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Engineering-Economic Analysis of Single-Family Dwelling Thermal Performance

Paul F. Hutchins, Jr.
Eric Hirst

OAK RIDGE NATIONAL LABORATORY
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SINGLE-FAMILY DWELLING THERMAL PERFORMANCE

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ABSTRACT

Various levels of investment in energy-efficient designs are analyzed for new single-family detached dwellings. The purpose is to develop relationships between initial cost and annual energy savings in space heating and cooling for use in the ORNL residential energy use simulation model. The analysis is performed for a 1200 ft² ranch-style home in nine U.S. locations using both natural gas or electricity.

The annual loads calculation and cost surveys are based on a report by Petersen at the National Bureau of Standards, which used the NBSLD computer code. The economic analyses, which minimize lifecycle costs, were conducted using an updated version of a computer program written at ORNL.

Results define relationships between annual energy savings in space heating and cooling versus additional initial cost, which demonstrate the law of diminishing marginal returns. Curve characteristics are generally a function of climate, although the order of implementation for the various energy-conserving options (heating only) is basically constant across all regions. Potential reductions in annual energy use range from 30 to 60% when compared to the present 1974 Housing and Urban Development Minimum Property Standards (HUD-MPS).

Optimum levels of investment in energy-conserving design for heating only were computed for each location. When compared to the 1974 HUD-MPS, major differences were noted for all but the natural gas-heated homes in areas less than 5200 heating degree days. Paybacks for additional investment above the current standard range from 15 to 20 years for natural gas users and four to six years for electrically-heated homes.

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ENGINEERING-ECONOMIC ANALYSIS OF SINGLE-FAMILY DWELLING THERMAL PERFORMANCE

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1. INTRODUCTION

This report analyzes different levels of investment in energy-efficient designs for new single-family detached dwellings. The purpose is to define relationships between annual energy use for home space heating/cooling and initial investment in the structure shell for a range of climates in the United States. These relationships are then used to define the "optimum" design configuration for single-family homes in each location. The optimum is defined as the design configuration that minimizes the lifecycle cost of home purchase plus space heating and cooling operating costs. Because of differences in climate, the optimum differs from location to location.

This study is similar to our earlier evaluation of the thermal performance of mobile homes. The methodology established and discussed in detail in the mobile home report¹ will be used in this study.

The results will be incorporated into the Oak Ridge National Laboratory (ORNL) residential energy use simulation model.² This simulation model, developed for the Department of Energy, is being used to evaluate national and regional energy consumption and economic effects of various energy conservation policies, programs, and technologies.

Results of this analysis should also be useful to government policymakers involved with development of thermal performance standards. Title III of the Energy Conservation and Production Act of 1976³ requires development and implementation of new standards "to achieve maximum practicable improvements in energy efficiency." The methodology used here allows selection of energy-efficient designs based on not only thermodynamics and heat transfer, but also economics for a variety of circumstances. This allows for more flexible standards sensitive to the economic and climatic conditions of the location.

The residential sector accounts for a significant portion of United States primary energy use (about twenty percent). Space heating and cooling represent about 55 and five percent, respectively, of sector fuel use.⁴ Single-family detached housing accounts for about 50 percent of all new residential construction each year, and about 65 percent of the existing housing stock.⁵ Each year slightly more than one million new single-family detached homes are constructed. Table 1 shows the distribution and growth patterns of single-family homes between 1970 and 1975 for census regions and divisions.

Table 1. Existing households in single-family detached dwellings

Locations	Occupied homes (millions)*			
	1970	1973	1974	1975
Northeast	7.78 (17)	8.30 (17)	8.32 (17)	8.4 (17)
New England	2.11 (5)			
Middle Atlantic	5.66 (13)			
North Central	13.3 (30)	13.8 (29)	13.9 (29)	14.2 (29)
East North Central	9.03 (20)			
West North Central	4.24 (9)			
South	15.7 (35)	17.1 (36)	17.2 (36)	17.8 (36)
South Atlantic	7.08 (16)			
East S. Central	3.37 (8)			
West S. Central	5.24 (12)			
West	8.08 (18)	8.70 (18)	8.86 (18)	9.1 (18)
Mountain	1.97 (4)			
Pacific	6.11 (14)			
United States Total	44.8 (100)	47.9 (100)	48.2 (100)	49.5 (100)

* Numbers in parentheses are the fractions of the total U.S. single-family detached dwelling stocks. Totals may not agree with the sum of the components due to round-off errors.

Source: reference 5.

Because single-family detached homes represent such a large portion of the U.S. housing stock, thermal standards should be economically defined to minimize home purchase and operating costs. In the past, thermal standards were based on judgments by representatives of home builders and government personnel. This absence of detailed analysis makes existing thermal standards economically inadequate for future buildings because of rising fuel prices.

The methodology used in this study is shown schematically in Fig. 1. Annual and peak heating and cooling loads for the dwelling were calculated using a thermal loads computer code called NBSLD⁶ (National Bureau of Standards Loads Determination). These results plus design option cost and other economic parameters (interest rates, fuel costs, property tax, insurance rates, etc.) are inputs to the Economic Analysis Program (EAP). Various inputs are combined with EAP to yield two basic results: the relationship between annual energy load and additional initial investment in energy conserving design and the optimal design that minimizes lifecycle costs for each location.

Fig. 1. Schematic of analytical methodology.

All results generated by the NBSLD program were provided by Petersen⁷ at the National Bureau of Standards (NBS). Petersen combined these results with appropriate cost data to define the most cost-effective order of implementation for the various design options. The objective of this study is, therefore, to present and evaluate the annual load versus cost relationships for use in the ORNL residential energy use simulation model and perform an optimization analysis for each location.

2. DEFINITION OF SINGLE-FAMILY DWELLING

Description

The single-family residence studied by Petersen is a 1200 ft² single-story ranch-style house over a vented crawlspace. Important envelope area parameters are listed in Table 2.⁷ The basic dimensions of the residence were chosen to be representative of new house construction.⁸

Table 2. Single-family dwelling envelope parameters

				Area in ft ²
Ceiling				1200
Windows				
North facing	4 @ 13.8 =	55.1		
South facing	1 @ 20			
	1 @ 12			
Sliding glass door (South facing)				1 @ 40
Total glass area				127.1
Entry door				20
Opaque wall area:				
	Insulated	+	Stud	= Total
North facing	181.3		63.6	244.9
East facing	209.1		30.9	240.0
South facing	189.4		58.6	248.0
West facing	209.1		30.9	240.0
Total	788.9		184	972.9
Floor (30' x 40')				1200
Total envelope area				3520

Source: reference 7.

The baseline wall construction is 2x4 studs on 24" centers with no insulation. All windows are single-pane. This baseline design has slightly less thermal protection than was required by the 1965 U.S. Department of Housing and Urban Development Minimum Property Standards for One and Two Family Dwellings (HUD-MPS).

The house is oriented so that a vector normal to the longer wall faces due north. Fifty percent shading of windows (to represent curtains) is assumed during cooling operations. Sensitivity of heating and cooling loads to both orientation and shading is discussed in Section 5.

The minimum and maximum indoor temperatures are assumed to be 68 and 78°F for heating and cooling, respectively, with no night setback.* More detailed information on the single-family house construction characteristics is in ref. 7.

The design options studied include only those currently available to the consumer in new housing construction. These options are permanent and passive and do not affect occupant lifestyle. The improvements considered are:

1. additional insulation in walls, ceiling, and floor
2. multi-pane windows
3. multi-pane sliding glass door
4. storm door
5. six-inch insulated walls
6. styrofoam wall sheathing

Costs for each design option are from information provided by the National Association of Home Builders.¹⁰ Figures include dealer mark-up and represent the U.S. average cost to the consumer. Local price variations are evaluated later in Section 4. The costs (adjusted from 1977 to 1975 dollars) represent the incremental expense to the consumer as a

* Petersen evaluated the effects of night setback on each conservation option in Washington, D.C. His results show that the effects of setback are essentially independent of structure thermal performance. For the other cities, Petersen assumed night setback for each option; he also evaluated one option in each city with a constant winter thermostat setting of 68°F. We used the ratio of heating loads with and without setback for that option in each city to adjust Petersen's results for constant winter thermostat setting.

result of purchasing a single-family home with energy-efficient options in addition to those present in the baseline configuration. These costs are listed in Table 3.

As the thermal integrity of the building shell is improved, heating and cooling equipment capacities needed to meet the design (or peak) load become smaller. Reference 10 provides cost information necessary to account for savings due to HVAC (heating, ventilation, and air conditioning) equipment size reductions. The average incremental cost (1975 dollars) to the consumer for gas and electric heating furnaces is \$2.60/kBtu/hr (kBtu = 10^3 Btu) and \$2.10/kBtu/hr output, respectively.

Table 3. Design option cost data

Item	Average unit cost* (1975-\$)	Amount	Additional costs (1975-\$)	
			Labor only	Total
Wall insulation				
0 → R-11	13.4¢/ft ^{2†}	1120 ft ^{2†}	40	150
R-11 → R-13	4.5¢/ft ²	1120 ft ²	0	50
R-13 → R-19 [§]	17.8¢/ft ²	1120 ft ²	40	200
R-19 → R-23 [#]	17.8¢/ft ²	1120 ft ²	60	200
Attic insulation				
0 → R-11	13.4¢/ft ²	1200 ft ²	43	160
R-11 → R-19	6.2¢/ft ²	1200 ft ²	0	75
R-19 → R-30	9.8¢/ft ²	1200 ft ²	0	117
R-30 → R-38	6.2¢/ft ²	1200 ft ²	0	75
R-38 → R-49	9.8¢/ft ²	1200 ft ²	0	117
Floor insulation				
0 → R-11	16.0¢/ft ²	1200 ft ²	75	192
R-11 → R-19	7.1¢/ft ²	1200 ft ²	0	85
Glazing				
Double	\$1.78/ft ²	87 ft ²	36	155
Triple	\$2.00/ft ²	87 ft ²	36	174
Door				
Storm	\$2.69/ft ²	20 ft ²	30	107
Double glazed sliding glass	\$3.12/ft ²	40 ft ²	31	125

* Includes labor cost.

† Gross area, includes windows and doors.

R-19 plus styrofoam sheathing.

§ Includes additional cost for 2x6 studs.

|| Three doors, each with a ten year life, discounted to present.

Source: reference 7.

For air conditioning the incremental cost is \$23/kBtu/hr output.*

Both the cases of heating only and heating plus cooling are evaluated.

The heating fuel choices in new single-family housing in 1975-1976 for the nine Census divisions are shown in Table 4.¹¹ Electricity represents half of the U.S. total, gas (mostly natural gas) 43%, and oil

Table 4. Distribution of heating fuels for new single-family detached homes, 1975-1976

Heating fuel source (%)	New England	Mid Atlantic	East North Central	West North Central	South Atlantic*	East South Central	West South Central	Mountain	Pacific	U.S. Total
Gas	19	18	49	72	16	29	38	61	61	43
Electric	32	51	48	26	76	71	62	39	39	50
Oil	49	31	3	2	7	0	0	0	0	7

* About 1% of new homes in the South Atlantic division are solar heated.

Source: reference 11.

the remainder. Oil dominates only in New England, while electricity and gas are popular in all other areas. Because of their widespread use, natural gas and electricity are selected for study here. However, the results for natural gas can be used for oil by substituting the appropriate fuel price and combustion efficiency.

Locations

Nine of the cities selected for study by Petersen are shown in Figure 2 and listed in Table 5. These selections represent a wide range of climates among densely populated areas. Cities were chosen to represent climates similar to those used in the mobile home study.¹ Seven locations are the same. Phoenix was substituted for San Diego. Fort Worth replaced Cheyenne to fill the gap between Miami and Atlanta cooling loads noticeable in the mobile home analysis. The particular weather data used for each city is the Test Reference Year¹² recommended by ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers). Detailed discussion on the site selection process is in ref. 7.

* These figures do not include labor costs. It is assumed that the HVAC systems are present in the baseline design to allow the size reductions and therefore involve no additional labor costs.

Fig. 2. Cities chosen for analysis.

Table 5. Weather data for cities selected

Code	City	Weather tape year	Annual degree days (Base 65°F)	
			Heating	Cooling
MN	Minneapolis	1970	8316	919
BS	Boston	1969	5781	667
SE	Seattle	1960	5562	143
KC	Kansas City	1968	5058	1485
DC	Washington, D.C.	1957	4161	1482
AT	Atlanta	1975	2959	1359
FW	Fort Worth	1975	2373	2495
PH	Phoenix	1951	1571	3434
MI	Miami	1964	130	4176

3. ANNUAL HEATING AND COOLING LOADS

Heat flows through the shell of a single-family residence are extremely complicated. Such mechanisms as infiltration and heat storage make steady-state models unreliable. For this study a sophisticated computer code, NBSLD, was used to calculate the dynamic thermal response of a residence using hourly weather data tapes.

As stated earlier, all analyses necessary to produce the annual and peak heating and cooling loads were provided by Petersen at NBS. The NBSLD code was improved to account for heat flows through the floor, and the output was expanded to provide a more useful research tool. Details on the updated NBSLD code are in ref. 13.

4. ECONOMIC ANALYSIS

The Economic Analysis Program performs three tasks:

1. Develops relationships between annual heating and cooling loads and additional investment in thermal improvements to the building shell.
2. Computes the payback period and net present worth (using lifecycle cost analysis) of each design option to select the optimum.
3. Performs sensitivity analysis to determine the effects on above results of changes in input parameters (insurance and tax rates, fuel prices, interest rates, etc.).

Inputs include peak and annual heating and cooling loads, additional costs for each of the sixteen design options (Table 3), and other variable parameters that affect energy-related lifecycle costs; see Table 6. The nominal value column represents typical values for each item in the U.S. These numbers vary from region to region as indicated by the range column values.

The material and labor indices represent cost factors relative to the average U.S. price. This factor is multiplied by the nominal design option or HVAC equipment price to account for regional price variations. The effects of changes in property taxes and income tax deductions are also included. The real interest rate is the cost of borrowed money for

Table 6. Values of energy-related parameters

	Nominal value	Range [*]	Source
Material cost index	1.0	<u>0.85</u> -1.15	14
Labor cost index	1.0	<u>0.85</u> -1.15	14
State property tax (% of home value)	2.5	<u>1.0</u> -6.0	15
Marginal federal income tax rate (married filing jointly)	0.25	0.22- <u>0.28</u>	
Marginal annual insurance premium (% of home value)	0.4	<u>0.2</u> -0.8	
Annual real interest rate (%)	5.0	<u>2.0</u> -11.0	
Time horizon (years)	30	25- <u>35</u>	
Seasonal fuel utilization efficiency			
Gas heating (%)	60	50-70	16
Electric resistance heating (%)	100	100	
Air conditioning (EER) [†]	7.0	<u>6.0</u> -8.0	17
Fuel prices (\$/MBtu) [‡]			
Natural gas	2.00	1.00- <u>16.00</u>	
Electricity [§]	10.00	1.70- <u>27.00</u>	

* Underlined values are those that encourage investment in energy-conserving design options.

[†] EER = energy efficiency ratio (in Btu of heat removed per watt-hour used).

[‡] Average 1975 fuel prices, MBtu = 10⁶ Btu.

[§] To convert from \$/MBtu to ¢/kWhr, multiply by 0.34.

home financing minus inflation. The discount rate, used in the net present worth analysis is assumed to be equal to the real interest rate. The time horizon is equal to the loan term for this study.

The relationships between inputs and the Economic Analysis Program results are shown in Fig. 3. Peak loads from NBSLD plus incremental cost data for shell improvements and HVAC equipment size reductions are used to compute the additional initial cost for each design option. These are combined with the annual loads data from NBSLD to form the annual load versus additional cost relationships.

A net present worth (NPW) analysis is used to compare the cost-effectiveness of different design options. The objective is to maximize

Fig. 3. Economic analysis program flowchart.

the net present worth of savings, which is the difference between the present worths of savings and costs. Additional costs incurred for each design option include the material and labor costs plus resulting increases in property tax and insurance premium. Annual fuel savings are due to reduced energy use as a result of design option additions.

The NPW for each design option is calculated using equations presented in Section IV of ref. 1, with a few changes: state sales tax is eliminated and savings due to federal income tax deductions are included. Calculations show that savings due to income tax deductions of mortgage interest and property tax cancel almost exactly additional costs due to property tax and insurance premiums using nominal values in Table 6. Therefore, the mobile home approach can be used for the single-family analysis by using zero state sales tax, insurance premium, and property tax. The NPW is calculated in the same manner. The maximum value of NPW among the various combinations of options for any location is the optimum.

Because economic parameter inputs used in the Economic Analysis Program vary significantly (see Table 6), it is necessary to evaluate their effect on the final result. The values in the range column of

Table 6 are divided into two extremes — those that encourage investment in energy-conserving design and those that discourage the same. Values of each extreme are used independently to determine the maximum effects on the results. Other runs are made eliminating the variables which cause negligible changes, so that the important factors are discovered and evaluated.

5. RESULTS AND INTERPRETATION

Thermal Analysis

Many computer runs were made to determine the order in which the different design options (Table 3) should be added to obtain maximum cost-effectiveness. The most economical order of implementation depends not only on the ability of the design option to reduce energy consumption, but also on the additional initial expense to the consumer. Therefore, by combining results of thermal loads analysis and cost data from Table 3, the order for adding energy-efficient designs is determined. Since heating fuel bills dominate cooling in all but the mildest climates, the following order is based on heating only:*

1. Baseline
2. R-11 attic insulation
3. R-11 wall insulation
4. R-19 attic insulation
5. R-11 floor insulation
6. Storm windows
7. R-30 attic insulation
8. R-19 floor insulation
9. Double glazed sliding glass door (SGD)
10. R-13 wall insulation
11. R-38 attic insulation
12. R-19 wall insulation
13. Triple pane windows
14. R-49 attic insulation
15. Storm door
16. R-23 wall insulation (using styrofoam)

* Each step is cumulative, i.e., the decision to proceed from one step to the next is based on benefits and costs relative to those incurred from previous steps.

NBSLD results for Kansas City are shown in Table 7 using the heating-only order. Results for the other locations are in Appendix Tables A-1 through A-9.

To demonstrate the relationship between climate and energy use, a graph of baseline annual heating and cooling loads versus heating and cooling degree days, respectively, is presented in Fig. 4. The identification codes for the locations in Fig. 4 and others to follow are in Table 5. Results demonstrating linear relationships* between annual loads and degree days are similar to those found in other analyses.^{1,4} The equations that define the relationships in Fig. 4 are:

$$AHL(1) \approx 0.0171 \cdot HDD$$

$$ACL(1) \approx 0.0110 \cdot CDD$$

where

$AHL(1)$ = annual heating load for baseline configuration (MBtu),

HDD = annual number of heating degree days (base 65°F),

$ACL(1)$ = annual cooling load for baseline configuration (MBtu), and

CDD = annual number of cooling degree days (base 65°F).

* There is one notable exception to the linear relationships described in Fig. 4. The baseline cooling load for Phoenix (51.5 MBtu/year) is about 50 percent greater than would be predicted by the results from other U.S. locations. Investigations by Petersen⁷ show that for some locations the degree day calculation (computed by subtracting a reference temperature, in this case 65°F, from the average of the daily high and low temperatures) is not effective. When 65°F-plus daytime temperatures are followed by sub-65°F temperatures at night, there is a cancellation, and the cooling needed during the day does not affect the degree day total. Other complexities (such as variation in the percentage of latent to the total load) cause the cooling loads to be much less predictable than heating loads. However, the effects of these problems are minimized by the use of marginal analysis. In this method systematic errors are reduced by comparing absolute values and presenting results in terms of relative quantities.

Table 7. NBSLD load calculation results - Kansas City

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	83.3	17.5	66.8	29.2	0.	0.
2	R-11 attic ins.	63.7	15.0	54.1	23.5	133.	2.
3	R-11 wall ins.	52.3	13.5	46.8	20.1	268.	59.
4	R-19 attic ins.	49.2	12.9	44.7	18.7	339.	97.
5	R-11 floor ins.	42.6	14.2	42.6	19.5	526.	303.
6	Storm windows	37.6	13.9	37.8	19.0	671.	436.
7	R-30 attic ins.	35.5	13.4	36.9	18.1	786.	531.
8	R-19 floor ins.	34.0	13.6	36.3	18.4	870.	621.
9	2-paned SGD	32.0	13.4	35.3	18.1	993.	738.
10	R-13 wall ins.	31.2	13.3	35.1	17.9	1042.	783.
11	R-38 attic ins.	30.5	13.2	34.7	17.7	1117.	852.
12	R-19 wall ins.	28.4	12.8	33.2	17.2	1313.	1037.
13	3-paned windows	26.8	12.6	32.1	16.9	1485.	1202.
14	R-49 attic ins.	26.1	12.4	31.5	16.6	1601.	1311.
15	Storm door	25.7	12.4	31.2	16.6	1707.	1418.
16	R-23 wall ins.	24.6	12.3	30.4	16.5	1906.	1613.

* These figures include labor and material costs less savings due to HVAC equipment size reductions.

Fig. 4. Regional variation in annual baseline configuration loads.

Dividing annual heating and cooling loads by the number of heating and cooling degree days, respectively, and by floor space, yields a figure of merit often discussed.^{4,18} For the baseline configuration these numbers are 14.3 Btu/HDD/ft² and 9.13 Btu/CDD/ft². These numbers are comparable to those in other documents.

Home orientation had insignificant effects on annual heating. This is expected because of the squareness of the residence design. During cooling hours, however, the annual heat gains on the east and west walls were 30 to 45% greater than those on the north and south. Therefore, cooling loads were minimized with respect to orientation by keeping the majority of the glass on the north-south walls of the house. Although not evaluated as a design option, awnings reduce annual cooling loads 10 to 25% when installed on south-facing windows.⁷ However, paybacks for this feature are greater than 15 years, even in the warmer climates. Properly designed roof overhang will yield similar results with shorter paybacks. Due to low sun angles in the morning and late afternoon, awnings are not as effective on east- and west-facing windows.

The effects of variation in window size on heating loads was investigated by Petersen.⁷ For single-glazing, windows are a net heat loss during the heating season in all locations. However, using design option #11 (see Table 7), which includes double-pane windows, houses in the following cities showed a net heat gain through the windows during the winter: Kansas City, Boston, and Atlanta. Therefore, increasing window size to improve wintertime thermal performance of this characteristic house is limited to only a few locations with storm windows. It should be noted, however, that this residence has very low heat storage capacity compared to houses of brick construction and was not designed to perform in a passive solar mode.

Economic Analysis

Annual heating loads for each option are normalized to the baseline configuration and graphed as a function of additional initial cost. Results for Kansas City are in Fig. 5. Graphs for each of the locations

Fig. 5. Heating load/cost relationship - Kansas City

are in Appendix Figs. A-1 through A-9. The optimal order of the options varies little from location to location. The curve shape, similar for all locations, demonstrates the law of diminishing marginal returns.

Also shown on the heating load versus cost curves are approximate positions of past and present single-family thermal standards and guidelines. The amounts of insulation necessary to meet the HUD-MPS and ASHRAE Standard 90-75 were found in the literature.^{19,20,21}

To evaluate how the heating load versus additional cost curves (Figs. A-1 through A-9) vary by location, two curve characteristics are investigated. The initial slope (K) is the slope of the load/cost curve at the baseline point. The asymptote (T_{∞}) is the annual load percentage

value that the load/cost curve tends to approach as the additional initial cost increases toward infinity. The initial slope and terminal asymptote of the heating load/cost curves are plotted versus annual heating degree days for each location in Figs. 6 and 7, respectively. The initial negative slope is approximately a linear function of heating degree days:

$$K \approx 3.13E-5 \cdot HDD + 0.015$$

where

K is MBtu saved per additional dollar invested (Fig. 6).

This result implies that energy savings per additional dollar invested are greater and the options are more cost-effective for cold than for warm climates.

Fig. 6. Regional variation in heating load versus cost curve parameter = slope (K).

Fig. 7. Regional variation in heating load versus cost curve parameter - asymptote (T_{∞}).

The asymptote, T_{∞} , is also an approximate linear function of heating degree days:

$$T_{\infty} \approx 3.33E-5 \cdot HDD + 0.055$$

This relationship implies that larger percentage reductions in heating load are possible in mild climates than in cold climates.

The slope results are similar to those computed for mobile homes. The asymptote versus HDD relationship is slightly different. T_{∞} increases linearly up to about 3600 HDD in the mobile home study and then remains constant for colder locations. However, variations in the two curve shapes are not large after subtracting the bias due to differences in the reference design.

The relationship between annual heating and cooling loads for Kansas City is shown in Fig. 8. Results for all locations are in Appendix Figs. A-10 through A-18. The potential for energy conservation in cooling is much less than for heating. Internal loads, which are not

Fig. 8. Heating/cooling load relationship — Kansas City.

affected by the design options studied here, is the major reason for reduced savings. Maximum reductions range from 20 to 40 percent of the baseline. Options #5 and #8 (additional floor insulation) increase the cooling load (see Fig. 8 and Figs. A-10 through A-18). This means that during the cooling season, the net heat flow through the floors is outward. Insulation impedes this flow, resulting in a greater cooling load.

The optimization analysis was performed for electric and natural gas heat, with and without air-conditioning, at a 5% real interest rate (using nominal values listed in Table 6). Table 8 contains results for Kansas City. Results for all nine locations are in Appendix Tables A-10 through A-18. The results include columns labeled NPW (net present worth of savings) and PB (simple payback period). The largest NPW value, the optimal solution, is underlined for each case. Negative

Table 8. Economic analysis results - Kansas City

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	880.	1.9	1198.	-0.1	2886.	0.7	3235.	0.0
3	1330.	2.5	1839.	0.4	4496.	0.9	5005.	0.2
4	1423.	2.9	2009.	0.6	4913.	1.0	5499.	0.3
5	1574.	3.8	2044.	1.9	5738.	1.3	6208.	0.7
6	1688.	4.3	2192.	2.5	6362.	1.5	6866.	0.9
7	1679.	4.8	2242.	2.9	6566.	1.6	7128.	1.1
8	1671.	5.2	2212.	3.3	6707.	1.8	7248.	1.2
9	1655.	5.7	2217.	3.8	6903.	1.9	7465.	1.4
10	1643.	5.9	2217.	3.9	6966.	2.0	7540.	1.4
11	1606.	6.3	2193.	4.2	7004.	2.1	7591.	1.6
12	1516.	7.1	2145.	5.0	7126.	2.4	7754.	1.8
13	1427.	7.8	2077.	5.6	7198.	2.6	7848.	2.0
14	1349.	8.3	2021.	6.0	7195.	2.8	7867.	2.2
15	1261.	8.8	1933.	6.5	7145.	3.0	7817.	2.4
16	1120.	9.6	1801.	7.2	7115.	3.2	7797.	2.6

* A/C = air conditioning.

† NPW = net present worth of savings.

‡ PB = payback period.

paybacks occasionally occur when savings due to size reduction in HVAC equipment exceed the additional design option cost, resulting in no net cost for the option.

Figure 9 shows the regional variation in additional cost relative to the baseline configuration for the optimal design selection. The existing thermal standard, 1974 HUD-MPS, is also shown. The results are similar to those found in the mobile home analysis. The existing HUD-MPS compares favorably to the optimum for natural gas users where the number of heating degree days is less than 3500. The large difference between the curves for electricity and natural gas demonstrates the need for a standard based on fuel price as well as climate. Breakpoints at 2500, 4500, and 8000 heating degree days on the HUD-MPS curve in Fig. 9 (and other figures to follow) are due to discontinuities in the requirements of the standard. A requirement based on a continuous function, such as recommended in ASHRAE 90-75²¹ would provide greater sensitivity to changes in climate.

Figures 10, 11, and 12 show regional variation in annual primary energy savings, additional initial investment, and annual fuel bill

Fig. 9. Regional variation in additional cost for optimal design selection.

Fig. 10. Regional variation in energy savings relative to 1974 HUD-MPS.

Fig. 11. Regional variation in additional investment for optimal design relative to 1974 HUD-MPS.

Fig. 12. Regional variation in annual fuel bill savings for optimal design relative to 1974 HUD-MPS.

savings, respectively, relative to the 1974 HUD-MPS standards. Using Fig. 10, an estimate of energy savings is possible for the optimum design relative to the existing HUD-MPS. Approximately one million homes are purchased each year; 50 percent use electric heating; 40 percent use natural gas (Table 4) for heating. The estimated annual primary energy saving is about 25 trillion Btu. Assuming a primary energy cost of \$2.50/MBtu, this amounts to \$63 million annually or about \$60 per new homeowner.

Figures 11 and 12 show that the additional initial investment relative to HUD-MPS is 500 to \$1200 for electricity with an average of six years payback, and zero to \$500 for natural gas with paybacks around 20 years.

Sensitivity Analysis

Because of the many variables that affect these results, a strategy was developed to reduce the number of cases needed to test sensitivity of results. Keeping fuel costs and interest rates constant, two different conditions were investigated. The first uses the underlined variables in the range column of Table 6 in an optimization analysis for maximum investments. The second optimization analysis was performed with the other range column values to determine minimum investments. Results are shown in Tables 9 and 10 for natural gas and electric heating. For gas the maximum variation in additional investment ranges from zero to \$800 (zero to \$400 for deviation from the nominal). Except for gas heating in the three coldest locations, Seattle, Boston, and Minneapolis, these results are similar to those for mobile homes. Variations for electricity are much smaller. This is because the nominal optimum values for the higher-priced electricity are located on the "flat" part of the load/cost curve. In this region the optimum is less sensitive to changes in parameters.

The effects of varying fuel prices and interest rates, using nominal values for other variables in Table 6, are shown in Fig. 13. Lines in the diagram define boundaries of the areas where a particular design option is optimum. Results show high sensitivity to fuel prices at current real (nominal minus inflation) interest rates, about 5%

Table 9. Effects of changes in variable parameters on optimal design selection -- natural gas heat*

	Design option			Incremental investment (1975-\$) (max.-min.)	Difference in energy use (MBtu/yr) (max.-min.)
	Max.	Nom.	Min.		
Minneapolis	13	10	6	800	28.7
Boston	10	9	6	400	11.5
Seattle	10	9	6	400	12.1
Kansas City	9	6	6	340	9.7
Washington, D.C.	6	6	4	300	15.5
Atlanta	6	4	4	300	10.7
Fort Worth	4	4	3	60	2.4
Phoenix	4	4	3	60	3.4
Miami	1	1	1	0	0

* Fuel price = \$2.00/MBtu; real interest rate = 5%.

Table 10. Effects of changes in variable parameters on optimal design selection -- electric heat*

	Design option			Incremental investment (1975-\$) (max.-min.)	Difference in energy use (MBtu/yr) (max.-min.)
	Max.	Nom.	Min.		
Minneapolis	16	16	16	0	0
Boston	14	14	14	0	0
Seattle	14	14	13	150	1.8
Kansas City	14	13	13	150	1.2
Washington, D.C.	13	13	13	0	0
Atlanta	11	10	10	80	0.5
Fort Worth	10	10	7	240	1.8
Phoenix	7	6	4	450	3.5
Miami	2	2	2	0	0

* Fuel price = \$10/MBtu; real interest rate = 5%.

annually. On the other hand, the results are rather insensitive to the range of interest rates considered.

To evaluate the effects of rising fuel prices (relative to inflation) with Fig. 13, a uniform series (uniform series capital recovery factor, USCR) equivalent of an escalating fuel price was computed.¹ The coefficients used to modify the constant-valued energy price by multiplication are in Table 11.

Fig. 13. Optimal design selection sensitivity to changes in fuel cost and interest rates - Kansas City.

Table 11. Fuel price escalation factors (USCR)

Real fuel price escalation rate (%)	USCR	Constant-valued annual fuel cost for present fuel cost equivalent to:	
		\$2/MBtu	\$10/MBtu
1	1.06	2.12	10.60
2	1.12	2.24	11.20
3	1.19	2.38	11.90
4	1.27	2.54	12.70
5	1.35	2.70	13.50

6. SUMMARY AND CONCLUSIONS

This report presents results of detailed thermal analyses of new single-family dwellings in nine U.S. cities. Results include annual heating load versus additional initial cost relationships and optimization analysis for each location (contained in the Appendix). The annual loads calculation and cost surveys were based on a report by Petersen at the National Bureau of Standards which used the NBSLD computer code. The economic analyses were conducted with an updated version of a computer program written at ORNL.

The purpose of this report is to evaluate the cost-effectiveness of various energy-conserving design options. An optimal design (i.e., one that minimizes lifecycle cost of purchase and operation) is defined for each location (see Figs. 10-12). Design options studied include additional wall, attic, and floor insulation, multiple-paned windows and sliding glass doors, storm doors, 6" exterior walls, and styrofoam wall sheathing.

Figure 4 shows that annual heating and cooling loads vary linearly with number of heating and cooling degree days, respectively. Petersen⁷ showed that this holds true for homes of varying degrees of thermal protection by adjusting the degree day reference temperature.

The most cost-effective order of implementation was generally constant for all locations for heating only (Tables A-1 through A-9 and Figures A-1 through A-9 in the Appendix). However, the cost-effectiveness of floor insulation did decrease relative to the other options for milder climates. Regional variation in basic heating load versus initial cost relationships is shown in Figs. 6 and 7.

Results of the optimization analysis for heating only are compared to the existing single-family thermal standard, 1974 HUD-MPS, in Figs. 9-12. For natural gas-heated homes the comparison is favorable for much of the nation, with major differences only in areas above 5200 heating degree days. All areas above 1000 heating degree days for electric heating show large differences. Paybacks for natural gas range from 15 to 25 years and for electricity, four to six years. These

results indicate that the HUD-MPS would be more effective if they were sensitive to fuel prices as well as to climate.

The National Association of Home Builders offers a good example of flexible thermal performance guidelines, *NAHB Thermal Performance Guidelines for One and Two Family Dwellings*.²² The document recommends various levels of insulation, storm windows, and storm doors based on climate and fuel price. An economic analysis is performed to require a specified payback period at a chosen interest rate and investment lifetime. Neither the present HUD-MPS nor the ASHRAE Standard 90-75 is sensitive to fuel prices.

A sensitivity analysis is also performed to evaluate the effects of changes in various economic parameters (with constant fuel price and interest rate) on the optimization and analysis. Results, listed in Tables 9 and 10, show that except for areas above 5500 heating degree days, even extreme cases (i.e., using extreme values which encourage or discourage investment) yield moderate results. Sensitivity to changes in fuel prices and interest rates was also examined; see Fig. 13.

In conclusion, results of the single-family dwelling analysis were similar to those found in the mobile home analysis. The format and method of analysis was established in the mobile home study and followed here. Results contained here should prove helpful in the evaluation of cost-effective thermal standards and their impact on the single-family home buyer.

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APPENDIX

Analysis Results for all Locations

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Fig. A-1. Heating Load/Cost Relationship - Minneapolis.

Fig. A-2. Heating Load/Cost Relationship - Boston.

Fig. A-3. Heating Load/Cost Relationship - Seattle.

Fig. A-4. Heating Load/Cost Relationship - Kansas City.

Fig. A-5. Heating Load/Cost Relationship - Washington, D.C.

Fig. A-6. Heating Load/Cost Relationship - Atlanta.

Fig. A-7. Heating Load/Cost Relationship - Fort Worth.

Fig. A-8. Heating Load/Cost Relationship - Phoenix.

Fig. A-9. Heating Load/Cost Relationship - Miami.

Fig. A-10. Heating/Cooling Load Relationship - Minneapolis.

Fig. A-11. Heating/Cooling Load Relationship — Boston.

Fig. A-12. Heating/Cooling Load Relationship — Seattle.

Fig. A-13. Heating/Cooling Load Relationship — Kansas City.

Fig. A-14. Heating/Cooling Load Relationship — Washington, D.C.

Fig. A-15. Heating/Cooling Load Relationship — Atlanta.

Fig. A-16. Heating/Cooling Load Relationship — Fort Worth.

Fig. A-17. Heating/Cooling Load Relationship — Phoenix.

Fig. A-18. Heating/Cooling Load Relationship — Miami.

Table A-1. NBSLD load calculation results -- Minneapolis

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	143.5	9.5	81.9	23.7	0.	0.
2	R-11 attic ins.	114.7	7.9	67.9	21.1	131.	71.
3	R-11 wall ins.	96.6	6.9	59.2	19.3	262.	161.
4	R-19 attic ins.	91.7	6.5	56.8	18.4	332.	211.
5	R-11 floor ins.	81.1	7.5	53.5	19.4	517.	419.
6	Storm windows	73.0	7.3	49.8	17.7	665.	527.
7	R-30 attic ins.	65.7	7.1	48.1	16.0	778.	601.
8	R-19 floor ins.	67.3	7.2	47.1	17.3	861.	714.
9	2-paned SGD	63.8	7.1	45.5	16.0	983.	806.
10	R-13 wall ins.	62.7	7.0	44.9	15.5	1031.	843.
11	R-38 attic ins.	61.3	6.9	44.3	15.2	1105.	910.
12	R-19 wall ins.	58.3	6.7	42.8	14.7	1302.	1095.
13	3-paned windows	55.4	6.6	41.4	14.4	1473.	1259.
14	R-49 attic ins.	54.4	6.5	40.9	14.2	1589.	1370.
15	Storm door	53.7	6.5	40.6	14.2	1695.	1477.
16	R-23 wall ins.	51.8	6.4	39.6	14.0	1893.	1670.

*These figures include labor and material costs less savings due to HVAC equipment size reductions.

Table A-2. NBSLD load calculation results -- Boston

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	98.8	5.1	55.2	21.5	0.	0.
2	R-11 attic ins.	77.0	4.4	45.0	18.2	139.	63.
3	R-11 wall ins.	63.9	3.9	39.0	15.8	276.	145.
4	R-19 attic ins.	60.4	3.7	37.4	15.0	348.	198.
5	R-11 floor ins.	50.9	4.3	34.9	16.1	534.	410.
6	Storm windows	44.8	4.2	32.1	15.5	684.	546.
7	R-30 attic ins.	42.2	4.1	31.0	14.8	798.	644.
8	R-19 floor ins.	40.4	4.2	30.1	15.4	881.	741.
9	2-paned SGD	37.8	4.1	29.0	14.9	1004.	852.
10	R-13 wall ins.	37.0	4.0	28.6	14.8	1053.	899.
11	R-38 attic ins.	36.0	4.0	28.2	14.5	1127.	966.
12	R-19 wall ins.	33.7	3.9	27.0	14.1	1325.	1155.
13	3-paned windows	31.8	3.8	26.1	13.8	1497.	1320.
14	R-49 attic ins.	31.0	3.8	25.8	13.6	1613.	1432.
15	Storm door	30.5	3.8	25.5	13.6	1720.	1538.
16	R-23 wall ins.	25.2	3.7	24.9	13.5	1918.	1734.

*These figures include labor and material costs less savings due to HVAC equipment size reductions.

Table A-3. NBSLD load calculation results - Seattle

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	91.1	1.8	37.6	25.0	0.	0.
2	R-11 attic ins.	67.5	1.4	30.0	19.3	144.	13.
3	R-11 wall ins.	53.7	1.2	25.6	15.2	285.	59.
4	R-19 attic ins.	50.0	1.1	24.4	13.9	357.	102.
5	R-11 floor ins.	41.2	1.3	23.0	15.4	547.	326.
6	Storm windows	35.1	1.3	21.0	14.5	697.	456.
7	R-30 attic ins.	32.6	1.3	20.2	13.7	812.	553.
8	R-19 floor ins.	30.8	1.3	19.4	14.5	896.	554.
9	2-paned SGD	28.2	1.3	18.6	13.7	1019.	759.
10	R-13 wall ins.	27.4	1.3	18.4	13.7	1069.	809.
11	R-38 attic ins.	26.4	1.2	18.0	13.3	1143.	874.
12	R-19 wall ins.	24.1	1.2	17.2	12.7	1341.	1058.
13	3-paned windows	22.2	1.1	16.4	12.2	1514.	1219.
14	R-49 attic ins.	21.4	1.1	16.1	12.0	1630.	1331.
15	Storm door	21.0	1.1	16.0	12.0	1737.	1438.
16	R-23 wall ins.	19.6	1.1	15.7	12.0	1936.	1637.

* These figures include labor and material costs less savings due to HVAC equipment size reductions.

Table A-4. NBSLD load calculation results - Kansas City

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	83.3	17.5	66.8	29.2	0.	0.
2	R-11 attic ins.	63.7	15.0	54.1	23.5	133.	2.
3	R-11 wall ins.	52.3	13.5	46.8	20.1	268.	59.
4	R-19 attic ins.	49.2	12.9	44.7	18.7	339.	97.
5	R-11 floor ins.	42.6	14.2	42.6	19.5	526.	303.
6	Storm windows	37.6	13.9	37.8	19.0	671.	436.
7	R-30 attic ins.	35.5	13.4	36.9	18.1	786.	531.
8	R-19 floor ins.	34.0	13.6	36.3	18.4	870.	621.
9	2-paned SGD	32.0	13.4	35.3	18.1	993.	738.
10	R-13 wall ins.	31.2	13.3	35.1	17.9	1042.	783.
11	R-38 attic ins.	30.5	13.2	34.7	17.7	1117.	852.
12	R-19 wall ins.	28.4	12.8	33.2	17.2	1313.	1037.
13	3-paned windows	26.8	12.6	32.1	16.9	1485.	1202.
14	R-49 attic ins.	26.1	12.4	31.5	16.6	1601.	1311.
15	Storm door	25.7	12.4	31.2	16.6	1707.	1418.
16	R-23 wall ins.	24.6	12.3	30.4	16.5	1906.	1613.

* These figures include labor and material costs less savings due to HVAC equipment size reductions.

Table A-5. NBSLD load calculation results - Washington, D.C.

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	66.3	14.8	32.7	43.4	0.	0.
2	R-11 attic ins.	49.1	12.4	23.6	35.3	141.	-45.
3	R-11 wall ins.	39.5	10.9	18.1	30.7	279.	-13.
4	R-19 attic ins.	36.7	10.3	16.6	29.4	351.	29.
5	R-11 floor ins.	30.6	11.5	17.5	27.5	545.	180.
6	Storm windows	26.5	11.2	16.8	25.3	699.	282.
7	R-30 attic ins.	24.8	10.8	15.9	24.4	814.	377.
8	R-19 floor ins.	23.5	11.0	16.3	23.7	900.	447.
9	2-paned SGD	21.8	10.8	15.9	22.7	1024.	548.
10	R-13 wall ins.	21.3	10.8	15.9	22.5	1074.	593.
11	R-38 attic ins.	20.6	10.6	15.3	22.1	1148.	658.
12	R-19 wall ins.	18.9	10.3	14.8	21.2	1347.	836.
13	3-paned windows	17.6	10.1	14.4	20.5	1520.	993.
14	R-49 attic ins.	17.0	9.9	14.1	20.2	1636.	1102.
15	Storm door	16.6	9.9	14.1	20.0	1743.	1205.
16	R-23 wall ins.	15.7	9.8	13.9	19.5	1943.	1393.

* These figures include labor and material costs less savings due to HVAC equipment size reductions.

Table A-6. NBSLD load calculation results - Atlanta

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	45.8	14.8	44.7	30.4	0.	0.
2	R-11 attic ins.	32.4	12.1	35.8	22.4	141.	-43.
3	R-11 wall ins.	25.2	10.4	29.5	17.4	278.	-21.
4	R-19 attic ins.	23.3	9.8	28.0	15.6	350.	9.
5	R-11 floor ins.	19.9	10.6	26.2	18.4	538.	262.
6	Storm windows	16.9	10.3	23.9	17.7	688.	396.
7	R-30 attic ins.	15.7	10.0	22.9	16.9	803.	493.
8	R-19 floor ins.	14.9	10.2	22.3	17.4	887.	588.
9	2-paned SGD	13.7	10.0	21.4	16.9	1010.	700.
10	R-13 wall ins.	13.3	9.9	21.1	16.7	1059.	744.
11	R-38 attic ins.	12.8	9.8	20.7	16.4	1134.	812.
12	R-19 wall ins.	11.6	9.5	19.7	15.8	1331.	956.
13	3-paned windows	10.7	9.3	18.8	15.4	1504.	1159.
14	R-49 attic ins.	10.3	9.1	18.5	15.1	1620.	1268.
15	Storm door	10.1	9.1	18.4	15.0	1727.	1373.
16	R-23 wall ins.	9.5	9.0	17.8	14.8	1925.	1567.

* These figures include labor and material costs less savings due to HVAC equipment size reductions.

Table A-7. NBSLD load calculation results - Fort Worth

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	35.4	28.2	36.6	35.0	0.	0.
2	R-11 attic ins.	24.0	24.1	24.6	21.1	135.	-185.
3	R-11 wall ins.	18.0	21.1	24.6	21.1	285.	-35.
4	R-19 attic ins.	16.5	20.2	23.6	19.2	358.	-6.
5	R-11 floor ins.	14.5	21.1	22.2	21.1	547.	227.
6	Storm windows	12.0	20.5	20.0	20.5	697.	364.
7	R-30 attic ins.	11.0	19.8	19.2	19.8	813.	463.
8	R-19 floor ins.	10.6	19.8	18.9	19.8	897.	547.
9	2-paned SGD	9.6	19.5	18.0	19.4	1020.	661.
10	R-13 wall ins.	9.3	19.3	17.7	19.2	1069.	706.
11	R-38 attic ins.	8.9	19.0	17.5	18.8	1144.	771.
12	R-19 wall ins.	8.0	18.4	16.7	18.3	1342.	958.
13	3-paned windows	7.3	18.0	16.1	17.9	1515.	1122.
14	R-49 attic ins.	7.0	17.7	15.8	17.6	1631.	1231.
15	Storm door	6.8	17.7	15.8	17.6	1738.	1338.
16	R-23 wall ins.	6.3	17.4	15.4	17.3	1937.	1530.

* These figures include labor and material costs less savings due to HVAC equipment size reductions.

Table A-8. NBSLD load calculation results - Phoenix

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	29.0	51.5	29.1	39.2	0.	0.
2	R-11 attic ins.	17.2	44.6	21.1	31.2	143.	-41.
3	R-11 wall ins.	11.2	37.6	17.1	23.2	285.	-93.
4	R-19 attic ins.	9.5	35.5	16.0	21.0	357.	-61.
5	R-11 floor ins.	9.1	36.7	15.4	22.3	548.	160.
6	Storm windows	7.2	35.3	13.7	22.3	700.	311.
7	R-30 attic ins.	6.5	34.8	12.9	22.3	815.	426.
8	R-19 floor ins.	6.2	33.7	12.8	22.3	900.	511.
9	2-paned SGD	5.5	32.9	12.1	22.4	1023.	637.
10	R-13 wall ins.	5.3	32.7	12.0	22.4	1073.	607.
11	R-38 attic ins.	5.0	32.5	11.5	22.4	1147.	761.
12	R-19 wall ins.	4.3	31.6	10.7	22.0	1345.	950.
13	3-paned windows	3.7	30.4	10.2	21.5	1518.	1111.
14	R-49 attic ins.	3.5	30.0	10.0	21.3	1635.	1223.
15	Storm door	3.4	29.8	9.8	21.2	1741.	1327.
16	R-23 wall ins.	3.0	29.4	9.3	21.0	1941.	1522.

* These figures include labor and material costs less savings due to HVAC equipment size reductions.

Table A-9. NBSLD load calculation results - Miami

Design option	Additional feature	Annual loads (MBtu)		Peak demands (kBtu/hr)		Additional initial cost (1975-\$)*	
		Heating	Cooling	Heating	Cooling	Heat only	Heat + A/C
1	Baseline	2.6	45.5	25.9	29.6	0.	0.
2	R-11 attic ins.	1.5	41.7	18.6	25.0	145.	39.
3	R-11 wall ins.	0.9	38.9	15.3	21.3	288.	97.
4	R-19 attic ins.	0.8	38.0	14.3	20.2	361.	144.
5	R-11 floor ins.	0.7	39.5	13.2	21.5	550.	364.
6	Storm windows	0.5	38.9	11.4	21.0	701.	504.
7	R-30 attic ins.	0.5	38.3	10.9	20.5	817.	608.
8	R-19 floor ins.	0.5	38.3	10.9	20.5	902.	693.
9	2-paned SGD	0.4	38.0	10.0	20.2	1025.	809.
10	R-13 wall ins.	0.4	37.8	9.8	20.0	1075.	854.
11	R-38 attic ins.	0.3	37.5	9.4	19.8	1149.	924.
12	R-19 wall ins.	0.3	36.9	8.6	19.4	1348.	1113.
13	3-paned windows	0.2	36.5	8.1	19.1	1521.	1279.
14	R-49 attic ins.	0.2	36.2	8.1	18.9	1638.	1391.
15	Storm door	0.2	36.1	7.9	18.9	1744.	1498.
16	R-23 wall ins.	0.2	35.9	7.5	18.7	1943.	1693.

*These figures include labor and material costs less savings due to HVAC equipment size reductions.

Table A-10. Economic analysis results - Minneapolis

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW† (1975-\$)	PB‡ (years)	NPW† (1975-\$)	PB‡ (years)	NPW† (1975-\$)	PB‡ (years)	NPW† (1975-\$)	PB‡ (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	1354.	1.3	1530.	0.6	4303.	0.5	4479.	0.2
3	2156.	1.6	2450.	0.9	6958.	0.6	7252.	0.3
4	2338.	1.9	2681.	1.1	7641.	0.6	7584.	0.4
5	2658.	2.4	2945.	1.9	9086.	0.8	9333.	0.7
6	2967.	2.8	3268.	2.1	10183.	0.9	10484.	0.7
7	3024.	3.1	3382.	2.3	10578.	1.1	10935.	0.8
8	3064.	3.3	3380.	2.6	10863.	1.1	11179.	0.9
9	3119.	3.6	3474.	2.8	11267.	1.2	11622.	1.0
10	3129.	3.8	3501.	2.9	11393.	1.3	11766.	1.0
11	3125.	4.0	3511.	3.1	11530.	1.3	11916.	1.1
12	3067.	4.5	3502.	3.6	11806.	1.5	12221.	1.3
13	3063.	4.9	3495.	4.0	12073.	1.7	12506.	1.4
14	3000.	5.3	3444.	4.3	12115.	1.8	12559.	1.5
15	2928.	5.6	3374.	4.6	12114.	1.9	12560.	1.6
16	2830.	6.1	3286.	5.1	12214.	2.1	12669.	1.8

*A/C = air conditioning.

†NPW = net present worth of savings.

‡PB = payback period.

Table A-11. Economic analysis results — Boston

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	565.	1.8	1117.	0.8	3218.	0.6	3350.	0.3
3	1520.	2.3	1746.	1.1	5088.	0.8	5313.	0.4
4	1630.	2.6	1888.	1.4	5560.	0.9	5817.	0.5
5	1933.	3.3	2120.	2.4	6836.	1.1	7023.	0.8
6	2057.	3.7	2306.	2.9	7624.	1.3	7833.	1.0
7	2114.	4.2	2348.	3.3	7904.	1.4	8137.	1.1
8	2126.	4.5	2338.	3.7	8102.	1.5	8314.	1.3
9	2135.	4.9	2365.	4.0	8373.	1.6	8603.	1.4
10	2130.	5.0	2364.	4.2	8455.	1.7	8689.	1.4
11	2106.	5.3	2350.	4.4	8531.	1.8	8775.	1.5
12	2027.	6.0	2290.	5.1	8690.	2.0	8952.	1.8
13	1950.	6.6	2226.	5.7	8799.	2.2	9075.	2.0
14	1877.	7.1	2160.	6.1	8814.	2.4	9097.	2.1
15	1796.	7.5	2079.	6.5	8783.	2.5	9066.	2.2
16	1666.	8.2	1955.	7.2	8790.	2.8	9079.	2.5

*A/C = air conditioning.

†NPW = net present worth of savings.

‡PB = payback period.

Table A-12. Economic analysis results — Seattle

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	1667.	1.8	1225.	0.1	3478.	0.6	3636.	0.1
3	1638.	2.2	1910.	0.4	5465.	0.8	5736.	0.2
4	1755.	2.6	2063.	0.7	5961.	0.9	6268.	0.2
5	2016.	3.2	2271.	1.9	7119.	1.1	7375.	0.7
6	2182.	3.7	2462.	2.4	7916.	1.2	8196.	0.8
7	2154.	4.1	2496.	2.8	8180.	1.4	8482.	0.9
8	2202.	4.4	2482.	3.2	8370.	1.5	8650.	1.1
9	2212.	4.8	2514.	3.5	8647.	1.6	8949.	1.2
10	2205.	5.0	2507.	3.7	8724.	1.7	9026.	1.3
11	2180.	5.3	2493.	4.0	8797.	1.8	9110.	1.3
12	2102.	6.0	2433.	4.6	8957.	2.0	9288.	1.6
13	2028.	6.5	2373.	5.2	9080.	2.2	9425.	1.8
14	1954.	7.0	2306.	5.6	9090.	2.3	9441.	1.9
15	1868.	7.4	2220.	6.0	9046.	2.5	9398.	2.0
16	1739.	8.1	2091.	6.7	9057.	2.7	9409.	2.3

*A/C = air conditioning.

†NPW = net present worth of savings.

‡PB = payback period.

Table A-13. Economic analysis results - Kansas City

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	880.	1.9	1198.	-0.1	2886.	0.7	3205.	0.0
3	1330.	2.5	1839.	0.4	4496.	0.9	5005.	0.2
4	1423.	2.9	2009.	0.6	4913.	1.0	5499.	0.3
5	1574.	3.8	2044.	1.9	5738.	1.3	6208.	0.7
6	1688.	4.3	2192.	2.5	6362.	1.5	6866.	0.9
7	1679.	4.8	2242.	2.9	6566.	1.6	7128.	1.1
8	1671.	5.2	2212.	3.3	6707.	1.8	7248.	1.2
9	1655.	5.7	2217.	3.8	6903.	1.9	7465.	1.4
10	1643.	5.9	2217.	3.9	6966.	2.0	7540.	1.4
11	1606.	6.3	2193.	4.2	7004.	2.1	7591.	1.6
12	1516.	7.1	2145.	5.0	7126.	2.4	7754.	1.8
13	1427.	7.8	2077.	5.6	7198.	2.6	7848.	2.0
14	1349.	8.3	2021.	6.0	7195.	2.8	7867.	2.2
15	1261.	8.8	1933.	6.5	7145.	3.0	7817.	2.4
16	1120.	9.6	1801.	7.2	7115.	3.2	7797.	2.6

* A/C = air conditioning.

† NPW = net present worth of savings.

‡ PB = payback period.

Table A-14. Economic analysis results - Washington, D.C.

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	743.	2.4	1109.	-0.7	2497.	0.8	2863.	-0.2
3	1101.	3.0	1685.	-0.2	3840.	1.0	4424.	-0.0
4	1172.	3.5	1831.	0.2	4194.	1.2	4853.	0.1
5	1289.	4.5	1902.	1.3	4933.	1.5	5546.	0.5
6	1345.	5.2	2031.	1.8	5409.	1.8	6055.	0.7
7	1319.	5.8	2055.	2.3	5558.	2.0	6295.	0.9
8	1300.	6.3	2038.	2.7	5675.	2.1	6413.	1.0
9	1264.	6.8	2040.	3.2	5814.	2.3	6590.	1.2
10	1241.	7.1	2022.	3.4	5846.	2.4	6626.	1.3
11	1201.	7.5	2006.	3.8	5873.	2.5	6678.	1.4
12	1091.	8.5	1938.	4.6	5938.	2.8	6786.	1.7
13	985.	9.3	1864.	5.3	5968.	3.1	6847.	1.9
14	856.	9.9	1794.	5.8	5933.	3.3	6831.	2.1
15	810.	10.5	1713.	6.3	5887.	3.5	6791.	2.3
16	657.	11.5	1582.	7.2	5829.	3.8	6754.	2.6

* A/C = air conditioning.

† NPW = net present worth of savings.

‡ PB = payback period.

Table A-15. Economic analysis results - Atlanta

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	549.	3.1	936.	-0.8	1918.	1.1	2304.	-0.3
3	784.	3.9	1413.	-0.3	2886.	1.4	3515.	-0.1
4	814.	4.5	1532.	0.0	3118.	1.6	3836.	0.0
5	800.	6.1	1391.	2.4	3450.	2.1	4041.	0.9
6	803.	7.0	1433.	3.3	3755.	2.4	4384.	1.3
7	754.	7.9	1425.	3.9	3835.	2.7	4507.	1.5
8	706.	8.5	1350.	4.6	3860.	2.9	4504.	1.8
9	647.	9.3	1318.	5.3	3925.	3.1	4596.	2.0
10	619.	9.7	1301.	5.5	3939.	3.3	4621.	2.1
11	569.	10.2	1270.	5.9	3938.	3.4	4639.	2.3
12	432.	11.6	1168.	7.0	3923.	3.9	4659.	2.7
13	309.	12.7	1068.	8.0	3896.	4.3	4655.	3.1
14	213.	13.6	989.	8.6	3840.	4.6	4616.	3.3
15	117.	14.4	897.	9.3	3766.	4.8	4546.	3.6
16	-49.	15.8	745.	10.4	3664.	5.3	4452.	4.0

* A/C = air conditioning.

† NPW = net present worth of savings.

‡ PB = payback period.

Table A-16. Economic analysis results - Fort Worth

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	453.	3.4	1080.	-3.3	1611.	1.2	2238.	-1.4
3	609.	4.8	1461.	-0.4	2378.	1.6	3230.	-0.2
4	617.	5.6	1580.	-0.1	2546.	1.9	3509.	-0.0
5	530.	7.8	1382.	2.1	2662.	2.6	3514.	0.9
6	502.	8.8	1419.	3.1	2894.	3.0	3804.	1.3
7	443.	9.9	1422.	3.7	2929.	3.3	3908.	1.6
8	382.	10.8	1361.	4.4	2912.	3.6	3891.	1.9
9	309.	11.8	1320.	5.1	2940.	4.0	3951.	2.2
10	277.	12.2	1307.	5.3	2941.	4.1	3971.	2.3
11	221.	12.9	1283.	5.7	2923.	4.3	3985.	2.5
12	71.	14.6	1189.	6.8	2866.	4.9	3985.	3.0
13	-65.	16.1	1093.	7.8	2805.	5.4	3963.	3.4
14	-166.	17.1	1022.	8.4	2734.	5.7	3922.	3.7
15	-265.	18.2	923.	9.1	2651.	6.1	3839.	4.0
16	-439.	19.9	778.	10.2	2527.	6.7	3742.	4.5

* A/C = air conditioning.

† NPW = net present worth of savings.

‡ PB = payback period.

Table A-17. Economic analysis results - Phoenix

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	464.	3.5	1165.	-0.6	1666.	1.2	2367.	-0.3
3	631.	4.7	2040.	-0.7	2443.	1.6	3853.	-0.3
4	644.	5.4	2262.	-0.5	2628.	1.8	4246.	-0.2
5	479.	8.2	1977.	1.1	2512.	2.8	4010.	0.6
6	423.	9.5	2026.	2.0	2646.	3.2	4249.	1.0
7	346.	10.8	1987.	2.7	2644.	3.6	4284.	1.4
8	273.	11.8	1996.	3.1	2594.	4.0	4317.	1.6
9	188.	13.0	1969.	3.7	2586.	4.4	4367.	2.0
10	150.	13.5	1946.	4.0	2571.	4.5	4366.	2.1
11	90.	14.2	1900.	4.4	2538.	4.8	4348.	2.3
12	-70.	16.2	1817.	5.2	2452.	5.4	4339.	2.8
13	-215.	17.9	1774.	5.9	2364.	6.0	4352.	3.1
14	-319.	19.1	1704.	6.4	2285.	6.4	4308.	3.4
15	-420.	20.3	1621.	6.9	2194.	6.8	4235.	3.7
16	-600.	22.3	1475.	7.8	2052.	7.5	4127.	4.1

*A/C = air conditioning.

†NPW = net present worth of savings.

‡PB = payback period.

Table A-18. Economic analysis results - Miami

Design option	Natural gas heating				Electric heating			
	No A/C*		With A/C*		No A/C*		With A/C*	
	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)	NPW [†] (1975-\$)	PB [‡] (years)
1	0.	0.0	0.	0.0	0.	0.0	0.	0.0
2	-81.	35.9	310.	1.6	36.	12.3	427.	1.3
3	-193.	48.8	492.	2.4	-21.	16.6	665.	2.0
4	-258.	56.3	520.	3.2	-70.	19.1	708.	2.6
5	-444.	83.9	192.	10.0	-251.	28.3	385.	7.5
6	-586.	98.8	106.	12.7	-377.	33.3	315.	9.5
7	-699.	****	50.	14.2	-484.	37.7	265.	10.7
8	-783.	****	-34.	16.2	-567.	41.3	182.	12.2
9	-902.	****	-124.	18.2	-680.	45.6	99.	13.7
10	-951.	****	-153.	18.8	-727.	47.4	71.	14.2
11	-1024.	****	-199.	19.6	-797.	50.1	28.	14.9
12	-1219.	****	-339.	22.2	-987.	57.4	-107.	17.0
13	-1389.	****	-473.	24.5	-1153.	63.6	-237.	18.9
14	-1505.	****	-562.	25.9	-1267.	68.0	-324.	20.0
15	-1611.	****	-660.	27.6	-1372.	72.1	-422.	21.4
16	-1809.	****	-838.	30.6	-1567.	79.4	-597.	23.7

*A/C = air conditioning.

†NPW = net present worth of savings.

‡PB = payback period.

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