**Manufactured Homes
Simulated
Thermal Analysis
and
Cost Effectiveness
Report**

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Table of Contents

1 Introduction	1
1.1 Thermal Analysis	1
1.2 Cost-Effectiveness	1
1.3 Report Organization	1
2 Methodology	2
2.1 Thermal Analysis	2
2.1.1 Heat Loss Analysis	2
2.1.2 Engineering Simulations	2
2.2 Cost-Effectiveness Analysis	3
2.2.1 RCDP Cost-Effectiveness	3
2.2.2 Optimum Conservation Package	3
2.3 Presentation of Analysis	4
3 Thermal Analysis: Component Performance and Heat Loss Rates	5
3.1 Component Performance	5
3.1.1 Windows	5
3.1.2 Walls	5
3.1.3 Floors	6
3.1.4 Ceilings	9
3.1.5 Heat Pumps and Duct Systems	12
3.2 Overall Building Heat Loss Rate	12
3.2.1 SGC Compliance	14
3.2.2 Heat Loss Rates	15
4 Thermal Performance: Energy Savings	18
4.1 Simulation Assumptions	18
4.2 Weather Sites	18
4.3 Heating Systems	19
4.4 Results	21
5 Cost-Effectiveness	23
5.1 Assumptions and Life Cycle Cost Adjustments	23
5.2 Cost-Benefit Analysis	23
5.2.1 Package Costs	23
5.2.2 Cost-Benefit	24
5.2.3 Consumer Benefits	25
5.3 Optimum Conservation Packages	26
5.3.1 Optimization Assumptions	26
5.3.2 Results	31
6 References	34
7 Appendix A	35
8 Appendix B	40
9 Appendix C	56

Table of Figures

Typical Floor Construction	6
Baffle as Part of Ceiling Insulation Strategy	10
Stepped Batt Ceiling Insulation Strategy	10
Home Size by Manufacturer	17
Sample Optimization Output	29

Table of Tables

Floor Heat Loss Rates	8
Ceiling Heat Loss Rates	11
Most Common Conservation Measures	13
Component Heat Loss by Climate Zone	14
Window Areas	14
Heat Loss Rates by Manufacturer	15
Heat Loss Rates by Climate Zone	16
Weather Sites	19
Simulated Heating Energy Performance and Savings	21
Simulated Annual Energy Savings by Manufacturer	22
SGC Package Prices	24
SGC Conservation Package Savings	25
Consumer Cash Flow	26
Base Case Assumptions	27
Conservation Options for Cost Optimization	30
Optimum Package with Conventional Floors	32
Optimum Package with Optimum Floor Construction	32

Executive Summary

In 1988 and 1989, 150 manufactured homes were built to comply with Super Good Cents (SGC) specifications adapted from the existing specifications for site-built homes under the Residential Construction Demonstration Project (RCDP). Engineering calculations and computer simulations were used to estimate the effects of the SGC specifications on the thermal performance of the homes. These results were compared with consumer costs to establish the cost-effectiveness of individual measures. The most cost-effective measures were combined in an optimum conservation package.

Heat loss U-factors for windows, walls, floors and ceilings were established using the standard ASHRAE parallel heat flow method. Adjustments were made to the U-factors to take into account the actual construction practices used in the manufactured homes (such as stepped batt placement in attics and the location of an uninsulated heating duct between two layers of insulation in the floors). These adjustments resulted in higher U-factors for ceilings and floors than assumed at the time the homes were approved as meeting the SGC specifications. As a result, except for those homes which included heat pumps, most of the homes did not meet the SGC compliance standards. Nonetheless, these homes achieved substantial reductions in overall heat loss rate (UA) compared to UAs estimated for the same homes using the standard insulation packages provided by the manufacturers in the absence of the RCDP program. Homes with conventional electric furnaces showed a 35% reduction in total UA while homes with heat pumps had a 25% reduction. A regression analysis showed no significant relationship between climate zone, manufacturer and UA.

A modified version of the SUNDAY building simulation program which simulates duct and heat pump performance was used to model the thermal performance of each RCDP home as built and the same home as it would have been built without the SGC specifications (base case). Standard assumptions were used for thermostat setpoint, thermal mass, internal gains and infiltration rates. The only variations were UAs (based on the engineering calculations described above) and weather sites (which were assigned to match the sites on which the homes were located). The SUNDAY program calculated a predicted annual heating energy requirement for each RCDP and base case home. The difference between these two predictions was the energy savings. The results confirmed the pattern seen in the UA-only analysis. There was little difference in energy savings between manufacturers except where related to house size. Higher energy savings were found in the colder climate zones, 2 and 3, because larger energy requirements resulted in larger savings, given the same UA. The overall savings for RCDP homes was 51% for all homes--44% for homes with forced air furnaces and 71% for homes with heat pumps.

We applied a levelized cost factor to the present value of the entire SGC package over the life of each home to arrive at a cost-benefit ratio expressed in \$/kWh saved. The SGC package cost per manufacturer derived in an earlier report (Baylon, Lubliner & Davis, 1990) was converted to a present value retail cost using the following assumptions: a life expectancy of 45 years for all envelope measures except windows, 30 years for windows, 15 years for heat pumps, and an annual real discount rate of 3%. The levelized costs are shown in Table A.1.

Financial benefits to the consumer were calculated by comparing the cost of implementing the conservation measures to the savings in heating energy costs. For homes without heat pumps, the net first year cash flow is \$125 per year when the SGC incentive is taken into account. In the absence of the incentive, the consumer does not see a positive cash flow at current energy costs. Homes with heat pumps did not demonstrate a positive cash flow either with or without the incentive; however, cooling benefits and costs were not examined in this analysis.

Table A.1
SGC Conservation Package Savings

Climate Zone	Heating System Type	N	Average Annual kWh Savings	Average Present Value Retail Price (\$)	UA/ft² (living area)	Levelized Cost of Savings (\$/kWh)
1	Elect	60	6021	3851	.223	.027
	HP	24	10869	9327	.267	.036
2	Elect	51	7963	4552	.218	.025
	HP	8	12473	9716	.271	.032
3	Elect	5	11000	4916	.216	.019
	HP	0	--	--	--	--
ALL	Elect	116	6725	4205	.221	.026
	HP	32	11270	9425	.268	.035
TOTAL		148	7707	5330	.231	.028

SUNDAY simulations were used to assess individual conservation measures applied to a prototype building to determine the contribution of each measure to the cost-effectiveness of an entire package. We used a cost ceiling of 52 mills for all measures. Table A.2 shows the area-normalized cost and levelized cost of energy saved for each measure applied to the prototype.

Fifteen separate packages were analyzed using different combinations of conservation measures for each of the three climate zones. Although the inclusion of the heat pump saved substantially more energy than any other measure, it was not cost-effective in Climate Zones 1 and 2. Argon-filled windows were the preferred window option, producing twice the savings achieved by plain vinyl windows. Except in the coldest climates, attic and ceiling insulation optimized at about R-30, somewhat below the SGC specifications. The use of a cardboard baffle (which compresses insulation at the ceiling edges) improves cost-effectiveness, as does the use of blow-in insulation. For manufactured homes built using conventional floor construction methods, the optimum package uses an R-22 belly blanket and R-22 cavity insulation in Zones 2 and 3 and R-11 cavity insulation and R-11 belly blanket for heat pump cases. Using an improved floor insulation strategy (in which the floor insulation is cut in beneath the heating duct) improves floor insulation performance dramatically. Duct insulation is by far the most cost-effective option, increasing performance about 16% at a minimal cost, and should be a required part of SGC packages.

Table A.2
Conservation Options
for Cost Optimization

Component	Option	U-factor (Btu/hr-ft ²)	Cost (\$/ft ²)	Mills/kwh for Climate Zones		
				1	2	3
Window	Vinyl Frame	.45	10.82	39.9	29.3	25.2
	Argon Filled Vinyl Frame	.39	12.27	27.7	20.0	17.1
Wall	R-19	.062	.23	9.5	7.3	6.3
	R-22	.060	.31	46.1	32.8	28.1
Floor	R-11 Belly	.088	.09	5.2	3.9	3.4
	R-11 Belly, R-11 Cavity	.053	.35	9.7	7.8	6.8
	R-11 Belly, R-22 Cavity	.047	.61	37.5	28.8	24.9
	R-22 Belly, R-22 Cavity	.036	.87	53.6	34.0	28.7
	R-11 Cut In	.066	.09	4.9	3.7	3.2
	R-19 Cut In	.048	.28	10.5	7.7	6.6
	R-22 Cut In	.044	.35	19.7	14.5	12.5
	R-33 Cut In	.036	.61	38.6	27.8	23.9
Ceiling (Attic)	R-19 Batt	.055	.13	12.7	9.5	8.2
	R-30 Batt	.043	.40	24.3	18.2	15.6
	R-38 Batt	.040	.60	78.4	141.7	48.6
	R-49 Batt	.036	.88	82.0	148.2	124.3
	R-52 Batt	.035	.95	82.4	148.9	125.0
	R-49 Blown In	.026	.44	2.8	2.0	1.8
Ceiling (Vaulted)	R-19 Batt	.055	.13	12.7	9.5	8.2
	R-30 Batt	.043	.44	30.5	22.8	19.6
	R-38 Baffle	.041	.62	70.5	50.6	43.5
	R-38 Blown In	.035	.31	10.3	7.7	6.6
Ducts	R-4		31./home	1.77	1.16	1.01
	Sound*		10./home	0.77	0.52	0.45
Heating System	Heat Pump		5431/home	102.2	56.3	49.4

* Insulation on one side of duct only

1 Introduction

This report analyzes the simulated thermal performance and cost-effectiveness of conservation measures installed in manufactured homes built under the Residential Construction Demonstration Project (RCDP) Manufactured Homes Program sponsored by the Bonneville Power Administration (BPA). In 1988 and 1989, 150 homes were built under this project by 8 manufacturers located in Washington and Oregon. The homes were built using Super Good Cents (SGC) specifications adapted from the existing specifications for site-built homes. These specifications set performance standards for building envelope components (doors, windows, ceilings, floors and walls) and ventilation systems.

We used engineering calculations and simulations to estimate the effects of the SGC specifications on the thermal performance of the homes. These methods permit analysis of the effects of various measures. Thus, they can be used to evaluate alternative packages of measures with the goal of developing an optimum package containing the most cost effective and thermally efficient conservation measures which can be used in manufactured homes. Empirical data on actual energy use is not appropriate for this purpose because the effects of interaction between conservation measures and occupant behavior are masked. However, in a future study, we will use submetered data collected from these homes to refine and confirm the results of the engineering analysis.

1.1 Thermal Analysis

We used the standard parallel heat flow method (ASHRAE, 1989) to establish the heat loss U-factors for each building component. Some adjustments were necessary to the nominal U-factors to compensate for the actual methods used by the manufacturers to meet the specifications. A steady-state heat loss rate was determined for each home using the results of the component analysis and an assumed building infiltration rate. We used the SUNDAY building load analysis program to simulate the thermal performance of each home, using the heat loss rate and other parameters (heating and duct system description, thermostat setpoint, building mass, local climate data, etc.) as inputs. The version of SUNDAY we used is modified to take into account the impact of forced air heating systems and heat pumps. The SUNDAY simulation was run twice on each home, once for the home as built under the RCDP program and once for the same home in the absence of any SGC conservation options (base case). The difference between the two was the amount of energy saved.

1.2 Cost-Effectiveness

This report evaluates the cost-effectiveness of the various conservation measures by comparing the energy savings estimated in the thermal analysis with the standardized component costs developed in an earlier report (Baylon, Lubliner & Davis, 1990). Since the purpose of this analysis is to determine the most cost-effective conservation measures for manufactured homes--even if they were not used by manufacturers in this project--we also conducted an optimization analysis. This involved assessing individual conservation measures, sequentially installed in a prototype building, to determine the most cost-effective combination.

1.3 Report Organization

This report contains five sections. The first section introduces the report and summarizes the goals of the analysis. The second section discusses the methodologies used in both the thermal analysis and the cost-effectiveness analysis. The third section describes the U-factor corrections and evaluates the component conservation measures. The fourth section details the results of the simulation analysis and energy savings estimates. The fifth section documents the cost-effectiveness of the individual components and packages.

2 Methodology

2.1 Thermal Analysis

2.1.1 Heat Loss Analysis

Thermal analysis was based on a standard engineering method for determining parallel heat flow and thus total heat loss rate (U-factor). This method requires detailed evaluation of individual components based on drawings, direct observation of manufacturing techniques and reports from the manufacturers who participated in the program. The basic method is described in the 1989 ASHRAE Fundamentals Handbook, the SGC Heat Loss Reference Manual (Baylon and Heller, 1988) and other engineering texts.

The parallel heat flow method was applied to all components of the building envelope and individualized for each manufacturer. The methods used by manufacturers for insulating the ceilings and floors varied significantly from the assumptions and methodologies listed in the original SGC specifications. For these two components, we made substantial alterations in the nominal SGC U-factors to take into account the methods actually used by the manufacturers.

We generated two building heat loss rates for each home. One was a total conductive heat loss rate which ignored all equipment and duct effects in the floor system. The second was a modified heat loss rate which included a detailed correction for the heating duct systems as installed.

We also generated heat loss rates for each base case home. The base case home was identical to the RCDP home except it did not contain any of the SGC conservation measures. We determined the base case components and insulation levels using information on the basic model for each home provided by the manufacturers in response to the cost data questionnaires used in the previous report (Weakley, Eckert & Lee, 1990).

2.1.2 Engineering Simulations

We used the total building heat loss rate (UA) and the window, door and floor specifications as inputs to the building simulation program.

We used SUNDAY for the thermal simulations rather than WATTSUN, the standard tool used for performance assessments in the SGC program. SUNDAY is a numerical simulation program which uses local weather data to simulate the effect of climate on building heating requirements. WATTSUN is a simpler tool which uses an equation derived from numerous SUNDAY simulations to estimate thermal performance of a building. Since SUNDAY was the basis of WATTSUN, the results of both programs will agree (within the range of acceptable statistical error) given identical inputs. However, many important assumptions are built in to the WATTSUN program and cannot be changed to reflect actual conditions in a particular home. These assumptions include thermostat setpoint, occupant-induced heat gains and (to some extent) building size. Thus, SUNDAY is more flexible than WATTSUN in simulating equipment and permitting varied assumptions on building operating characteristics. Using SUNDAY will allow a better comparison to the data on submetered energy use, which will be analyzed in future reports on these homes.

SUNDAY simulations were done for each base case and RCDP home, using the same assumptions used in the WATTSUN runs: 65°F thermostat setpoint, 3000 Btu/hr of internal thermal gains, a mass level appropriate to light-frame construction and 0.35 Air Changes per Hour (ACH). Since we had no data on the orientation of the buildings, we used the same assumptions as the WATTSUN runs and divided the window area evenly among the four cardinal orientations (North, East, South and West). These assumptions will be revised once we have data on actual building configuration and operation from field investigations. We assumed the duct systems in the base case homes were identical in placement and sizing to those in the RCDP homes. The only differences were in insulation levels, window specifications and heating systems (for those homes in which heat pumps were installed as an SGC option).

The difference between the heating energy required by the base case and RCDP home was considered energy savings due to the SGC specifications. We also considered the impact of equipment on heat loss rate. Heat pump savings were calculated separately for the 32 homes in which heat pumps were installed as part of the SGC package.

2.2 Cost-Effectiveness Analysis

Cost-effectiveness was calculated using the BPA levelizing procedure for conservation programs (James, 1990). We used the following measure lifetime assumptions: a building life of 45 years, a 30 year life for windows, and a 15 year life for heat pumps. For windows and heat pumps, we estimated that a full cost replacement would occur as often as necessary to make them last as long as the building envelope (45 years). Thus we assumed that windows would be replaced with new windows at 30 years and the heat pump would be replaced twice, once at 15 years and again at 30 years. The entire cost stream was discounted to its present value with a 3% annual real discount rate.

2.2.1 RCDP Cost-Effectiveness

We computed a present value retail cost for the SGC package used for each RCDP home; this cost included adjustments for the replacement costs of heat pumps and windows. Thus the retail price of the conservation package escalated somewhat over the standardized package price calculated in the cost analysis report (Baylon, Lubliner & Davis, 1990). The present value package cost was then divided by the energy savings found in the SUNDAY analysis to generate an estimated cost of heating energy saved (in \$/kWh) for each home.

2.2.2 Optimum Conservation Package

To review the cost-effectiveness of each conservation measure, we developed five optimum cost-benefit packages which were evaluated separately. Two packages (one with a heat pump and one without) used the measures detailed in the SGC specifications and actually used by the manufacturers in the RCDP. Two packages (one with a heat pump and one without) used an alternative floor insulation strategy. Some RCDP packages included blow-in ceiling insulation. We reviewed this as a separate package for homes without heat pumps since the manufacturers that used blow-in ceiling insulation did not install heat pumps in their homes.

A typical manufactured home was selected from the database for use as a prototype base case home. We selected typical insulation levels using the information provided by the manufacturers. Using the component areas from the prototype home and the typical base insulation specifications, we derived an initial heat loss rate and ran a SUNDAY simulation to estimate the amount of energy required to heat the prototype. Then, each potential conservation measure was added to the prototype individually and an energy savings was derived by comparing the new estimate of energy used with the energy predicted in the base case. A cost-benefit ratio (\$/kWh) was calculated based on the present value cost and incremental energy savings of each measure. The most cost-effective measure was then added to the prototype to form a new base case. All the remaining options were then re-run against the "revised" prototype base case. This process was repeated with a cost-benefit ratio calculated for each successive measure to avoid double counting of savings. For those packages without heat pumps in the base case, the heat pump was added at that cost-benefit level where it competed with the other conservation measures.

The entire process was repeated using heat pumps as the base case heating system. A cost-benefit ratio was computed for each measure in the context of the reduced heating load caused by using the heat pump at the start.

2.3 Presentation of Analysis

The procedures described above were applied to each home. The detailed data derived from the Manufactured Homes Cost Data Collection database (Weakley, Eckert & Lee, 1990), SUNDAY runs and engineering analysis are contained in a working database. This report contains summaries of the results.

3 Thermal Analysis: Component Performance and Heat Loss Rates

The thermal analysis was conducted in two parts. During the first part, which is summarized in this section, we looked at both component performance and overall heat loss rates. This included reviewing and revising the UAs estimated by the WATTSUN runs. During the second part, we used the SUNDAY simulation program to predict the thermal performance of the homes. The following section, Section 4, describes the results of these simulations.

3.1 Component Performance

Buildings lose heat through walls, floors, ceilings, windows, doors and infiltration. SUNDAY uses the heat loss rates (U-factors) for each of these components to determine the overall heat loss rate (UA) of a building.

3.1.1 Windows

Four types of windows were used to meet the SGC specifications:

- 1) a vinyl frame window with a tested U-factor of 0.44;
- 2) an argon-filled, vinyl frame, double-glazed window with a tested U-factor of 0.39;
- 3) a thermally broken aluminum-frame window with low-E coating with a tested U-factor of 0.45;
- 4) an interior storm window added to the window already used by the manufacturers as their base case window specification, with a tested U-factor of 0.43.

The base case window was a non-thermally-broken aluminum frame window with a U-factor of 0.75. For some homes where heat pumps were used as part of the SGC qualification, this base case window was part of the SGC package.

The window U-factors used in this analysis were based on tests conducted by window manufacturers according to American Architectural Manufacturers Association (AAMA) standards.

3.1.2 Walls

Almost all walls were framed with 2x6 studs and insulated with R-19 or R-22 batts. There were two exceptions. In one case, an R-25 batt was crushed into a 2x6 wall and in another case, a strap wall was used in an effort to bring the R-factor to a higher level. We did a thermal analysis for this latter case but did not include this house in the cost-benefit analysis since we did not have sufficient data to establish the cost-effectiveness or even wholesale price of this measure.

The U-factors associated with the wall options were computed using a standard heat loss spreadsheet developed for the SGC Heat Loss Reference (Baylon & Heller, 1988). This spreadsheet accounts for all characteristics of the parallel heat flow in walls (framing fraction, insulation batt compression and construction components) and provides a reasonably accurate engineering value for the overall wall U-factor.

Using the parallel heat flow method described in the SGC reference manual and the SGC spreadsheet, we computed an overall U-factor of 0.062 for R-19 walls and a U-factor of 0.060 for R-22 walls.

3.1.3 Floors

Because of the construction methods used in manufactured homes, the floor was the most complex component in the analysis.

The RCDP homes are all double-wide manufactured homes which means they are made up of two sections each approximately 14 feet wide. Each section is constructed on a steel carriage which is used to transport the home down the highway and then serves as a foundation for the home.

In the plant, the steel structure is welded together and a layer of insulation called a belly blanket is stretched over the entire structure. Heating ducts, one per section, each running the full length of the house in the center of each section, are laid between the main steel I-beams on top of the belly blanket. Heat registers are cut into the tops of these ducts and boots are added as desired for individual rooms.

The floors are framed on top of the I-beams and the belly blanket. The floor is usually framed with 2x6 studs, although one manufacturer used 2x8s. In the base case construction, no floor joist insulation is added--the R-value of the belly blanket represents the total floor insulation value. In the base case, this blanket is either a 3-1/2 inch R-11 batt or a 2-1/2 inch R-7 batt. In about two thirds of the RCDP homes, additional insulation was added to the belly blanket. Figure 3.1 illustrates the typical floor construction of a manufactured home and the location of the insulation as installed.

The SGC specifications required an additional layer of insulation placed between the floor joists in the floor framing. However, the floor construction of manufactured homes differs considerably from site-built homes and the performance of these floors differs significantly from the steady-state performance assumed in SGC specifications. Manufactured homes use a forced-air heating system with supply ducts located between the floor joists and the belly blanket. One manufacturer (who built 29 homes) insulated

the ducts; however, in the rest of the cases, the ducts were not insulated. When uninsulated heating system ducts are located in the space between the belly blanket and the floor insulation, this space is actually maintained at a temperature very similar to the house temperature. As a result that portion of the floor insulation immediately above the duct is not effective in reducing the overall heat loss rate. A steady-state analysis would mistakenly give credit for the R-value of this floor insulation equal to the value of the insulation itself plus the appropriate parallel heat flow adjustments for surface films and framing.

Our analysis corrects the floor U-factor for the effect of the uninsulated ducts. We also corrected the floor U-factor to take into account the reduced value of the belly blanket where it is compressed by the steel structure against the bottom of the floor framing.

Corrections were made in three stages. First, we calculated a revised steady-state heat loss rate for each component of the floor insulation system. This was done using standard parallel heat flow methods that took into account the compression of the belly blanket and the insulation in the floor joists (where appropriate). Second, we used a duct simulation program to adjust the steady-state U-factor. Third, we used the revised steady-state U-factor and the duct effects as inputs to a SUNDAY simulation. The combined correction was then applied to all 150 homes.

The impact on floor U-factors is shown in Table 3.1. This table represents a reasonable approximation of the impact of the duct insulation on floor conductivity. The values shown here were calculated for a prototype manufactured home. (See section 5.3.1 for a discussion of this home and Appendix A for building plans.) The duct U-factors are calculated for the prototype house in Seattle (Climate Zone 1). The "SGC steady-state" U-factors were taken from the SGC specifications. As can be seen, the revisions in steady-state and duct-influenced U-factors result in an increase in the heat loss rate of the floor system above that which would be predicted using the nominal SGC U-factors.

Table 3.1 also includes the steady-state U-factor for an alternative floor insulation strategy in which the insulation is extended beneath the heating duct (the "cut-in" strategy). This strategy was assessed in the optimization analysis.

Table 3.1 Floor Heat Loss Rates (U-factors) (Btu/hr-ft²)					
Nominal Insulation R-Value		SGC Steady-state	Revised Steady-state	Corrected Unwrapped duct	Corrected R-4 duct insulation
Belly	Floor Joist				
7 11 22	0	.095 .081 .065	.098 .081 .063	.123 .100 .076	.107 .088 .068
7 11 22	11	.046 .041 --	.049 .045 .039	.079 .068 .062	.059 .053 .047
7 11 22	19	.036 .033 --	.039 .036 .031	.072 .061 .050	.050 .044 .038
7 11 22	22	.032 .030 --	.034 .032 .029	.068 .059 .048	.045 .041 .036
7 11 22	25	.030 .028 --	.032 .030 .027	.066 .058 .047	.043 .039 .034
11 19 22 33	Cut-in		.066 .048 .044 .037	.075 .054 .049 .041	.070 .050 .046 .038

3.1.4 Ceilings

Ceiling insulation values were derived using the standard heat loss method described in the SGC Reference Manual (Baylon & Heller, 1988) and associated spreadsheet, which were developed for site-built homes. While the spreadsheet was used to get an approximate value, some adjustments were necessary to account for the actual procedures used in the construction of manufactured homes.

There are two features of ceiling construction that are unique to manufactured homes. First, the absolute height of the structure is limited by the height of bridges and overpasses on the road systems which are used to transport the home to the building site. Thus, the slope of the roof and the amount of space between the truss cords is limited. Second, the trusses themselves are standardized and built largely to the same specifications used by all manufacturers.

The method by which insulation is installed varies from plant to plant. Two of the plants used blow-in insulation to fill the attic space. The SGC reference manual and spreadsheet was used to calculate U-factors for blown-in insulation since this method produces a fairly uniform insulation blanket which covers the truss cords as well as the area between the trusses. The remaining two-thirds of the homes in the sample, however, used fiberglass batts. This technique leaves an uninsulated slot over the trusses, thereby increasing the amount of ceiling area which has no insulation other than framing and wallboard. In addition, the batts must be placed to allow 1 inch of clearance for ventilation. One manufacturer achieved this by using a cardboard baffle, which compresses the batts at the edges below the roof sheathing. We corrected the ceiling U-factor to account for this compression. The other manufacturers ensured adequate ventilation by placing the batts in a stepped configuration (like stair steps). This meant an even larger correction must be made to account for the relatively large area of the attic where insulation is a fraction of the nominal total. Because of the dimensions of the truss in vaulted ceilings, there is less space available for the batts and the impact of staggering the batts on the overall ceiling U-factor is increased. These two ceiling insulation strategies are illustrated in Figures 3.2 and 3.3.

Table 3.2 shows the U-factor corrections made for flat and vaulted ceilings. These are compared to the values in the SGC specifications to illustrate the level of corrections that were necessary. Overall, these corrections amounted to a 10% to 15% increase in the amount of heat loss predicted by the SGC specifications.

Figure 3.2
Baffle Used in Ceiling Insulation Strategy

Cardboard Baffle
Min. 1" Air Space

Figure 3.3
Stepped Batt Ceiling Insulation Strategy

Min. 1" Air Space

Table 3.2 Ceiling Heat Loss Rates		
Flat Ceiling Standard Framing		
Nominal-R	SGC U-factor	Revised U-factor
19	.053	.055
22	.047	.051
25	.042	.050
30	.037	.043
33	.035	.042 *
38	.032	.040 **
45	.029	.038 ***
49	.027	.036 ***
Blow-in 49	.027	.029
* First 2 R-11 batts partially compressed, 3rd stacked ** First R-19 batt partially compressed, 2nd stacked *** First 2 batts crushed; last 2 batts stacked together		
Vaulted Ceiling		
Nominal-R	SGC U-factor	Revised U-factor
19	.054	.055
22	.048	.052
25	.044	.051
30	.039	.044
33	.037	.043 *
38	.035	.041 **
Blow-in 38	.031	.035
* First 2 R-11 batts partially compressed ** First R-19 batt compressed, second stacked		

3.1.5 Heat Pumps and Duct Systems

The RCDP program permitted the inclusion of heat pumps using an energy budget compliance approach. Only 32 of the homes in the sample used this approach.

Heat pumps were expected to have a minimum Heating System Performance Factor (HSPF) of 6.75. The heat pumps were manufactured by the Coleman Corporation and, for the most part, had performance ratings acceptable to the SGC program.

A modified version of the SUNDAY program was used to evaluate heat pump performance. We did not evaluate heat pump cooling energy use although in some of the climates where the heat pump was installed, a substantial cooling load might be expected, depending on occupant behavior.

We used the same program to simulate the duct system. The effect of the duct system and air distribution system were factored into a determination of heating system efficiency for homes with heat pumps and those with electric resistance furnaces. Duct losses were accounted for in two different ways:

- 1) Duct losses which resulted from uninsulated ducts located between the belly blanket and the floor insulation or from air leaks through the floor were used to correct and reduce floor insulation U-factors.
- 2) Duct losses due to infiltration were considered as a reduction in furnace efficiency and not in envelope performance. The heating systems in the manufactured homes consists of two continuous ducts tied together by a cross-over duct. The return side of the furnace is located in the utility room at one end of one side of the building. As a result, substantial differential pressure can be expected across the home, resulting in induced infiltration and air leakage from the warm supply duct to the outside.

The simulation procedures used to correct for heating system performance are explained in more detail in Section 4 of this report.

3.2 Overall Building Heat Loss Rate

Except for windows, the component heat loss rates derived from our analysis were higher than those calculated in the WATTSUN runs. Because of these differences, the overall building heat loss rate increased when compared with those from the WATTSUN runs. Since the results of the WATTSUN runs were never entered into the database, only a visual comparison was possible. A cursory review revealed an average 10% increase in overall heat loss rate. Even though the adjustments made in the floor and ceiling heat loss estimates increased the overall heat loss rate considerably, this increase was balanced by reductions in window U-factors. We used the tested U-factors for windows in our calculations, while the values used in the submittals were those supplied by the manufacturers and were over-estimated in some cases.

We calculated overall heat loss rates for each RCDP home and a corresponding base case home. In all cases, the base case was modelled as including the same window, door, wall, ceiling and floor areas as specified in the RCDP homes.

The Department of Housing and Urban Development (HUD) sets health, safety and energy efficiency standards for manufactured homes. The minimum insulation level is expressed as U_o (overall heat loss rate), which is determined by dividing the sum of the steady-state conductivities for all components (except infiltration) by the total building surface area. For the Pacific Northwest, HUD regulations mandate a U_o of 0.126 BTU/ft²-hr-°F.

Table 3.3 summarizes the most common nominal component R-values for the base case and RCDP homes. As can be seen, the most common strategy for meeting the SGC specifications in buildings without heat pumps was to use a window with an R-value of about 2.3 (U-factor of 0.43-0.45), an R-19 wall, an R-30 floor (belly blanket and cavity insulation combined) and an R-38 ceiling.

The individual manufacturers chose a variety of strategies to meet the SGC specifications but (with the exception of the heating system) there was little variation in results. Even with corrected floor and ceiling U-values, different packages of conservation measures resulted in similar heat loss rates. Three manufacturers used heat pumps for heating equipment and these homes required less insulation to meet the SGC specifications. Nevertheless, these manufacturers also upgraded the insulation in the homes they built (although only one of them upgraded the windows).

Table 3.3 Most Frequent Conservation Measures By Manufacturer (R-Values)									
	Window		Wall		Floor		Ceiling		RCDP Heating System*
Manufacturer	Base	RCDP	Base	RCDP	Base	RCDP	Base	RCDP	
1	1.33	1.33	11	19	11	22	21	38	HP
2	1.33	2.22	11	19	11	30	19	38	EF
3	1.33	2.08	11	19	11	33	14	38	EF
4	1.33	2.32	11	19	7	22	14	33	HP
5	1.33	1.33	11	19	7	30	14	33	HP
6	1.33	2.32	11	19	11	36	14	33	EF
7	1.33	2.08	11	22	7	33	19	49	EF
8	1.33	2.22	11	22	11	44	14	38	EF
* HP = Heat pump EF = Electric furnace									

3.2.1 SGC Compliance

Manufacturers used one of two paths for compliance with the SGC specifications: thermal performance and energy budget (heat pumps only). Most of the RCDP manufactured homes (79%) used the thermal performance standards.

Thermal Performance Compliance: The thermal performance path requires the calculation of a reference heat loss rate using the values specified in Table 3.4. A reference heat loss uses assumed values for floor, wall and ceiling areas and assumes a window area equal to 15% of the heated floor area.

Table 3.4 Component Heat Loss by Climate Zone						
Component	Zone 1		Zone 2		Zone 3	
	U-factor	R-value	U-factor	R-value	U-factor	R-value
Wall	.057	19	.043	24	.040	26
Floors	.029	33	.029	33	.029	33
Windows	.39	2.32	.39	2.32	.39	2.32
Doors	.19	5.2	.19	5.2	.19	5.2
Ceilings	.032	38	.032	38	.021	49

Energy Budget Compliance: The energy budget path uses the reference heat loss values as inputs to a WATTSUN simulation which predicts the heating energy required by the proposed home in the climate where it is to be located. The proposed home is then modelled using the WATTSUN program and including a heat pump. The heat pump produces more heat per kWh of input energy and thus offsets the heating requirement. As a result, the manufacturer can produce a home which requires less insulation or has additional glazing than a similar home with electric resistance heat.

The insulation packages used in the RCDP program generally did not meet the nominal U-factors used to compute the reference building heat loss rate. To compensate, the manufacturers reduced the amount of window area below the 15% anticipated in the SGC specifications. This gave them more flexibility with the component values used to meet the SGC specifications. Table 3.5 summarizes the window areas used in the RCDP manufactured homes.

Table 3.5 Average Window Areas				
Climate Zone	Electric Furnace		Heat Pump	
	Area	% of Floor Area	Area	% of Floor Area
1	145	10.2	178	11.0
2	153	9.8	214	12.8
3	161	9.6	--	--

A review of the WATTSUN compliance runs indicated that most manufacturers were within 1% of the reference heat loss when using the thermal performance path. As a result, the homes complying under this path did not meet the compliance standards when the corrected U-factors for ceilings and floors were used.

The homes complying using the energy budget approach generally exceeded the standards by more than 10% and thus would have complied without major changes in reference heat loss values.

3.2.2 Heat Loss Rates

These RCDP homes achieved substantial reductions in heat loss rate over the heat loss rates estimated for the same homes using the standard (base) insulation packages provided by the manufacturers.

Table 3.6 summarizes the reduction in overall heat loss rate and illustrates the impact of the heat pump compliance path on the conservation program. Homes which used conventional electric furnaces show a 35% reduction in total UA, while homes which use heat pumps have a 25% reduction. All R-values and U-factors used in these calculations are steady-state and do not take into account furnace efficiency, duct losses or corrections to the floor insulation due to duct placement.

The U_o value is equal to the UA (minus the infiltration heat loss) divided by the surface area of the house and is used to compensate for differences in average house size among manufacturers and thus facilitate comparison of thermal performance.

Table 3.6 Average Heat Loss Rates By Manufacturer (Btu/hr)									
		Base		RCDP with ER			RCDP with HP		
Manu- facturer	Avg Area	UA	U _o	UA	U _o	% UA Re- duction	UA	U _o	% UA Re- duction
1	1742	588	.102	--	--	--	482	.080	19.1
2	1550	522	.101	341	.061	33.0	415	.074	24.3
3	1519	503	.098	349	.062	30.8	--	--	--
4	1387	482	.108	324	.061	35.1	308	.068	33.7
5	1559	563	.110	306	.060	38.2	453	.080	24.3
6	1268	451	.105	266	.055	41.2	--	--	--
7	1632	549	.107	363	.063	33.8	464	.070	33.7
8	1478	519	.103	319	.057	38.6	--	--	--
ALL	1576	527	.104	327	.059	35.8	436	.077	25.2

The impact of the SGC specifications was similar across manufacturers. The only significant difference between the base case and RCDP homes occurs for homes with heat pumps. UA changes were about 10% less for heat pump homes. All other differences were not significant, despite the fact that a more stringent code was enforced in climate zones 2 and 3.

The differences between manufacturers in overall heat loss rates can be explained almost entirely by the size of the homes. Manufacturer #6, for example, had the smallest homes in the sample and as a result lower heat loss rates compared to the other manufacturers. Furthermore, this manufacturer had a 12% lower ratio between glass and floor area than the overall average.

Since the SGC compliance requirements were more stringent for Zone 2 and Zone 3 climates, a summary of UA by climate should reveal a reduced UA. This did not occur as shown in Table 3.7.

<p align="center">Table 3.7 Average Heat Loss Rates by Climate Zone</p>								
	Base		RCDP with ER			RCDP with HP		
Zone	UA	Uo	UA	Uo	% UA Re- duction	UA	Uo	% UA Re- duction
1	517	.105	319	.060	36.2	430	.077	26.1
2	537	.102	339	.059	35.5	453	.078	22.6
3	556	.100	366	.059	34.8	--	--	--

While the total heat loss rate increases with climate zone, the Uo does not. The slight downward trend is not statistically significant although it is consistent with values which might be expected from the SGC specifications.

To examine the determinants of heat loss rates among manufacturers, we conducted a regression analysis using UA as a dependent variable. When overall floor area was used as a predictor of the UA for the RCDP homes (controlling for heating system), the model explained 92% of the variance. The addition of other independent variables (manufacturer and climate zone) did not have a significant impact on the regression or the overall R^2 . When the Uo is used as a dependent variable, the combination of climate zone and manufacturer explains about 34% of the variance in Uo. Climate zone by itself, however, does not have a significant relationship with Uo or UA.

Figure 3.3 shows the range of home sizes by manufacturer. The variation in sizes remains significant throughout the thermal analysis as the major determinant of overall performance.

Figure 3.3
Home Size by Manufacturer

4 Thermal Performance: Energy Savings

The thermal performance of the RCDP homes was estimated by running a thermal simulation of each home as built and on the same home as it would have been built without the SGC specifications (base case). To define the base case home, we used the dimensions of the home as built, the components provided by the manufacturers in their basic model homes and the insulation levels specified by the manufacturers to comply with Housing and Urban Development (HUD) regulations for manufactured homes. Although consumers may request changes which affect the energy efficiency of the homes they purchase, we did not use consumer preference as a basis for our savings estimates in this report since it is not standardized or predictable.

4.1 Simulation Assumptions

Several assumptions are necessary to produce a thermal simulation. These assumptions are all linked to occupant behavior or field performance and not to building heat loss rate and heating system type.

The thermal simulation program requires inputs of thermal mass, thermostat setpoints, internal gains and infiltration rates. We used the same values which were used in the WATTSUN program. These included a thermostat setpoint of 65°F, a thermal mass assuming light-frame construction, 3,000 Btu/hr of internal gains, and an infiltration rate of 0.35 ACH.

In real life, these variables are affected by the occupant's life style. By standardizing them to particular values, the underlying impact of the SGC specifications on performance can be determined. However, since particular occupants might interact with their homes in different ways, the relationship between the simulation results and the actual heating requirements may be quite poor. In later phases of this study, data collected during field tests will be used to refine the simulation results.

4.2 Weather Sites

The SUNDAY simulation uses weather data from 33 sites throughout the Northwest region to simulate the weather in each locality. These sites correspond to the weather stations used by the WATTSUN program.

A weather site was assigned to each RCDP home based on the address of the final location of the home. This weather site was allocated based on the geographic and climatic proximity of the site to one of the SUNDAY sites. Table 4.1 lists the 16 weather sites used in the analysis and the number of homes assigned to each of these sites.

In addition, we identified the climate zone of each home based on the degree days at those sites. Sites with less than 6,000 degree days were considered to be in Climate Zone 1, sites with 6,000 to 8,000 degree days were in Zone 2, and sites with over 8,000 degree days were assigned to Zone 3. These assignments varied somewhat from the climate zones used in the WATTSUN simulations. For example, the Republic site in northeast Washington was considered Zone 2 for the WATTSUN run. It is, in fact, a Zone 3 site by our definition. Similarly, Yakima was defined as a Zone 1 site but was in fact a Zone 2 site. As a result, several homes assigned to these weather sites were reclassified to ensure that the climate zone variable could be used in the performance analysis. In all cases, we summarized the data using our zone designations.

Table 4.1 Weather Sites (Number of Homes)			
SUNDAY Weather Station	Climate Zone 1	Climate Zone 2	Climate Zone 3
Astoria, OR	4		
Bellingham, WA	6		
Kalispell, MT			1
Lewiston, ID	1		
Newport, OR	2		
Olympia, WA	20		
Pendleton, OR	1		
Portland, OR	5		
Redmond, OR		20	
Republic, WA			4
Richland, WA	2		
Salem, OR	2		
Seattle, WA	35		
Spokane, WA		14	
Whidbey Island, WA	6		
Yakima, WA		25	
TOTAL	84	59	5

4.3 Heating Systems

The SUNDAY program has been enhanced to include a direct simulation of ducts and heating systems, especially heat pumps. These modifications were developed using the work of Palmiter and Kennedy (1983), Robison (1988), Modera (1988) and Kennedy (1990). The enhanced program takes into account the principal factors of duct performance: duct leakage from the supply and return ducts into the buffer space, heat conductivity from the supply ducts into the buffer space, and induced infiltration brought on by differential pressure across the envelope as a result of supply air being delivered at a substantial distance from the furnace.

The main duct losses associated with the manufactured home floor system are caused by conductivity and leakage in the buffer space between the belly blanket and the floor structure. These effects reduce the nominal R-value of floor insulation, and hence, increase the U-factors as can be seen in Table 3.1. The impact of the duct losses on the total floor is much less when there is no insulation between the duct and the floor, as is the case in the base case insulation strategies. We elected to account for the extra losses associated with the supply duct system as a reduction in the effective U-factor of the floor, since the same insulation could be installed within the floor system in such a way as to minimize this effect. The thermal losses associated with induced infiltration were translated into reduced furnace efficiency, although some proportion of the supply duct losses could be counted as reduced furnace efficiency.

We used the actual capacity of the heating system and the specifications for the floor to determine the mass flows and cycle times of the air handler operation. The standard ASHRAE bin method was used to determine the duty cycle of the furnace and the temperature of the duct system. A full discussion of this simulation technique is contained in Kennedy (1990).

One manufacturer insulated the full length of all the ducts in the floor system. As a result this manufacturer was not as heavily penalized in performance of floor systems as the others, who used mostly uninsulated ducts. This is significant since this manufacturer also produced approximately 60% of all the RCDP homes with heat pumps, thus enhancing the performance of the heat pumps and the energy savings associated with them.

Another manufacturer used a longitudinal floor joist system so that the joists ran parallel to the underlying I-beam. This allowed the ducts to be placed inside the floor cavity so they were not insulated from the home. In this case, the ducts performed much better than in cases where the ducts were below the floor joist insulation.

In the remaining cases, the ducts were located below the floor structure but above the belly blanket and thus duct losses were contained within this buffer area.

We simulated both types of heating systems used in the manufactured homes. For electric resistance furnaces, we assumed that the furnaces themselves were 100% efficient and that all inefficiencies resulted from duct losses and induced infiltration.

For this analysis, an adjusted HSPF was calculated across the entire range of thermal loads. We simulated heat pumps using the specifications provided by the heat pump manufacturer, including HSPF and rated Coefficient of Performance (COP). These values are determined by standard tests throughout the industry (ARI, 1989). Since heat pump performance varies substantially with outdoor temperature and load, each home was simulated with the heat pump to get an estimate of performance. The heat pump performance was calculated using the bin method for each point over the range of temperatures contained in the SUNDAY weather file. The adjusted HSPF differed appreciably from the published HSPF. Nevertheless, since the simulation uses the actual temperatures for the site on which the home is located, this estimate of performance should be much more accurate than the general HSPF published by the manufacturer. In fact, since the standard rating assumes a climate harsher than most of the climates in Washington and Oregon, the performance of the heat pump is enhanced by using this simulation.

The difficulty here is that the simulation assumes that the heat pump is operating properly with minimum setbacks and duty cycles appropriate to the outside temperature and a fixed thermostat setpoint. If the occupant insists on large night setbacks--which force the heat pump into a substantial warm-up cycle in the morning--the heat pump will operate the resistance coils and the system will function very much like an electric resistance heater. This mode of operation could account for a substantial portion of the heat load of the building during the heating season. In these circumstances, the apparent efficiency of the system would be better described as an electric resistance furnace than as a heat pump. In the absence of any direct evidence about how these buildings are operated, we assumed that the heat pump was operated appropriately to ensure its maximum efficiency. When field data have been collected and reviewed, this assumption will be evaluated.

4.4 Results

Table 4.2 summarizes the results of the thermal simulation estimates. These runs use the same standard assumptions; the only variables are UA, weather site and heating system type.

The variation between manufacturers remains minimal except insofar as some manufacturers produced smaller or larger homes than average. Variation by climate zone is a function of the colder temperatures in Zones 2 and 3--larger energy requirements result in larger potential savings, given the same UA. As we have already seen, the variation in UA between climate zones is not significant. In this evaluation of energy savings, climate zone is a good predictor, although savings are largely due to changes in heat loss and the use of heat pumps.

The SUNDAY evaluation confirmed the pattern seen in the UA-only analysis. The homes of Manufacturer #6 were more energy-efficient than the average, largely because of the reduced glass area, and the homes of Manufacturer #5 were more efficient than the average, largely because of the insulated ducts and thus more effective floor insulation.

Savings from duct insulation and the resulting improved floor insulation performance are estimated at 1000 kWh/year in the RCDP homes, as shown in Appendix B. This represents an increase in savings of 10-20% in homes without heat pumps.

Table 4.2 Simulated Heating Energy Performance and Savings (Average Values)											
		Base		RCDP (Electric Resistance)				RCDP (Heat Pump)			
Zone	N	kWh	kWh/ft ²	N	kWh	kWh/ft ²	Savings (kWh)	N	kWh	kWh/ft ²	Savings (kWh)
1	84	12513	8.4	60	5544	3.8	6021	24	4014	2.5	10869
2	59	17952	11.3	51	9823	6.2	7963	8	6538	3.9	12473
3	5	26278	15.7	5	15278	9.1	11000	0	--	--	--
ALL	148	15146	9.80	116	7845	5.1	7089	32	4645	2.8	11270

The overall savings for the RCDP homes is approximately 51% for both heating system types. Savings of 44% on average were achieved for the systems using forced air furnaces and 71% for heat pumps.

While various manufacturers used different combinations of components to comply with the SGC specifications, the net effect on building performance was very similar across manufacturers. To illustrate this point, we used a regression and a 2-way analysis of variance to analyze the relationship between overall heating performance, climate zone and floor area for homes with electric resistance furnaces. The results achieved an R-square of 0.95, indicating that less than 5% of the remaining variance in performance was not explained by climate zone and floor area. In the case of heat pumps, the relationship was not as strong, since the heat pump performance is partly a function of individual climates and variations in heat pump size were requested by the consumer. Nevertheless the R-square of this regression was 0.84, suggesting that less than 16% of the variance could be explained by all other factors including heat pump sizing and performance. When the manufacturer is added as a variable to this model, the correlation does not improve.

Variations in performance and savings estimates among manufacturers were not statistically significant even after controlling for climate and floor area. Table 4.3 compares savings and building size by manufacturer.

Table 4.3 Simulated Annual Energy Savings by Manufacturer				
Manufacturer	Electric Resistance (kWh)	Average House Size (ft ²)	Heat Pump (kWh)	Average House Size (ft ²)
1			11036	1742
2	6546	1547	10990	1567
3	5519	1519		
4	6021	1493	9100	1280
5	7424	1390	11400	1648
6	6437	1268		
7	8273	1594	13414	1884
8	7997	1479		

Taken as a whole, the thermal performance of RCDP homes in this project represents a significant improvement over the base case manufactured homes. While the specifications need some refinement, the initial engineering review of these homes suggests savings in electricity used for heating in excess of 50%. This is largely due to the base case R-value specifications for these products, which are dramatically below the standards set by either the Washington or Oregon state energy codes and below any current practice in site-built homes. However, once the SGC specifications are applied to these homes, performance at the same level as, or better than, site-built homes with similar specifications might be anticipated.

5 Cost-Effectiveness

To establish the cost-effectiveness of the SGC specifications for manufactured homes, we used a two-part process. First, we applied a levelized cost factor to the present value of the entire package over the life of each home to arrive at a cost-benefit ratio expressed in \$/kWh saved. Then, by estimating the cost-effectiveness of each potential conservation measure when applied to a prototypical manufactured home in each climate zone, we identified optimum packages of conservation measures.

The cost-benefit analysis is based on data from 149 of the 150 RCDP manufactured homes; one home was eliminated from the sample due to an unusual wall-framing technique.

5.1 Assumptions and Life Cycle Cost Adjustments

BPA (James, 1990) provided us with standard assumptions to determine the cost-effectiveness of conservation measures applied to manufactured homes. These are:

- 1) a life expectancy of 45 years for all envelope measures, except windows
- 2) a life expectancy of 30 years for windows,
- 3) a life expectancy of 15 years for heat pumps,
- 4) an annual real discount rate of 3%,
- 5) 52 mills/kWh avoided cost of electricity.

To ensure that all conservation measures last for the full economic life of the manufactured home, we assumed that the entire incremental heat pump cost is incurred (outdoor unit and indoor coil) at 15 years and again at 30 years, at the full cost discounted to present value. No additional maintenance costs were included. While this is probably a simplification, the replacement cost could be considered the cost of maintaining a heat pump in working order over the life of the building. We assumed that the windows will be replaced at the same incremental cost as the initial windows and thus all window prices were adjusted to account for replacement at the end of 30 years.

5.2 Cost-Benefit Analysis

5.2.1 Package Costs

For the first step in cost-benefit analysis, we computed the price of the SGC package for each home built under RCDP.

Table 5.1 summarizes the reported and standardized wholesale costs and the standardized and present value retail costs of the SGC package. The reported wholesale costs were those costs provided by the manufacturers and summarized in the cost analysis report (Baylon, Lubliner & Davis, 1990). These costs were then standardized to compensate for variations in the wholesale pricing policies of different manufacturers by computing a median mark-up for each component and multiplying this by the cost of materials to produce a standardized wholesale cost. The standardized wholesale component costs were summed to get a standardized wholesale package cost. The standardized retail cost is the standardized wholesale cost multiplied by a standardized dealer mark-up. The present value retail cost reflects the adjustment in costs for replacing heat pumps and windows during the life of the home.

Table 5.1 SGC Package Prices (\$/home)								
Manufacturer	Manufacturers Wholesale		Standardized Wholesale		Standardized Retail		Present Value Retail	
	Elec	HP	Elec	HP	Elec	HP	Elec	HP
1		4291		4702		5132		8578
2	3096	4720	2954	5512	3841	6185	4344	10044
3	2343		3126		4064		4777	
4	2617	4747	2073	5248	2694	5733	2861	9241
5	3217	5438	2532	5066	3292	5432	3482	8697
6	2431		2071		2693		2869	
7	3518	6469	3839	7907	4991	9623	5797	14461
8	3401		2805		3646		4114	
ALL	3088	5244	2864	5355	3724	5892	4205	9425

Once heating systems are included, the variance in price is largely explained by the size of the home and window area. Climate zone is also significant in determining the final price of the packages. This suggests that manufacturers did attempt to respond to the SGC requirements with higher nominal insulation values, but the corrections made to the floor and ceiling U-factors mask these differences.

5.2.2 Cost-Benefit

SGC package savings were analyzed in Section 4 of this report. The savings are computed as a difference between energy used in the RCDP and base case home. The savings estimates are largely a function of U-factor, climate zone and heating system types.

Table 5.2 summarizes the results of the cost analysis and the savings analysis and derives a cost per kWh saved.

There is a large difference between buildings with heat pump systems and buildings with conventional electric furnaces. This difference is consistent across all zones, although we have no cases where heat pumps were used in Zone 3. Furthermore, the cost of the heat pump drives up the cost of energy saved by almost 25% even though it results in a 60% increase in energy savings. The increased cost for heat pump packages reflects the relatively high life cycle cost associated with replacing the heat pump during the life of the home.

Table 5.2 SGC Conservation Package Savings						
Climate Zone	Heating System Type	N	Average Annual kWh Savings	Average Present Value Retail Price (\$)	UA/ft ² (living area)	Levelized Cost of Savings (\$/kWh)
1	Elect	60	6021	3851	.223	.027
	HP	24	10869	9327	.267	.036
2	Elect	51	7963	4552	.218	.025
	HP	8	12473	9716	.271	.032
3	Elect	5	11000	4916	.216	.019
	HP	0	--	--	--	--
ALL	Elect	116	6725	4205	.221	.026
	HP	32	11270	9425	.268	.035
TOTAL		148	7707	5330	.231	.028

Table 5.2 shows the UA per square foot of living space for each zone by heating system. This table illustrates the similarity in performance of homes in this sample across all climate zones. The average U-factor per square foot in Climate Zone 3 is only 5% below the average in Climate Zone 1. As a result of this, conservation in Zone 3 is considerably more cost-effective, since the same measures applied in a colder climate offer a larger potential savings. This also indicates that more marginal measures would have been cost-effective in this climate zone since the packages that were used reduced the life cycle cost of conservation by almost 30% from the cost for Zone 1. On average, the UA/ft² for these homes is about 10% above the SGC reference heat loss.

Taking the region as a whole, the levelized cost per kWh of saved energy is 28 mills. For packages with electric resistance furnaces, this average is 26 mills; for packages with heat pumps the average is 35 mills. These levelized costs are based on the standardized retail cost to the consumer, taking into account (where appropriate) the cost of replacing windows and heat pumps.

5.2.3 Consumer Benefits

Another way to look at the SGC package cost is to construct a consumer scenario in which the consumer borrows on a 20 year note at 13% interest. Table 5.3 summarizes these results.

Financing the cost of the SGC package without the BPA subsidy results in a negative cash flow during the first year. With the subsidy, the first year cash flow is positive for electric resistance homes in all zones. Heat pumps only exhibit a positive cash flow in Zone 2. This suggests that the cost-effectiveness of the heat pump option is less attractive than the envelope measures, particularly in Climate Zone 1.

Table 5.3 Consumer Cash Flow SGC Packages (Year One Averages)			
Climate Zone	Heating System	No Incentive	SGC Incentive
1	Electric	-207	78
	Heat Pump	-324	-39
2	Electric	-195	161
	Heat Pump	-265	91
3	Electric	-101	326
	Heat Pump	--	--
ALL	Electric	-197	125
	Heat Pump	-309	-7

The assumptions used to generate this table include a cash flow based on an annualized (levelized) payment on a 20 year loan at 13% interest (consistent with the current rates offered by local financial institutions) and a regional average cost for electricity of 47 mills. Package costs include only the first cost of the individual measures and do not take into account maintenance costs or tax benefits that might accrue from interest payments. With SGC subsidies, even without optimization of the cost-benefit ratio of the SGC package, the manufactured home buyer will see a positive cash flow despite a relatively short loan life and high interest rate.

5.3 Optimum Conservation Packages

In addition to evaluating the cost-effectiveness of the SGC packages as applied to the RCDP homes, we identified optimum conservation strategies for these homes using an optimization analysis. For all components but floors, this analysis included energy conservation measures that were used by manufacturers during the RCDP. These measures were assigned costs as determined by the standardized cost analysis and were assigned U-factors as discussed in Section 3 of this report.

5.3.1 Optimization Assumptions

Optimization is a cost-benefit analysis in which individual conservation measures are assessed separately to determine their contribution to the cost-effectiveness of an entire package. Optimum packages were developed using a cost ceiling of 52 mills for all measures. We used a SUNDAY-based optimization program similar to that developed for the conservation supply curve (Palmiter and Baylon, 1982) to calculate actual performance. The SUNDAY runs were conducted using a series of component upgrades applied to a base building.

The base building is described in Table 5.4 and reflects the average size manufactured home from the database. To make the evaluation more realistic, we used specifications from a home in the database. The plans and construction for this prototype manufactured home are shown in Appendix A.

Table 5.4 Base Case Assumptions		
	Area (ft ²)	Nominal Values R- and U-Factors
Windows	150	U = .75 Btu/°F-hr
Walls	1056	R-11 (2x6 framing), U = .088
Floors	1493	R-7 (Belly blanket only), U = .097
Ceilings, Flat	747	R-14, U = .066
Ceilings, Vaulted*	756	R-14, U = .066
Doors	40	U = .19 Btu/°F-hr
Infiltration	(11750)	.35 ACH
Thermostat Setting	65°F	
Mass	Light frame	
Internal Gains	3,000 Btu/hr	
Heating System	Electric resistance furnace	
* Adjusted for ceiling slope		

The optimization procedure uses the SUNDAY program to predict the thermal performance of the base case building and then assess the impact of individual component upgrades. This is done by running the SUNDAY simulation on the base case building with the base assumptions, then adding each possible conservation option individually. Each run generates an estimate of the diminished heating energy requirements obtained with successive conservation measures.

Table 5.5 shows the levelized cost for each measure included in the basic package of options for optimization in each climate zone. To correctly determine the effect of mutually exclusive options, we did separate optimizations in these cases. For example, conventional floor construction was optimized independently of non-conventional floor construction. Blown-in attic insulation was applied by only two manufacturers and indeed most manufacturers did not have the equipment available for this technology. Thus, blow-in ceiling insulation was optimized separately from batt insulation. The heat pump was included in each optimization as one of the possible conservation measures. However, since many manufacturers chose the heat pump option as a marketing strategy, we also did two optimization runs using the heat pump as the base case heating system. The levelized costs included in Table 5.5 are from runs in which heat pumps were not included.

The optimization process moves each option into the optimization individually. It then selects the most cost-effective option against the base case. This option is entered as the first on the list and also included again in the "revised" base case and the entire process is repeated until all the options have been added in the order of their cost-effectiveness. The individual conservation assessment of each option is based on the new UA (heat loss rate) and characteristics of the building after its addition. The savings computed for each option are corrected for the non-linear relationship between heat loss rate and overall performance, thus preventing double-counting.

All optimization runs were redone for each climate zone. Weather data from Seattle, Washington was used to characterize Climate Zone 1, Spokane, Washington for Zone 2, and Missoula, Montana for Zone 3.

Figure 5.1 illustrates the process for one particular optimization run (Climate Zone 1, RCDP insulation strategies, no blow-in ceiling insulation). The summary table shows:

1. UA	The overall heat loss rate of the home after the particular conservation measure is applied.
2. kWh	The simulated heat energy requirements after the particular conservation measure is applied.
3. dkWh	The savings in heat energy resulting from the application of the particular conservation measure.
4. dCost	The cost of the particular conservation measure.
5. mills	The cost-benefit ratio for the particular conservation measure in \$/1000 kWh.

The base case assumptions are included at the top of the figure including the base heat loss rate (UA) and annual heat energy requirement in kWh.

Figure 5.1 Sample Optimization Output						
Marginal Cost Analysis for Climate Zone 1 Basic Run						
Location: SEATTLE, WASHINGTON						
Base Case UA - 534.4						
Base Case annual heating kWh - 14034						
Base Case Component Specifications & Nominal R-Values						
HEATING SYSTEM: Electric Resistance DUCT Unwrapped INFILTRATION 0.35 ACH DOOR R-5 WALL R-11 WINDOW R-1.33 FLOOR R-0 joist/R-7 belly blanket ATTIC R-14 VAULT R-14						
Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	13502	532.2	10	0.77
DUCT	R4	534.41	13015	487.0	21	1.76
SPECFLR	R0/R11	509.75	11969	1045.9	134	5.24
WALL	R19	482.26	10924	1044.7	243	9.49
SPECFLR	R11/R11	427.51	9282	1642.1	388	9.65
ATTIC	R19	419.19	8965	316.9	98	12.66
VAULT	R19	410.88	8650	315.6	98	12.71
ATTIC	R30	401.79	8306	343.4	204	24.26
VAULT	R30	393.47	7993	313.1	234	30.55
SPECFLR	R22/R11	379.18	7570	422.8	388	37.48
WINDOW	VINYL	333.96	5909	1661.4	1623	39.87
WINDOW	ARGON	324.99	5588	320.8	218	27.68
WALL	R22	322.87	5513	75.3	84	45.82
SPECFLR	R22/R22	317.11	5217	295.6	388	53.59
VAULT	R38BAF	314.85	5139	78.8	136	70.47
ATTIC	R38	312.58	5060	78.7	151	78.40
ATTIC	R49	309.56	4954	105.4	212	82.00
ATTIC	R52	308.81	4928	26.2	53	82.44
SYSTEM	HEATPUMP	308.81	2303	2625.6	6572	102.17

Table 5.5
Conservation Options
for Cost Optimization

Component	Option	U- factor (BTU/ hr-ft ²)	Cost (\$/ft ²)	Mills/kwH for Climate Zones		
				1	2	3
Window	Vinyl Frame	.45	10.82	39.9	29.3	25.2
	Argon Filled Vinyl Frame	.39	12.27	27.7	20.0	17.1
Wall	R-19	.062	.23	9.5	7.3	6.3
	R-22	.060	.31	46.1	32.8	28.1
Floor	R-11 Belly	.088	.09	5.2	3.9	3.4
	R-11 Belly, R-11 Cavity	.053	.35	9.7	7.8	6.8
	R-11 Belly, R-22 Cavity	.047	.61	37.5	28.8	24.9
	R-22 Belly, R-22 Cavity	.036	.87	53.6	34.0	28.7
	R-11 Cut In	.066	.09	4.9	3.7	3.2
	R-19 Cut In	.048	.28	10.5	7.7	6.6
	R-22 Cut In	.044	.35	19.7	14.5	12.5
	R-33 Cut In	.036	.61	38.6	27.8	23.9
Ceiling (Attic)	R-19 Batt	.055	.13	12.7	9.5	8.2
	R-30 Batt	.043	.40	24.3	18.2	15.6
	R-38 Batt	.040	.60	78.4	141.7	48.6
	R-49 Batt	.036	.88	82.0	148.2	124.3
	R-52 Batt	.035	.95	82.4	148.9	125.0
	R-49 Blown In	.026	.44	2.8	2.0	1.8
Ceiling (Vaulted)	R-19 Batt	.055	.13	12.7	9.5	8.2
	R-30 Batt	.043	.44	30.5	22.8	19.6
	R-38 Baffle	.041	.62	70.5	50.6	43.5
	R-38 Blown In	.035	.31	10.3	7.7	6.6
Ducts	R-4		31./home	1.77	1.16	1.01
	Sound*		10./home	0.77	0.52	0.45
Heating System	Heat Pump		5431./home	102.2	56.3	49.4
* Insulation on one side of duct only						

5.3.2 Results

We conducted fifteen separate optimization runs using different combinations of conservation measures for each of three climate zones. These optimizations are separately documented in Appendix B. The results of optimization are summarized in Table 5.6 and 5.7 for packages where the individual optimum components are documented.

Several packages which included the heat pump in the base case saved substantially more energy than the other packages in every case but Zone 3. In Zone 3, the heat pump was an optimum conservation measure when applied to the base case and since it entered the package as the least cost-effective option, all of the available conservation upgrades were included in the optimum package. As a result, when the heat pump option is used in the base case from the start, the more expensive conservation measures such as window conservation measures are eliminated from the optimum conservation package. This pattern is repeated in all climates but only in Zone 3 is the result a lower energy savings total.

For manufactured homes built using conventional floor construction methods, the optimum package uses an R-22 belly blanket and R-22 cavity insulation in Zones 2 and 3 and R-11 cavity insulation and an R-11 belly blanket for the heat pump cases. When the optimization is re-run using an improved floor system (with belly insulation cut in to the first I-beam and no floor joist insulation over the duct) a substantial improvement in the U-factor occurs. This revision gives R-33 floors which outperform the conventional R-44 floors included in the first optimization.

Duct insulation is by far the most cost-effective option available to the manufactured home builders. Duct insulation is included in all the optimizations and thus duct losses which cause substantial reduction in the U-factor have been eliminated from the optimization. A quick review of the floor U-factors in Table 3.2 shows that without this assumption, the improved floor systems would be substantially less effective. The cost-effectiveness of duct insulation suggests that it should be a required part of SGC packages.

Separate runs were conducted for the blow-in insulation in the attics since only two plants have the capability of using this type of insulation. This option results in similar conservation levels for ceilings at a much lower cost than batt insulation.

We assumed that manufacturers using fiberglass batts would set the batts away from the edge of the ceiling to preserve ceiling ventilation. However, one manufacturer uses a cardboard baffle which allows him to place the batts over the entire width of the ceiling and push the batt down to preserve the ventilation space at the edge. This makes a substantial difference in the U-factor and becomes an optimum method for achieving insulation when R-values above R-30 are used.

The optimization was run using wall insulation strategies that had 2x6 wall construction as part of the base case. Thus the additional wall insulation is extremely cost-effective in all cases. In some of the colder climates, R-22 walls are more cost-effective where the batts are crushed into the existing 2x6 wall to improve its performance. Some manufacturers used 2x4 walls with R-11 batts in their base models. We reviewed this approach separately (see Appendix C). The retail price of an R-19 wall in these cases is

Table 5.6 Optimum Package Conventional Floors Nominal R-Values									
Zone	Average Savings	Wall	Floor		Window	Ceiling		Ducts	Heat
	(kWh)		Belly	Cavity	(U-factor)	Attic	Vault		
1	8521	22	11	22	.39	30	30	4	ER
2	11967	22	22	22	.39	30	38 Baffle	4	ER
3	19402	22	22	22	.39	38	38 Baffle	4	HP
Heat Pump Package									
1	10338	19	11	11	Base	19	19	4	HP
2	15037	19	11	11	Base	30	19	4	HP
3	17322	19	11	11	.39	30	30	4	HP
Blown Attics *									
1	9060	22	19	22	.39	49	38	4	ER
2	12603	22	22	22	.39	49	38	4	ER
3	19518	22	22	22	.39	49	38	4	HP
* Base case differs because of lower ceiling heat loss									

Table 5.7 Optimum Package Optimum Floor Construction (Cut-In Belly Insulation) Nominal R-Values									
Zone	Average Savings	Wall	Floor	Window	Ceiling		Ducts	Heat	
			Belly	(U-factor)	Attic	Vault			
1	7829	22	33	.39	30	30	4	ER	
2	10656	22	33	.39	30	30	4	ER	
3	17878	22	33	.39	30	38	4	HP	
Heat Pump Package									
1	9417	19	19	Base	19	19	4	HP	
2	13981	19	22	Base	30	19	4	HP	
3	16335	19	22	Base	30	30	4	HP	

about 2.5 times greater than the price when manufacturers use 2x6 for wall framing. Nevertheless, this change resulted in virtually identical optimum conservation packages except where heat pumps were included in Climate Zone 1.

The effect of the heat pump on the optimization is substantial, especially in Zones 1 and 2. It should be pointed out that when the heat pump is included in the optimizations in competition with all conservation options, the marginal cost of the heat pump is predicted at 102 mills in Zone 1 and 56 mills in Zone 2 (as shown in Appendix B). In both cases, the heat pump fails to meet the 52 mill ceiling for inclusion in the optimum package. The heat pump does, however, save substantially more energy than any other measure in the package and thus, when it is included in the package, the amount of energy saved is substantially greater than when only envelope measures are employed. But it is not cost effective in Climate Zones 1 and 2.

We looked at only two window measures in the optimization runs: vinyl-frame windows and vinyl-frame windows with argon fill. The thermally-broken aluminum windows performed worse and cost more than any of the other windows and thus were excluded at the start of the optimization runs. The storm windows had nominally equivalent performance for less cost than the vinyl windows, although it was our judgement that the use of storm windows decreases the quality of the window. In all cases the argon-filled windows were the preferred window option. The incremental savings from argon windows are almost twice that from plain vinyl windows.

Attic and ceiling insulation optimized at about R-30 except in the coldest climates. This is somewhat below the SGC specifications and reflects the relatively poor performance of ceiling batt insulation due to the current manufacturing practices in this industry. At a minimum, manufacturers should be required to use insulation baffle and encouraged to switch to blow-in attic insulation. When blow-in insulation is used, much higher R-values are cost-effective in the optimization.

The floor insulation strategies recommended in the SGC specifications should be revised dramatically. Manufacturers should change the placement of the belly blanket. The belly blanket should be cut and lifted into the joist cavity above the outriggers and I-beams and extended below the duct at full depth. This improves floor insulation performance dramatically and is similar to base case manufacturing techniques. Duct insulation is cost-effective in *all* floor insulation strategies reviewed.

The optimization analysis recommended optimum packages somewhat different from those in the current SGC specifications. This suggests that more careful attention should be paid to the U-factors which can be achieved given the construction practices in this industry. Savings are equally important, since base case homes are not affected by local and state energy codes and the standards set by HUD are dramatically below the optimal package described here. A careful review of the specifications seems warranted.

Manufacturers would benefit from assistance in improving detailing and manufacturing techniques. Higher levels of energy efficiency than commonly obtained should be cost-effective, specifically the use of blow-in insulation techniques. The use of duct insulation should be required by the SGC specifications since it increases overall performance about 16% at a minimal cost in all homes, whether they have heat pumps or electric resistance heat.

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7 Appendix A

Prototype Manufactured Home

BACK

LEFT

RIGHT

FRONT

FLAT TRUSS

VAULTED TRUSS

VAULTED TRUSS

FLAT TRUSS

8 Appendix B

Appendix B Optimization Runs

Marginal Cost Analysis for Climate Zone 1 **Basic Run**

Location: SEATTLE, WASHINGTON

Base Case UA - 534.4

Base Case annual heating kWh - 14034

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	13502	532.2	10	0.77
DUCT	R4	534.41	13015	487.0	21	1.76
SPECFLR	R0/R11	509.75	11969	1045.9	134	5.24
WALL	R19	482.26	10924	1044.7	243	9.49
SPECFLR	R11/R11	427.51	9282	1642.1	388	9.65
ATTIC	R19	419.19	8965	316.9	98	12.66
VAULT	R19	410.88	8650	315.6	98	12.71
ATTIC	R30	401.79	8306	343.4	204	24.26
VAULT	R30	393.47	7993	313.1	234	30.55
SPECFLR	R22/R11	379.18	7570	422.8	388	37.48
WINDOW	VINYL	333.96	5909	1661.4	1623	39.87
WINDOW	ARGON	324.99	5588	320.8	218	27.68
WALL	R22	322.87	5513	75.3	84	45.82
SPECFLR	R22/R22	317.11	5217	295.6	388	53.59
VAULT	R38BAF	314.85	5139	78.8	136	70.47
ATTIC	R38	312.58	5060	78.7	151	78.40
ATTIC	R49	309.56	4954	105.4	212	82.00
ATTIC	R52	308.81	4928	26.2	53	82.44
SYSTEM	HEATPUMP	308.81	2303	2625.6	6572	102.17

Marginal Cost Analysis for Climate Zone 2 **Basic Run**

Location: SPOKANE, WASHINGTON

Base Case UA - 534.4

Base Case annual heating kWh - 20844

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	20061	783.4	10	0.52
DUCT	R4	534.41	19325	735.9	21	1.16
SPECFLR	R0/R11	509.75	17932	1392.5	134	3.94
WALL	R19	482.26	16568	1364.9	243	7.26
SPECFLR	R11/R11	427.51	14529	2038.1	388	7.77
ATTIC	R19	419.19	14107	422.6	98	9.49
VAULT	R19	410.88	13686	420.4	98	9.54
ATTIC	R30	401.79	13228	458.6	204	18.17
VAULT	R30	393.47	12808	420.2	234	22.76
WINDOW	VINYL	348.26	10550	2257.5	1623	29.34
WINDOW	ARGON	339.28	10107	443.0	218	20.04
SPECFLR	R192/R11	324.99	9558	549.7	388	28.83
WALL	R22	322.87	9452	105.3	84	32.75
SPECFLR	R22/R22	317.11	8987	465.5	388	34.04
VAULT	R38BAF	314.85	8877	109.9	136	50.55
SYSTEM	HEATPUMP	314.85	4111	4766.2	6572	56.28
ATTIC	R38	312.58	4067	43.6	151	141.66
ATTIC	R49	309.56	4009	58.3	212	148.15
ATTIC	R52	308.81	3994	14.5	53	148.93

Marginal Cost Analysis for Climate Zone 3 **Basic Run**

Location: Missoula, Montana

Base Case UA - 534.4

Base Case annual heating kWh - 24429

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	23526	902.7	10	0.45
DUCT	R4	534.41	22675	851.1	21	1.01
SPECFLR	R0/R11	509.75	21075	1599.9	134	3.43
WALL	R19	482.26	19509	1566.2	243	6.33
SPECFLR	R11/R11	427.51	17177	2332.6	388	6.79
ATTIC	R19	419.19	16687	490.1	98	8.18
VAULT	R19	410.88	16197	489.3	98	8.20
ATTIC	R30	401.79	15664	533.6	204	15.61
VAULT	R30	393.47	15176	487.6	234	19.62
WINDOW	VINYL	348.26	12543	2633.3	1623	25.16
WINDOW	ARGON	339.28	12024	518.6	218	17.12
SPECFLR	R22/R11	324.99	11389	635.5	388	24.93
WALL	R22	322.87	11266	122.9	84	28.05
SPECFLR	R22/R22	317.11	10714	552.1	388	28.70
VAULT	R38BAF	314.85	10586	127.6	136	43.53
ATTIC	R38	312.58	10459	127.1	151	48.55
SYSTEM	HEATPUMP	312.58	5027	5431.7	6572	49.39
ATTIC	R49	309.56	4958	69.5	212	124.29
ATTIC	R52	308.81	4941	17.3	53	125.03

**Marginal Cost Analysis for Climate Zone 1
Heat Pump-Only Case**

Location: SEATTLE, WASHINGTON

Base Case UA - 534.4

Base Case annual heating kWh - 5581

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Heat Pump

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	5392	188.3	10	2.17
DUCT	R4	534.41	5217	175.6	21	4.88
SPECFLR	R0/R11	509.75	4849	367.3	134	14.93
WALL	R19	482.26	4492	357.3	243	27.75
SPECFLR	R11/R11	427.51	3923	568.9	388	27.85
ATTIC	R19	419.19	3810	113.6	98	35.32
VAULT	R19	410.88	3696	113.5	98	35.34
ATTIC	R30	401.79	3572	124.0	204	67.21
VAULT	R30	393.47	3459	113.4	234	84.33
WINDOW	VINYL	348.26	2846	612.7	1623	108.12
WINDOW	ARGON	339.28	2724	122.1	218	72.71
SPECFLR	R22/R11	324.99	2567	157.0	388	100.94
WALL	R22	322.87	2538	29.0	84	118.78
SPECFLR	R22/R22	317.11	2415	122.6	388	129.28
VAULT	R38BAF	314.85	2385	30.6	136	181.26
ATTIC	R38	312.58	2354	30.7	151	201.21
ATTIC	R49	309.56	2313	41.2	212	209.89

Marginal Cost Analysis for Climate Zone 2 Heat Pump-Only Case

Location: SPOKANE, WASHINGTON

Base Case UA - 534.4

Base Case annual heating kWh - 8954

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Heat Pump

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	8576	377.8	10	1.08
DUCT	R4	534.41	8239	336.7	21	2.55
SPECFLR	R0/R11	509.75	7636	603.8	134	9.08
WALL	R19	482.26	7127	508.2	243	19.51
SPECFLR	R11/R11	427.51	6324	803.6	388	19.72
ATTIC	R19	419.19	6157	167.3	98	23.98
VAULT	R19	410.88	5990	166.6	98	24.08
ATTIC	R30	401.79	5807	183.0	204	45.52
VAULT	R30	393.47	5678	128.9	234	74.21
WINDOW	VINYL	348.26	4766	912.0	1623	72.63
WINDOW	ARGON	339.28	4585	180.9	218	49.07
SPECFLR	R22/R11	324.99	4383	202.6	388	78.22
WALL	R22	322.87	4341	41.7	84	82.68
SPECFLR	R22/R22	317.11	4154	186.5	388	84.93
VAULT	R38BAF	314.85	4111	43.6	136	127.28
ATTIC	R38	312.58	4067	43.6	151	141.66
ATTIC	R49	309.56	4009	58.3	212	148.15
ATTIC	R52	308.81	3994	14.5	53	148.93

Marginal Cost Analysis for Climate Zone 3 Heat Pump-Only Case

Location: Missoula, Montana

Base Case UA - 534.4

Base Case annual heating kWh - 10812

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Heat Pump

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	10361	450.7	10	0.91
DUCT	R4	534.41	9964	396.9	21	2.16
SPECFLR	R0/R11	509.75	9253	711.6	134	7.71
WALL	R19	482.26	8667	586.0	243	16.92
SPECFLR	R11/R11	427.51	7725	941.9	388	16.82
ATTIC	R19	419.19	7525	199.5	98	20.11
VAULT	R19	410.88	7326	199.5	98	20.11
ATTIC	R30	401.79	7107	219.1	204	38.03
WINDOW	VINYL	356.58	6069	1037.9	1623	63.82
WINDOW	ARGON	347.61	5852	217.0	218	40.91
VAULT	R30	339.28	5650	201.5	234	47.47
SPECFLR	R22/R11	324.99	5412	237.9	388	66.59
SPECFLR	R22/R22	319.23	5180	232.2	388	68.25
WALL	R22	317.11	5131	48.9	84	70.53
VAULT	R38BAF	314.85	5079	52.1	136	106.64
ATTIC	R38	312.58	5027	52.0	151	118.78
ATTIC	R49	309.56	4958	69.5	212	124.29
ATTIC	R52	308.81	4941	17.3	53	125.03

Marginal Cost Analysis for Climate Zone 1 **Basic Run With Blown-in Ceiling Insulation**

Location: SEATTLE, WASHINGTON

Base Case UA - 530.6

Base Case annual heating kWh - 13878

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14 (blown-in fiberglass)

VAULT R-14 (blown-in fiberglass)

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	530.63	13351	526.9	10	0.77
DUCT	R4	530.63	12869	482.0	21	1.78
SPECFLR	R0/R11	505.97	11825	1044.0	134	5.25
WALL	R19	478.48	10782	1043.1	243	9.50
SPECFLR	R11/R11	423.73	9138	1643.5	388	9.64
ATTIC	R49BLOW	373.83	7263	1015.0	333	13.37
VAULT	R38BLOW	401.04	8278	860.4	234	11.11
SPECFLR	R22/R11	359.53	6841	422.1	388	37.51
WINDOW	VINYL	314.32	5210	1630.6	1623	40.59
WINDOW	ARGON	305.34	4893	317.4	218	27.94
WALL	R22	303.22	4818	74.7	84	46.12
SPECFLR	R22/R22	297.47	4535	282.9	388	55.97
SYSTEM	HEATPUMP	297.47	2148	2387.3	6572	112.28

**Marginal Cost Analysis for Climate Zone 2
Basic Run With Blown-in Ceiling Insulation**

Location: SPOKANE, WASHINGTON

Base Case UA - 530.6

Base Case annual heating kWh - 20641

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14 (blown-in fiberglass)

VAULT R-14 (blown-in fiberglass)

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	530.63	19864	777.1	10	0.53
DUCT	R4	530.63	19135	729.6	21	1.17
SPECFLR	R0/R11	505.97	17745	1390.0	134	3.95
WALL	R19	478.48	16380	1364.7	243	7.26
SPECFLR	R11/R11	423.73	14337	2042.8	388	7.76
ATTIC	R49BLOW	373.83	11821	1368.5	333	9.91
VAULT	R38BLOW	401.04	13190	1147.5	234	8.33
WINDOW	VINYL	314.32	9029	2256.3	1623	29.34
WINDOW	ARGON	305.34	8586	442.3	218	20.06
SPECFLR	R22/R11	359.53	11285	536.3	388	29.52
WALL	R22	303.22	8482	104.2	84	33.06
SPECFLR	R22/R22	297.47	8038	443.9	388	35.66
SYSTEM	HEATPUMP	297.47	3776	4262.4	6572	62.88

Marginal Cost Analysis for Climate Zone 3 **Basic Run With Blown-in Ceiling Insulation**

Location: Missoula, Montana

Base Case UA - 530.6

Base Case annual heating kWh - 24198

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14 (blown-in fiberglass)

VAULT R-14 (blown-in fiberglass)

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	530.63	23303	895.6	10	0.46
DUCT	R4	530.63	22459	844.0	21	1.02
SPECFLR	R0/R11	505.97	20860	1598.5	134	3.43
WALL	R19	478.48	19294	1566.2	243	6.33
SPECFLR	R11/R11	423.73	16954	2340.0	388	6.77
ATTIC	R49BLOW	373.83	14030	1589.8	333	8.53
VAULT	R38BLOW	401.04	15619	1334.6	234	7.16
WINDOW	VINYL	328.61	11410	2619.0	1623	25.27
WINDOW	ARGON	319.64	10898	512.8	218	17.30
SPECFLR	R22/R11	305.34	10260	637.5	388	24.84
WALL	R22	303.22	10139	120.7	84	28.54
SPECFLR	R22/R22	297.47	9614	525.7	388	30.12
SYSTEM	HEATPUMP	297.47	4680	4933.4	6572	54.33

Marginal Cost Analysis for Climate Zone 1 Cut-in Belly Blanket Insulation

Location: SEATTLE, WASHINGTON

Base Case UA - 514.7

Base Case annual heating kWh - 12974

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	514.67	12561	413.7	10	0.99
DUCT	R4	514.67	12176	384.7	21	2.23
SPECFLR	R0/R11	487.47	11047	1129.3	134	4.86
WALL	R19	459.98	10009	1037.7	243	9.55
SPECFLR	R0/R19	432.69	8908	1100.6	284	10.52
ATTIC	R19	424.37	8608	300.1	98	13.36
VAULT	R19	416.05	8310	298.6	98	13.43
SPECFLR	R0/R22	410.35	8090	219.1	105	19.47
ATTIC	R30	401.26	7767	323.3	204	25.77
VAULT	R30	392.94	7472	294.7	234	32.46
SPECFLR	R0/R33	381.71	7052	420.8	388	37.65
WINDOW	VINYL	336.49	5512	1539.9	1623	43.02
WINDOW	ARGON	327.52	5214	297.3	218	29.86
WALL	R22	325.40	5145	69.7	84	49.46
VAULT	R38BAF	323.13	5070	74.2	136	74.88
ATTIC	R38	320.87	4996	74.0	151	83.35
ATTIC	R49	317.84	4897	99.0	212	87.30
ATTIC	R52	317.09	4873	24.6	53	87.84
SYSTEM	HEATPUMP	317.09	2269	2603.7	6572	103.02

Marginal Cost Analysis for Climate Zone 2 **Cut-in Belly Blanket Insulation**

Location: SPOKANE, WASHINGTON

Base Case UA - 514.7

Base Case annual heating kWh - 19401

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	514.67	18789	612.3	10	0.67
DUCT	R4	514.67	18208	581.3	21	1.47
SPECFLR	R0/R11	487.47	16705	1503.2	134	3.65
WALL	R19	459.98	15350	1354.0	243	7.32
SPECFLR	R0/R19	432.69	13850	1500.1	284	7.72
ATTIC	R19	424.37	13451	399.4	98	10.04
VAULT	R19	416.05	13053	397.5	98	10.09
SPECFLR	R0/R22	410.35	12758	295.9	105	14.42
ATTIC	R30	401.26	12326	431.4	204	19.31
VAULT	R30	392.94	11931	395.2	234	24.21
SPECFLR	R0/R33	381.71	11356	574.6	388	27.57
WINDOW	VINYL	336.49	9255	2101.1	1623	31.53
WINDOW	ARGON	327.52	8843	412.6	218	21.51
WALL	R22	325.40	8745	97.2	84	35.48
VAULT	R38BAF	323.13	8642	103.5	136	53.64
SYSTEM	HEATPUMP	323.13	3975	4667.1	6572	57.48
ATTIC	R38	320.87	3934	41.2	151	149.70
ATTIC	R49	317.84	3878	55.1	212	156.69
ATTIC	R52	317.09	3865	13.7	53	

Marginal Cost Analysis for Climate Zone 3 Cut-in Belly Blanket Insulation

Location: Missoula, Montana

Base Case UA - 514.7

Base Case annual heating kWh - 22777

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	514.67	22070	707.2	10	0.58
DUCT	R4	514.67	21392	678.1	21	1.26
SPECFLR	R0/R11	487.47	19663	1729.1	134	3.17
WALL	R19	459.98	18103	1560.1	243	6.35
SPECFLR	R0/R19	432.69	16358	1745.1	284	6.63
ATTIC	R19	424.37	15895	463.2	98	8.66
VAULT	R19	416.05	15433	461.8	98	8.69
SPECFLR	R0/R22	410.35	15088	345.0	105	12.36
ATTIC	R30	401.26	14586	501.9	204	16.60
VAULT	R30	392.94	14128	458.3	234	20.87
SPECFLR	R0/R33	381.71	13460	667.7	388	23.73
WINDOW	VINYL	336.49	11004	2455.8	1623	26.98
WINDOW	ARGON	327.52	10523	481.6	218	18.43
WALL	R22	325.40	10409	113.4	84	30.41
VAULT	R38BAF	323.13	10288	120.9	136	45.96
SYSTEM	HEATPUMP	323.13	4899	5389.4	6572	49.77
ATTIC	R38	320.87	4850	49.4	151	125.02
ATTIC	R49	317.84	4784	66.0	212	130.99
ATTIC	R52	317.09	4767	16.4	53	131.74

**Marginal Cost Analysis for Climate Zone 1
Cut-in Belly Blanket Insulation
Heat Pump-Only**

Location: SEATTLE, WASHINGTON

Base Case UA - 514.7

Base Case annual heating kWh - 5203

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM Heat Pump
DUCT Unwrapped
INFILTRATION 0.35 ACH
DOOR R-5
WALL R-11
WINDOW R-1.33
FLOOR R-0 joist/R-7 belly blanket
ATTIC R-14
VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	514.67	5059	143.7	10	2.84
DUCT	R4	514.67	4922	137.1	21	6.25
SPECFLR	R0/R11	487.47	4533	389.4	134	14.08
WALL	R19	459.98	4169	363.5	243	27.27
SPECFLR	R0/R19	432.69	3770	399.4	284	28.99
ATTIC	R19	424.37	3662	107.9	98	37.16
VAULT	R19	416.05	3557	104.7	98	38.32
SPECFLR	R0/R22	410.35	3478	79.2	105	53.84
ATTIC	R30	401.26	3361	117.4	204	70.96
VAULT	R30	392.94	3253	107.4	234	89.07
SPECFLR	R0/R33	381.71	3099	154.2	388	102.72
WINDOW	VINYL	336.49	2517	581.7	1623	113.87
WINDOW	ARGON	327.52	2402	114.9	218	77.26
WALL	R22	325.40	2375	27.1	84	127.39
VAULT	R38BAF	323.13	2346	28.9	136	192.47
ATTIC	R38	320.87	2317	28.9	151	213.82
ATTIC	R49	317.84	2279	38.7	212	223.41
ATTIC	R52	317.09	2269	9.6	53	224.38

**Marginal Cost Analysis for Climate Zone 2
Cut-in Belly Blanket Insulation
Heat Pump-Only**

Location: SPOKANE, WASHINGTON

Base Case UA - 514.7

Base Case annual heating kWh - 8280

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM Heat Pump
DUCT Unwrapped
INFILTRATION 0.35 ACH
DOOR R-5
WALL R-11
WINDOW R-1.33
FLOOR R-0 joist/R-7 belly blanket
ATTIC R-14
VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	514.67	8017	262.9	10	1.55
DUCT	R4	514.67	7755	262.4	21	3.27
SPECFLR	R0/R11	487.47	7175	579.9	134	9.46
WALL	R19	459.98	6600	574.9	243	17.24
SPECFLR	R0/R19	432.69	5991	609.6	284	18.99
ATTIC	R19	424.37	5867	123.7	98	32.43
VAULT	R19	416.05	5712	155.0	98	25.88
SPECFLR	R0/R22	410.35	5593	118.9	105	35.89
ATTIC	R30	401.26	5420	173.2	204	48.11
VAULT	R30	392.94	5261	159.1	234	60.13
SPECFLR	R0/R33	381.71	5027	233.6	388	67.82
WINDOW	VINYL	336.49	4218	808.9	1623	81.89
WINDOW	ARGON	327.52	4055	163.6	218	54.26
WALL	R22	325.40	4016	38.6	84	89.24
VAULT	R38BAF	323.13	3975	41.2	136	134.78
ATTIC	R38	320.87	3934	41.2	151	149.70
ATTIC	R49	317.84	3878	55.1	212	156.69
ATTIC	R52	317.09	3865	13.7	53	157.41

**Marginal Cost Analysis for Climate Zone 3
Cut-in Belly Blanket Insulation
Heat Pump-Only**

Location: Missoula, Montana

Base Case UA - 514.7

Base Case annual heating kWh = 10018

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM Heat Pump
DUCT Unwrapped
INFILTRATION 0.35 ACH
DOOR R-5
WALL R-11
WINDOW R-1.33
FLOOR R-0 joist/R-7 belly blanket
ATTIC R-14
VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	514.67	9708	309.8	10	1.32
DUCT	R4	514.67	9394	314.3	21	2.73
SPECFLR	R0/R11	487.47	8721	673.2	134	8.15
WALL	R19	459.98	8039	681.4	243	14.55
SPECFLR	R0/R19	432.69	7308	730.9	284	15.84
ATTIC	R19	424.37	7167	141.5	98	28.34
VAULT	R19	416.05	6982	184.5	98	21.74
SPECFLR	R0/R22	410.35	6839	142.9	105	29.85
ATTIC	R30	401.26	6632	207.3	204	40.19
VAULT	R30	392.94	6442	189.7	234	50.42
SPECFLR	R0/R33	381.71	6163	279.3	388	56.72
WINDOW	VINYL	336.49	5191	971.8	1623	68.17
WINDOW	ARGON	327.52	4995	196.5	218	45.17
WALL	R22	325.40	4948	46.4	84	74.32
VAULT	R38BAF	323.13	4899	49.5	136	112.22
ATTIC	R38	320.87	4850	49.4	151	125.02
ATTIC	R49	317.84	4784	66.0	212	130.99
ATTIC	R52	317.09	4767	16.4	53	131.74

9 Appendix C

Appendix C Wall Framing Optimization Analysis

Marginal Cost Analysis for Climate Zone 1 **Basic Run With Wall Framing Change**

Location: SEATTLE, WASHINGTON

Base Case UA - 534.4

Base Case annual heating kWh - 14034

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	13502	532.2	10	0.77
DUCT	R4	534.41	13015	487.0	21	1.76
SPECFLR	R0/R11	509.75	11969	1045.9	134	5.24
SPECFLR	R11/R11	455.00	10340	1628.7	388	9.73
ATTIC	R19	446.68	10018	322.2	98	12.45
VAULT	R19	438.37	9698	320.0	98	12.54
WALL	R19FC	410.88	8650	1048.4	602	23.43
ATTIC	R30	401.79	8306	343.4	204	24.26
VAULT	R30	393.47	7993	313.1	234	30.55
SPECFLR	R22/R11	379.18	7570	422.8	388	37.48
WINDOW	VINYL	333.96	5909	1661.4	1623	39.87
WINDOW	ARGON	324.99	5588	320.8	218	27.68
WALL	R22FC	322.87	5513	75.3	95	51.55
SPECFLR	R22/R22	317.11	5217	295.6	388	53.59
VAULT	R38BAF	314.85	5139	78.8	136	70.47
ATTIC	R38	312.58	5060	78.7	151	78.40
ATTIC	R49	309.56	4954	105.4	212	82.00
ATTIC	R52	308.81	4928	26.2	53	82.44
SYSTEM	HEATPUMP	308.81	2303	2625.6	6572	102.17

**Marginal Cost Analysis for Climate Zone 1
Heat Pump-Only With Wall Framing Change**

Location: SEATTLE, WASHINGTON

Base Case UA - 534.4

Base Case annual heating kWh - 5581

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Heat Pump

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	5392	188.3	10	2.17
DUCT	R4	534.41	5217	175.6	21	4.88
SPECFLR	R0/R11	509.75	4849	367.3	134	14.93
SPECFLR	R11/R11	455.00	4300	549.8	388	28.82
ATTIC	R19	446.68	4185	114.2	98	35.12
VAULT	R19	438.37	4072	113.8	98	35.26
WALL	R19FC	410.88	3696	375.5	602	65.42
ATTIC	R30	401.79	3572	124.0	204	67.21
VAULT	R30	393.47	3459	113.4	234	84.33
WINDOW	VINYL	348.26	2846	612.7	1623	108.12
WINDOW	ARGON	339.28	2724	122.1	218	72.71
SPECFLR	R22/R11	324.99	2567	157.0	388	100.94
SPECFLR	R22/R22	319.23	2444	122.9	388	128.90
WALL	R22FC	317.11	2415	28.7	95	135.34
VAULT	R38BAF	314.85	2385	30.6	136	181.26
ATTIC	R38	312.58	2354	30.7	151	201.21
ATTIC	R49	309.56	2313	41.2	212	209.89
ATTIC	R52	308.81	2303	10.3	53	210.61

Marginal Cost Analysis for Climate Zone 2 **Basic Run With Wall Framing Change**

Location: SPOKANE, WASHINGTON

Base Case UA - 534.4

Base Case annual heating kWh - 20844

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	20061	783.4	10	0.52
DUCT	R4	534.41	19325	735.9	21	1.16
SPECFLR	R0/R11	509.75	17932	1392.5	134	3.94
SPECFLR	R11/R11	455.00	15934	1998.4	388	7.93
ATTIC	R19	446.68	15508	425.7	98	9.42
VAULT	R19	438.37	15083	425.4	98	9.43
WALL	R19FC	410.88	13686	1396.5	602	17.59
ATTIC	R30	401.79	13228	458.6	204	18.17
VAULT	R30	393.47	12808	420.2	234	22.76
WINDOW	VINYL	348.26	10550	2257.5	1623	29.34
WINDOW	ARGON	339.28	10107	443.0	218	20.04
SPECFLR	R22/R11	324.99	9558	549.7	388	28.83
SPECFLR	R22/R22	319.23	9090	467.6	388	33.88
WALL	R22FC	317.11	8987	103.2	95	37.60
VAULT	R38BAF	314.85	8877	109.9	136	50.55
SYSTEM	HEATPUMP	314.85	4111	4766.2	6572	56.28
ATTIC	R38	312.58	4067	43.6	151	141.66
ATTIC	R49	309.56	4009	58.3	212	148.15
ATTIC	R52	308.81	3994	14.5	53	148.93

Marginal Cost Analysis for Climate Zone 2 **Heat Pump-Only With Wall Framing Change**

Location: SPOKANE, WASHINGTON

Base Case UA - 534.4

Base Case annual heating kWh - 8954

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Heat Pump

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	8576	377.8	10	1.08
DUCT	R4	534.41	8239	336.7	21	2.55
SPECFLR	R0/R11	509.75	7636	603.8	134	9.08
SPECFLR	R11/R11	455.00	6909	727.0	388	21.79
ATTIC	R19	446.68	6727	181.2	98	22.14
VAULT	R19	438.37	6546	181.4	98	22.12
WALL	R19FC	410.88	5990	556.1	602	44.18
ATTIC	R30	401.79	5807	183.0	204	45.52
VAULT	R30	393.47	5678	128.9	234	74.21
WINDOW	VINYL	348.26	4766	912.0	1623	72.63
WINDOW	ARGON	339.28	4585	180.9	218	49.07
SPECFLR	R22/R11	324.99	4383	202.6	388	78.22
SPECFLR	R22/R22	319.23	4195	187.3	388	84.58
WALL	R22FC	317.11	4154	40.9	95	94.78
VAULT	R38BAF	314.85	4111	43.6	136	127.28
ATTIC	R38	312.58	4067	43.6	151	141.66
ATTIC	R49	309.56	4009	58.3	212	148.15
ATTIC	R52	308.81	3994	14.5	53	148.93

Marginal Cost Analysis for Climate Zone 3 **Basic Run With Wall Framing Change**

Location: Missoula, Montana

Base Case UA - 534.4

Base Case annual heating kWh - 24429

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Electric Resistance

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	534.41	23526	902.7	10	0.45
DUCT	R4	534.41	22675	851.1	21	1.01
SPECFLR	R0/R11	509.75	21075	1599.9	134	3.43
SPECFLR	R11/R11	455.00	18801	2274.8	388	6.97
ATTIC	R19	446.68	18310	491.1	98	8.17
VAULT	R19	438.37	17818	491.1	98	8.17
WALL	R19FC	410.88	16197	1621.2	602	15.15
ATTIC	R30	401.79	15664	533.6	204	15.61
VAULT	R30	393.47	15176	487.6	234	19.62
WINDOW	VINYL	348.26	12543	2633.3	1623	25.16
WINDOW	ARGON	339.28	12024	518.6	218	17.12
SPECFLR	R22/R11	324.99	11389	635.5	388	24.93
SPECFLR	R22/R22	319.23	10834	555.1	388	28.54
WALL	R22FC	317.11	10714	119.9	95	32.36
VAULT	R38BAF	314.85	10586	127.6	136	43.53
ATTIC	R38	312.58	10459	127.1	151	48.55
SYSTEM	HEATPUMP	312.58	5027	5431.7	6572	49.39
ATTIC	R49	309.56	4958	69.5	212	124.29
ATTIC	R52	308.81	4941	17.3	53	125.03

Marginal Cost Analysis for Climate Zone 3 **Heat Pump-Only With Wall Framing Change**

Location: Missoula, Montana

Base Case UA - 530.6

Base Case annual heating kWh - 24198

Base Case Component Specifications & Nominal R-Values

HEATING SYSTEM: Heat Pump

DUCT Unwrapped

INFILTRATION 0.35 ACH

DOOR R-5

WALL R-11

WINDOW R-1.33

FLOOR R-0 joist/R-7 belly blanket

ATTIC R-14

VAULT R-14

Measure		UA	kWh	dkWh	dCost	mills
DUCT	SOUND	530.63	23303	895.6	10	0.46
DUCT	R4	530.63	22459	844.0	21	1.02
SPECFLR	R0/R11	505.97	20860	1598.5	134	3.43
WALL	R19	478.48	19294	1566.2	243	6.33
SPECFLR	R11/R11	423.73	16954	2340.0	388	6.77
ATTIC	R49BLOW	401.81	15665	1289.1	333	10.53
VAULT	R38BLOW	389.70	14956	709.1	234	13.49
WINDOW	VINYL	344.48	12325	2631.1	1623	25.18
WINDOW	ARGON	335.51	11807	517.7	218	17.15
SPECFLR	R22/R11	321.22	11170	637.0	388	24.87
WALL	R22	319.10	11048	121.9	84	28.29
SPECFLR	R22/R22	313.34	10502	546.6	388	28.99
SYSTEM	HEATPUMP	313.34	5045	5456.8	6572	49.16

END

DATE FILMED

11 / 02 / 90