
160 -  160.000        GO TO 73
```

```
161 -  161.000     72 I1=MAX(IFLAG(1,K,1),MPS(L,1))
162 -  162.000        IF(IP1.EQ.0)GO TO 74
163 -  163.000        I2=MAX(IFLAG(J,K,1),MPS(L,1))
164 -  164.000     74 S(J,K,1)=(((U(L,I1,1)*A1(J,1)+(U(L,I1,1)-U(L,I2,1))*A(J,1))*
165 -  165.000       2(T*(HFUEL/HE)+TEQ(N)*CH1*(CFUEL/CE)))/100000)*PV
166 -  166.000     73 CONTINUE
167 -  167.000  C GRS=GROUND RATIO SAVINGS FOR RESIDENCE
168 -  168.000        L=LL
169 -  169.000        GRS(J,K)=S(J,K,1)+S(J,K,2)+S(J,K,3)
170 -  170.000  C PR=TOTAL PROFIT FOR RESIDENCE FROM GRS AND INSULATION
171 -  171.000        I1=MAX(IFLAG(1,K,1),MPS(L,1))
172 -  172.000        IF(IP1.EQ.0)GO TO 65
173 -  173.000        I2=MAX(IFLAG(J,K,1),MPS(L,1))
174 -  174.000        IF(IP1.EQ.100)I3=1;GO TO 66
175 -  175.000     65 I3=MAX(IFLAG(J,K,2),MPS(L,2))
176 -  176.000     66 PR(J,K)=GRS(J,K)-EC(J)-ENT(J)+C(L,I1,K,1,1)*A(1,1)-C(L,I2,K,J,1)*
177 -  177.000       2A(J,1)-C(L,I3,K,J,2)*(A(J,2)+A(J,3))+P$(J,K)+CON(J)*CONCRETE
178 -  178.000     45 L=LL
179 -  179.000        IF(OPTION3.EQ.0)GO TO 58
180 -  180.000        GO TO 84
181 -  181.000     58 IF(OPTION2.EQ.0)GO TO 55
182 -  182.000        GO TO 56
183 -  183.000     55 IF(OPTION1.EQ.0)GO TO 54
184 -  184.000        GO TO 57
185 -  185.000     54 WRITE(2,80)ECSF123,ENSF123,HFUEL,(GRS(J,K),J=2,11)
186 -  186.000        GO TO 99
187 -  187.000     57 WRITE(2,81)ECSF123,ENSF123,HFUEL,(GRS(J,K),J=2,11)
188 -  188.000        GO TO 99
189 -  189.000     80 FORMAT(1H0,2X,I1,3X,I1,3X,'F',1X,F4.3,X,'NO',10F10.2)
190 -  190.000     81 FORMAT(1H0,2X,I1,3X,I1,3X,'U',1X,F4.3,X,'NO',10F10.2)
191 -  191.000     56 IF(OPTION1.EQ.0)GO TO 86
192 -  192.000        GO TO 87
193 -  193.000     86 WRITE(2,85)ECSF123,ENSF123,HFUEL,(GRS(J,K),J=2,11)
194 -  194.000        GO TO 99
195 -  195.000     85 FORMAT(1H0,2X,I1,3X,I1,3X,'F',1X,F4.3,X,'YES',F9.2,9F10.2)
196 -  196.000     87 WRITE(2,88)ECSF123,ENSF123,HFUEL,(GRS(J,K),J=2,11)
197 -  197.000        GO TO 99
198 -  198.000     88 FORMAT(1H0,2X,I1,3X,I1,3X,'U',1X,F4.3,X,'YES',F9.2,9F10.2)
199 -  199.000     84 IF(OPTION2.EQ.0)GO TO 89
200 -  200.000        GO TO 90
201 -  201.000     89 IF(OPTION1.EQ.0)GO TO 91
```

```
202 -  202.000       GO TO 92
203 -  203.000    91 WRITE(2,93)ECSF123,ENSF123,HFUEL,(PR(J,K),J=1,11)
204 -  204.000       GO TO 100
205 -  205.000    93 FORMAT(1H0,2X,I1,3X,I1,3X,'F',1X,F4.3,X,'NO',11F10.2)
206 -  206.000    92 WRITE(2,94)ECSF123,ENSF123,HFUEL,(PR(J,K),J=1,11)
207 -  207.000       GO TO 100
208 -  208.000    94 FORMAT(1H0,2X,I1,3X,I1,3X,'U',1X,F4.3,X,'NO',11F10.2)
209 -  209.000    90 IF(OPTION1.EQ.0)GO  TO 95
210 -  210.000       GO TO 96
211 -  211.000    95 WRITE(2,97)ECSF123,ENSF123,HFUEL,(PR(J,K),J=1,11)
212 -  212.000    97 FORMAT(1H0,2X,I1,3X,I1,3X,'F',1X,F4.3,X,'YES',F9.2,10F10.2)
213 -  213.000       GO TO 100
214 -  214.000    96 WRITE(2,98)ECSF123,ENSF123,HFUEL,(PR(J,K),J=1,11)
215 -  215.000    98 FORMAT(1H0,2X,I1,3X,I1,3X,'U',1X,F4.3,X,'YES',F9.2,10F10.2)
216 -  216.000       GO TO 100
217 -  217.000    99 RMAX=-1.0E+75
218 -  218.000       DO 60 J=2,11
219 -  219.000       IF(GRS(J,K).GT.RMAX)RMAX=GRS(J,K);J1=J
220 -  220.000    60 CONTINUE
221 -  221.000       IGR1=110-J1*10
222 -  222.000       I8=MAX(IFLAG(J1,K,1),MPS(L,1))
223 -  223.000       I9=MAX(IFLAG(J1,K,2),MPS(L,2))
224 -  224.000       IF(IGR1.EQ.100)GO TO 102
225 -  225.000       IF(IGR1.EQ.0)GO TO 103
226 -  226.000       WRITE(10,104)IGR1,I8-1,I9-1
227 -  227.000       GO TO 110
228 -  228.000   104 FORMAT(10X,I2,6X,I2,7X,I2)
229 -  229.000   102 WRITE(10,105)IGR1,I8-1
230 -  230.000       GO TO 110
231 -  231.000   105 FORMAT(9X,I3,6X,I2)
232 -  232.000   103 WRITE(10,106)IGR1,I9-1
233 -  233.000       GO TO 110
234 -  234.000   106 FORMAT(10X,I2,15X,I2)
235 -  235.000   100 RMAX=-1.0E+75
236 -  236.000       DO 61 J=1,11
237 -  237.000       IF(PR(J,K).GT.RMAX)RMAX=PR(J,K);J2=J
238 -  238.000    61 CONTINUE
239 -  239.000       IGR2=110-J2*10
240 -  240.000       I10=MAX(IFLAG(J2,K,1),MPS(L,1))
241 -  241.000       I11=MAX(IFLAG(J2,K,2),MPS(L,2))
242 -  242.000       IF(IGR2.EQ.100)GO TO 107
```

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243 -  243.000          IF(IGR2.EQ.0)GO TO 108
244 -  244.000          WRITE(10,109)IGR2,I10-1,I11-1
245 -  245.000          GO TO 110
246 -  246.000      109 FORMAT(10X,I2,6X,I2,7X,I2)
247 -  247.000      107 WRITE(10,111)IGR2,I10-1
248 -  248.000          GO TO 110
249 -  249.000      111 FORMAT(9X,I3,6X,I2)
250 -  250.000      108 WRITE(10,112)IGR2,I11-1
251 -  251.000          GO TO 110
252 -  252.000      112 FORMAT(10X,I2,15X,I2)
253 -  253.000      110 CONTINUE
254 -  254.000          END
```

```
1 -     1.000 C************************* COMPANION ************************************
2 -     2.000       WRITE(10,2)
3 -     3.000     2 FORMAT(1H1,17X,"INCREMENT NO.")
4 -     4.000       WRITE(10,1)
5 -     5.000     1 FORMAT(10X,"GR",5X,"COMP1",4X,"COMP23")
6 -     6.000       END
```

```
1 -     1.000 C******************************** SAVINGS ********************************
2 -     2.000       WRITE(2,2)
3 -     3.000     2 FORMAT(1H1,54X,'TOTAL SAVINGS FROM GROUND RATIO')
4 -     4.000       WRITE(2,1)
5 -     5.000     1 FORMAT(2X,'EXR',X,'ENR',X,'IN',X,'FUEL',X,'AIR',5X,'90',
6 -     6.000      27X,'80',8X,'70',8X,'60',8X,'50',8X,'40',8X,'30',8X,'20',8X,'10',
7 -     7.000      39X,'0')
8 -     8.000       END
```

```
1 -     1.000 C******************************** PROFIT **********************************
2 -     2.000       WRITE(2,2)
3 -     3.000     2 FORMAT(1H1,53X,'NET SAVINGS FROM INSULATION AND GROUND RATIO')
4 -     4.000       WRITE(2,1)
5 -     5.000     1 FORMAT(2X,'EXR',X,'ENR',X,'IN',X,'FUEL',X,'AIR',4X,'100',
6 -     6.000      27X,'90',8X,'80',8X,'70',8X,'60',8X,'50',8X,'40',8X,'30',8X,'20',
7 -     7.000      38X,'10',9X,'0')
8 -     8.000       END
```

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