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AN ANALYSIS OF RESIDENTIAL ENERGY CONSERVATION IN MISSOULA, MONTANA

by

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Chapter 1

INTRODUCTION

As the prices of natural gas and electricity have steadily risen during the past decade Missoulians have increasingly returned to wood to heat their homes. In 1977 approximately 8000 households burned 15,000 cords of wood (Otis 1977), in 1980 nearly 12,000 households burned 32,000 cords (Church 1980), and in 1983 survey results suggest that about the same number of households, 11,500, are now burning between 16,000 and 32,000 cords (Steffel 1983). Unfortunately, because Missoula lies in a narrow mountain valley subject to almost daily air inversions, increased wood burning has created increasingly dirty and unhealthy air.

Characteristically, Missoula's wintertime inversions have low ceilings which, coupled with low wind speeds, limit vertical mixing and prevent air from moving out of the valley (Robbins et al. 1980). In a pristine environment these conditions would create only a harmless fog. But Missoula is not pristine. Each winter Missoula's woodstoves pour tons of pollutants into the fog, including several known carcinogens, producing a murky brown haze. They all accumulate in the stagnant air.

Despite the obvious detriments, people continue to burn wood explaining that they can't afford to pay the power company for heat. Indeed, natural gas and electricity may have become too expensive for heating houses, but we need to find ways to keep warm without polluting the air. To continue burning wood as we do now is to gamble recklessly with our collective health. We can do nothing about the inversions; they unavoidably result from the topography and climate; but we can do something about how we heat our homes.

We could burn wood differently. Wood produces only carbon dioxide and water when burned completely- no smoke, no odor, and no noxious compounds (Shelton and Shapiro 1976). Such complete combustion is impossible in conventional woodstoves, but good collecting and burning practices and more efficient stoves such as the stick-wood boiler and Russian furnaces could significantly reduce wood smoke pollution (Steffel 1981).

Alternatively, we could insulate and weatherize our homes, decreasing wood smoke pollution by decreasing the amount of energy needed for heating. In this paper I have determined the optimum insulation levels for Missoula's houses given the prices of home heating fuels, the cost of conservation retrofits, and the characteristics of the housing stock. I have then compared the costs of the conservation retrofits to the cost of backfitting with a woodstove, hoping to show that insulating our houses and then heating them with gas or electricity is cheaper than buying a woodstove and heating with wood. This analysis is followed by a brief discussion of why Missoula's houses are underinsulated, and of some of the environmental and social reasons justifying a public insulation program. For a thorough discussion of various possible kinds of community insulation programs and how to finance them see McNairy (1983).

Chapter 2

THE AVERAGE MISSOULA HOUSE

Survey Data

In 1979 Elrick and Lavidge, Inc. surveyed 4030 homes in Washington, Oregon, Idaho, and Montana; 62 of these were in Missoula, 570 in Montana. The Bonneville Power Administration (BPA), goaded by the Northwest Power Planning and Conservation Act (Public Law 96-501), commissioned the survey to determine how much electricity could be conserved in BPA's marketing area. Besides asking questions about use of appliances such as washing machines, air conditioners, and hot water heaters, the survey also gathered information on factors influencing the amount of energy needed for space heating. These included floor area, indoor temperature, number of windows and doors, and the type and thickness of insulation.

The raw data from the survey are all contained on a massive computer tape stored at the Computer Center of the University of Montana. Sixty-two is a rather small sample of a population as large and varied as Missoula's houses; there are 14,531 residences in Missoula including trailers, apartments, and single family houses of all different ages and construction types (1980 Census of Population and Housing). Using the data from the entire state would increase the precision of the house description provided that the Missoula houses were not significantly different from the Montana ones.

Table 1 lists the characteristics of the Missoula and Montana samples with standard deviations calculated for those values, e.g. average floor area, which come directly from the tape. The other characteristics, such as window area and insulation levels for the Montana sample, were derived by manipulating data from the tape. No standard deviations are presented since these calculations were made using averages rather than the individual cases. The calculations are explained in the notes to Table 1 and discussed in the next section.

Table 2, a condensed version of Table 1, simplifies the comparison of the Missoula and Montana samples. The two samples are very similar; only the floor areas appear to be different. As can be seen from Figure 1, the house floor area distributions are not normal (i.e. bell-shaped). However, they are log-normal as measured by Davies' coefficient of skewness (Davies and Crowder 1933, see Appendix A). Using a standard difference of the means test, the average floor areas of the log-transformed samples are significantly different at the 5% level (1). The average floor area of the Montana sample is from 4% to 35% greater than that of the Missoula sample. I decided to use the Montana sample average because this difference is relatively small, probably smaller than the general uncertainty in the survey data, and no doubt smaller than the bias introduced by the large proportion of missing data for some of the house characteristics (see Table 1). Also, the test itself is not technically valid in this case since the two samples are not independent. The Missoula sample is a subset of the Montana one.

Table 3 summarizes the average Montana house. Since Elrick and

Sample Characteristics

Table 1

	Montana			Missoula		
	Sample (1) Mean	Sample (2) Std. Dev.	Std.Dev. (3) of Mean	Sample (1) Mean	Sample (2) Std. Dev.	Std. Dev. (3) of Mean
Floor Area (valid cases 566)	1312 SF	674 SF	28 SF	1118 SF	624 SF	79 SF
# of Stories	1.29	.50	.02	1.24	.53	.07
Avg. Indoor Temp.	66 deg. F	(from Vol. 3 hence no Std. Dev.)		66 deg. F	6 deg. F	.8 deg. F
# of Doors	2.2	.8	.03	1.9	.8	.1
# of Storm Doors	1.4	.9	.04	1.0	.7	.1
Door Area (4)	42 SF			42 SF		
Storm Door Area (5)	21 SF			21 SF		
R Value of Doors (6)	2.7			2.7		
# Lg. Windows	.96	1.5	.1	.60	1	.1
# Med. Windows	4.5	3.9	.2	4.5	4.3	.5
# Sm. Windows	5.9	4.7	.2	5.2	4.6	.6
# Lg. Window Storms	.88	1.4	.1	.48	.76	.1
# Med. Window Storms	4.0	3.9	.2	3.7	4.3	.5
# Sm. Window Storms	5.0	4.7	.2	3.7	4.1	.5
% Window Covered with Plastic	12%			18%		
Total SF Windows (8)	200			180		
Total SF Windows w/ Storms (8)	175			140		
Total SF Windows w/ Plastic (8)	25			30		
R Value of Windows (9)	1.7			1.6		

Table 1 (Cont.)

	Montana			Missoula		
	Sample (1) Mean	Sample (2) Std. Dev.	Std. Dev. (3) of Mean	Sample (1) Mean	Sample (2) Std. Dev.	Std. Dev. (3) of Mean
% Windows & Doors Weatherstripped (7)	56			44		
% Windows and Doors Caulked (7)	59			49		
% Wall Insulated (7) (valid cases 387)	83.5	34.3	1.7			
R Value of Wall Insulation (10)	8			8	5.0	.1
R Value of Wall (11)	11			11		
% Ceiling Insul. (valid cases 401)	89.0	29.6	1.5			
R Value of Ceiling Insul. (12)	16.7			15.3	9.3	1.7
% Roof Insulated (valid cases 366)	14.9	34.3	1.8			
R Value of Roof Insulation (13)	1.8			2.0	6.5	1.2
R Value of Ceiling/ Roof Insulation	19			17		
R Value of Ceiling (14)	22			20		
% Floor Insulated (valid cases 376)	14.4	33.0	1.7			
R Value of Floor Insulation (15)	1.4			0	1.3	.2
% Crawl Space Insul. (valid cases 162)	14.4	34.0	2.7			
R Value of Crawl Space Insulation (16)	.2			0	0	--
R Value of Floor & Crawl Space Insul.	2			0		
R Value of Floor (17)	8.7			6.7		

NOTES TO TABLE 1

1) $\bar{X}$ = sample mean = $\frac{\sum x_i}{n}$ where: n = number of houses
x_i = the value for the ith house

2) s = sample standard deviation = $\sqrt{\frac{\sum (x_i - \bar{X})^2}{n-1}}$

3) sx = the standard deviation of the mean = $\frac{s}{\sqrt{n}}$

4) rounded to 2 doors at 21 SF each
(Leckie et al. 1975, Intermountain Lumber)

5) rounded to 1 door

6) R value of door without storm = 2 hr.-SF- F/BTU
R value of door with storm = 3.3
(Leckie et al. 1975, Shelton 1976)

7) Results reported as "all", "some", or "none" - "some" was interpreted as 50%.

8) Assumes 36 SF for large windows, 25 SF for medium windows, and 9 SF for small windows (Elrick and Lavidge vol. 2 1980).

9) R of single pane window = .9
R of window with storm = 1.8
R of window with plastic= .95
(Leckie et al. 1975, Marshall and Argue 1981, Shelton 1976)

10) for MT, R of wall insulation is:
[(% walls insulated w/fiberglass)(R3.14/in.)+(% walls insulated w/loose fill)(R2.8/in.)+(% walls insulated w/foam)(R5.2/in.)][3.5 in.][% wall insulated]
= [(.703)(3.14)+(.109)(2.8)+(.053)(5.2)][3.5][.835]
= 8.14
(Leckie et al. 1975)

11) R of wall insulation + R of wall components
R of wall components is: .17(exterior air film) + .78(wood siding) + .62(.5 in. plywood sheathing) + .45 (.5in. drywall) + .68(interior air film) = 2.70
rounded to 3
(HUDAC 1980, Marshall and Argue 1981)

12) for MT, R of ceiling insulation is:
[(average in. of fiberglass)(3.14)+(average in. of loose fill)(2.8) +(average in. of foam)(5.2)][% ceiling insulated]
= [(2.82)(3.14)+(2.97)(2.8)+(.31)(5.2)][.89]
= 16.72

13) for MT, computed in same way as ceiling insulation :
[(2.99)(3.14)+(.21)(2.8)+(.37)(5.2)][.149]
= 1.78

14) R of ceiling insulation + R of roof insulation + R of ceiling/roof components
R of ceiling/roof components: .17(exterior air film) + .44(asphalt shingles) + 1.25(sheathing) + .62(.5 in. plywood) + .45(.5 in. drywall) + .61(interior air film) = 3.07
(HUDAC 1980, Marshall 1981)

15) for MT, computed in same way as ceiling insulation:
[(2.94)(3.14)+(.13)(5.2)][.144]
= 1.43

16) for MT, computed in same way as ceiling insulation:
[(.20)(3.14)+(.13)(5.2)][.144]
= .2

17) R of floor insulation = R of crawl space insulation + R of floor components
R of floor components = 6.7
(Shelton 1976)

Table 2

SAMPLE COMPARISONS

	Montana Sample	Missoula Sample
Floor Area	1312 SF	1118 SF
Number of Doors	2.2	1.9
Window Area	200 SF	180 SF
Number of Stories	1.29	1.24
Indoor Temperature	66°F	66°F
R of Ceiling Insul.	19	17
R of Floor Insul.	2	0
R of Wall Insul.	8	8
R of Windows	1.7	1.6
R of Doors	2.7	2.7

SAMPLE FLOOR AREA DISTRIBUTIONS

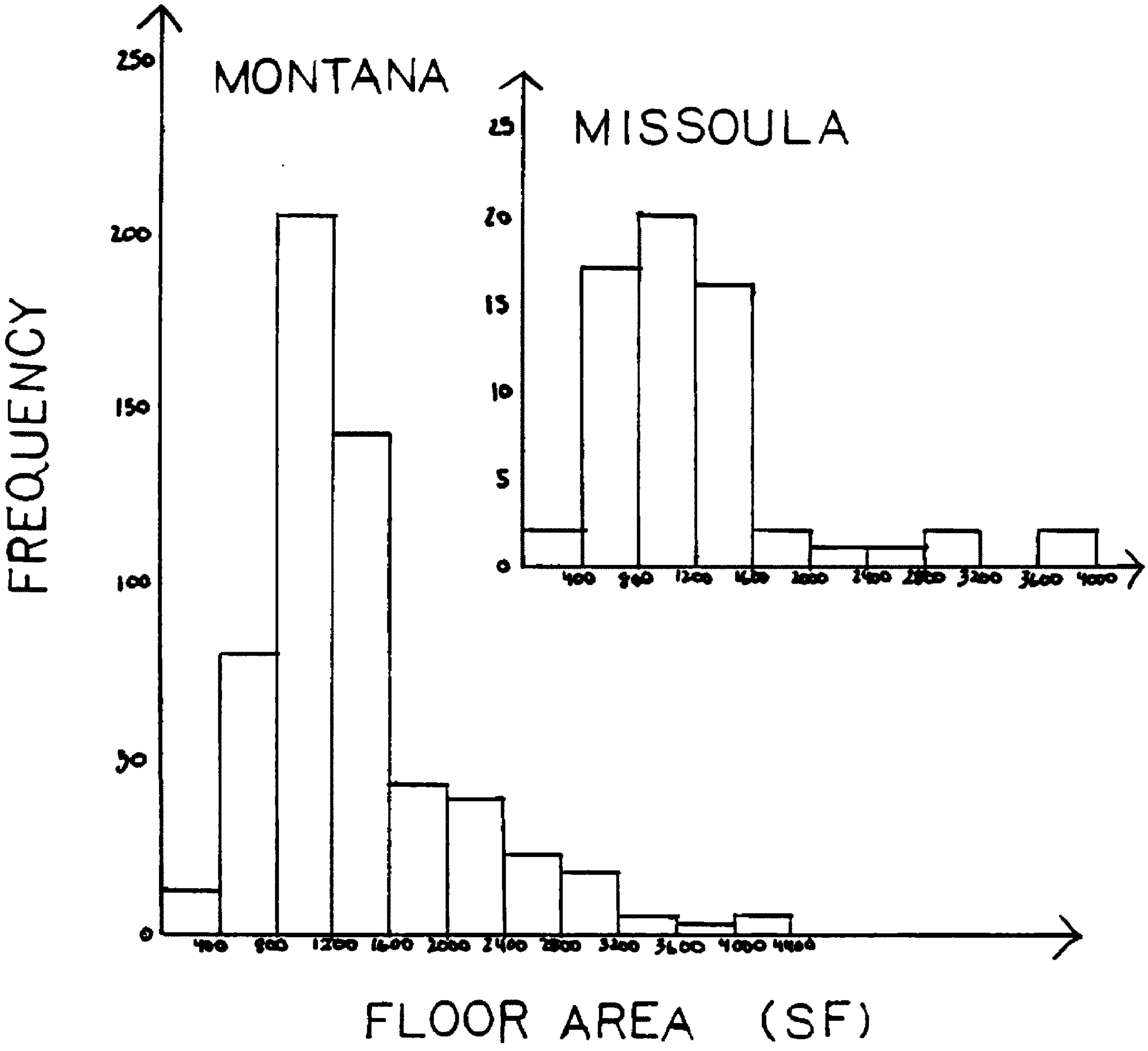


FIGURE 1

Lavidge measured neither ceiling heights nor perimeter dimensions, I had to estimate them. I assumed standard eight foot ceilings (Konigsberg 1980, HUDAC 1980). Palmiter and Baylin (1982), using the entire four-state sample, assumed the average single-family house was one and a half times as long as wide. Because the Montana sample included trailers and apartments in addition to single-family houses, I estimated that the average house here was twice as long as wide.

Theoretical Heat Load

Envelope Losses

Houses lose heat to the outdoors through their ceilings, walls, floors, windows, and doors - known collectively as the building envelope or shell. There are three basic ways by which heat is transferred . Heat radiates via electromagnetic waves from a warm surface to a colder one, and conducts via molecular interaction when the warmer surface actually touches the colder one. Conduction generally accounts for more heat loss from houses than does radiation. However, convection accounts for the majority of heat lost through an uninsulated house envelope. Heat convection results when air, touching a warm interior surface such as a wall, gains heat, moves through the air space between the interior plaster to the exterior siding where it loses heat, falls, and moves back to the interior wall ready to begin the process anew. Insulation, e.g. fiberglass batts or loose fill, greatly reduces convective heat transfer by trapping air in thousands of small pockets, thus creating enough resistance to

Table 3

AVERAGE HOUSE

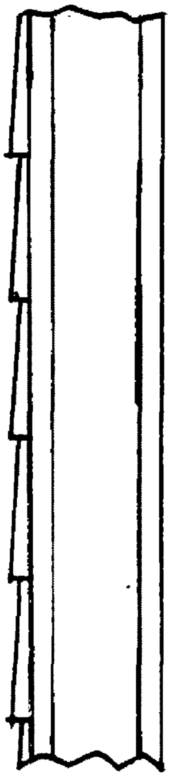
Ceiling Area	1300 SF
Floor Area	1300 SF
Wall Area	1278 SF
Length	50 SF
Width	26 SF
Door Area	42 SF
Window Area	200 SF
Number of Stories	1
Ceiling Height	10 FT
Indoor Temperature	66° F
R of Ceiling	22
R of Floor	8.7
R of Wall	11
R of Doors	2.7
R of Windows	1.7
Infiltration Rate	1 ACH

air movement to offset the interior/exterior temperature differences driving convection. Since most insulating materials conduct heat better than still air does, adding insulation actually increases conductive heat loss. However, the decrease in convective losses more than compensates for this. Storm windows, on the other hand, reduce conduction by inserting a 4-inch layer of air, a poor heat conductor, between two panes of glass. Both insulation and storm windows reduce radiation losses (Leckie et al. 1975, HUDAC 1980).

R values measure a material's resistance to heat transfer; the greater the R value the better the material insulates. For example, an inch of fiberglass with an R value of 3.14 hr-SF-degree F/BTU is a better insulator than a single pane of glass which has an R value of .9. The R value of a composite structure such as a wall is the sum of the R values of its components. An uninsulated frame wall thus has an R value of 3.4. (see Figure 2) (Leckie et al. 1975, HUDAC 1980, Marshall and Argue 1981).

For each house, the Elrick and Lavidge survey noted how much of the wall, ceiling, and floor was insulated, how thick the insulation was, and whether it was fiberglass, loose fill, or foam. For the 62 house Missoula sample I calculated the R value of each building component for every house and then averaged. For the 570 house Montana sample this would have been tedious. Therefore, I used sample averages to compute composite R values. For instance, on average, 89% of the ceiling was insulated with 2.82 inches of fiberglass, 2.97 inches of loose fill, and .31 inches of urea formaldehyde foam. In reality, no individual ceiling was built in such an odd way. Because of different

CROSS VIEW OF A WALL
UNINSULATED HOUSE



Structural Component	R-value
interior air film	.68
½" drywall	.45
3½" air space	.68
½" plywood sheathing	.62
wood siding	.78
exterior air film	.17
	3.38

FIGURE 2

construction styles some houses have insulated ceilings, others have insulated roofs, a few have both. I combined the average ceiling and roof R values to describe what I've called the "ceiling R value". Wall and floor R values were calculated in the same manner (see Table 1). In all cases I've rounded the insulation R to the nearest whole number. To be exact, I should have accounted for framing when calculating these R values; i.e. the R value through the studs is different from that through the insulation. I didn't do this because it makes little difference (2), and because I don't feel the survey data is precise enough to justify such fine-tuning.

Ideally, the sun's effect on the south wall and roof insulation also needs to be considered. The R values I've used are "steady-state" values determined by ASHRAE (the American Society of Heating, Refrigeration, and Air Conditioning Engineers) in laboratory tests. However, Tsongas (1979) measured wall R values for a house in Portland, Oregon and found the effective R value for fiberglass in the south-facing wall to be 5.42/inch rather than 3.14/inch. Similarly, the R value for an inch of cellulose was 3.75 rather than 3.3. On the other hand, the sun didn't increase the R value of the roof insulation perhaps because the attic of the test house was heavily insulated and shaded during most of the day. The sun's effect varies directly both with winter temperatures and with the amount of sunshine hitting the south wall. Like Portland, Missoula gets little winter sunshine. However, winters here are much colder; Portland has about 4600 annual heating degree days (DD), Missoula about 7900 DD (Leckie et al. 1975, U.S. Weather Bureau). Since I couldn't quantify the sun's effect on south wall insulation in Missoula, I ignored it.

I had to estimate the window area for the house. Elrick and Lavidge didn't measure windows but instead categorized them as "small", "medium", or "large". Using the guidelines in the survey instructions (Elrick and Lavidge vol. 2 1980), I assumed large windows were 36 SF (square feet), medium ones 25 SF, and small ones 9 SF. This implies a total window area of 200 SF or about 15% of the floor area, generally considered a reasonable estimate (Konigsberg 1980, Nordell 1982, Ecotope 1977).

Finally, the theoretical heat load for each of the house envelope components was calculated by dividing the area of that component by its R value (Balcomb et al. 1980, Konigsberg 1980, Leckie et al. 1975). These are listed in Table 4.

Infiltration

Houses also lose heat through cracks in their shells. Leaks commonly occur wherever two different materials meet, such as where the house frame joins the foundation, or wherever a hole is cut in the shell, e.g. for a window or electric meter. The rate of air infiltration depends not only on the size and location of the cracks, but also on wind speed, the temperature difference between indoors and out, how much air the furnace needs for combustion, and how often people open the windows and doors. People's habits are basically unquantifiable but wind speeds and temperatures can be measured. Furnaces are discussed in the next section.

The wind creates a pressure difference across the building shell

Table 4

THEORETICAL HOUSE HEAT LOAD

Envelope Heat Load

	Area	R Value	Heat Load	% Envelope Load
Ceiling	1300 SF	22	59 BTU/DH	12.9%
Wall	1278 SF	11	116 BTU/DH	25.3%
Floor	1300 SF	8.7	149 BTU/DH	32.6%
Windows	200 SF	1.7	118 BTU/DH	25.8%
Doors	42 SF	2.7	16 BTU/DH	3.5%
			458 BTU/DH	

Infiltration Heat Load

Number of ACH	Heat Load	% Total House Load	Total Load
1	208 BTU/DH	31.2%	666 BTU/DH
.6	125 BTU/DH	21.4%	583 BTU/DH
1.5	312 BTU/DH	40.4%	770 BTU/DH

which acts like a bellows, sucking air in through the windward side and pushing it out through the leeward side. The inside/outside temperature difference also creates a pressure difference, called the "stack effect". The stack pressure difference pulls air in through the house foundation and pushes it out through the attic (Dickinson et al. 1982, Blue et al. 1979, Marshall and Argue 1981).

Mathematically, infiltration is a complicated process defined approximately by the following equation:

$$Q = A\sqrt{(\text{stack term}) + (\text{wind term})} \qquad (3)$$

where: Q = the rate of infiltration
A = the effective leakage area

(Dickenson et al. 1982, Sherman and Grimsrud 1980).

The effective leakage area of a house can be measured precisely with a blower door, a door-mounted variable speed fan which pressurizes or evacuates the house providing steady air flow through cracks and openings. Used in conjunction with a smoke pencil, an infrared scanner, or even a low-tech candle, blower doors can easily locate air leaks. With a calibrated blower door and pressure censors one can quantify the percentage of infiltration attributable to the various air leaks in the house (Harrje et al. 1981). For example, Caffey (1977) measured infiltration rates for 50 houses in Dallas, Texas. The sill plate (where the house joins its foundation) accounted for 25% of air infiltration, switches and wall outlets for 20%, windows for 12%, doors for 7%, ductwork for 14%, and miscellaneous other cracks and openings for the remaining 22%. The average number of air changes per hour (ACH) for these houses was 1.49 (cited in Blue et al. 1979). At Midway, Washington the average infiltration rate for 20 houses was about .4 ACH (Dickenson et al. 1982). Gas tracers have also been used to determine effective leakage areas (Burch and Hunt 1978, Sherman 1980).

Elrick and Lavidge did not measure infiltration directly. Rather, they noted whether or not the windows and doors were weatherstripped and caulked. About 50% of the windows and doors in the Montana sample were (see Table 1). Considering that windows and doors may only account for 20% of infiltration losses, this doesn't provide much information. Therefore, to estimate the average ACH for Missoula's houses, I had to make an educated guess based on comparing Missoula's climate to the climates of Dallas and Midway. The Dallas site had an average wind speed of 15 MPH (miles per hour) and about 2400 annual heating degree days (Caffey 1977 cited in Blue et al. 1979, Leckie et al. 1975), windier but considerably warmer than Missoula which has an average wind speed of 6 MPH (Western Sun 1980) and over 7900 degree days per year (US Weather Bureau). Midway with 4600 degree days is also warmer than Missoula but has similar wind velocities, averaging 7 MPH (Dickinson et al. 1982). It seems likely that the average house in Missoula changes air faster than the ones in Midway. The climate here is much colder. Palmiter and Baylin (1982) assumed .6 ACH for the entire Elrick and Lavidge sample but didn't explain why. Again, both Washington and Oregon have milder winters than Missoula. Also, only 20% of the houses in these two states have gas furnaces as compared to 80% in Missoula. Sixty-five percent of the houses in the survey came from these two states (Elrick and Lavidge vol. 1 1980).

Considering all this, I assumed an air exchange rate of 1 ACH for the average Missoula house. Neither blower doors nor gas tracers measure infiltration caused by furnace cycling or people opening doors, so I estimated high. Because this estimate is far from certain, I also used infiltration rates of .6 ACH, Palmiter and Baylin's estimate, probably a reasonable lower limit, and 1.5 ACH as was measured in Texas. Perhaps the colder temperatures here just offset the more blustery winds there.

The following formula was used for calculating the theoretical heat load due to air infiltration:

Infiltration = (House volume)(.016)(# ACH)

where: .016 = heat capacity of air at 3000 ft. (Konigsberg 1980, Balcomb et al. 1980). Table 4 shows the predicted heat loads for air exchange rates of .6, 1, and 1.5 ACH respectively.

Furnace Losses

Furnace inefficiency is the third major source of heat loss in houses. Most gas furnaces are inherently inefficient, using large amounts of air for combustion and cycling on and off frequently, sending a lot of heat up the flue during start up and shut down periods. The major reason for frequent cycling is that gas furnaces are generally oversized, often to twice the maximum heating demand for the house. However, high flame settings and narrow control spans also lead to excessive cycling (Hise and Holman 1975, McGrew et al. 1979). McGrew et al. tested eight forced-air gas furnaces in homes and measured efficiencies between 32.5% and 56.9%, 46% being average. Hise and Holman (1975) give 50% as an average seasonal efficiency for gas furnaces. I assumed gas furnaces in Missoula were about 50% efficient.

Barnett (1982) measured the efficiency of several freestanding woodstoves in his home in upstate New York (4). Thin-walled (<.25 in.) stoves were 50% efficient at best. Thick-walled (>.25 in.) stoves could be 60% efficient with a hot-burning fire. Even the cadillac of woodstoves, the stick-wood boiler, is only 65% efficient (Hill 1979). Smoldering fires led to efficiencies of 35% or less no matter what kind of stove was used. I used 50% as an estimate for Missoula's woodstoves. This is probably generous since most Missoulians own thin-walled stoves (Church 1980), and many burn smoldering fires.

I assumed electric baseboard heaters were 100% efficient (Palmiter and Baylin 1982) and fuel oil furnaces 50% efficient (Burch and Hunt 1978, Duffield 1980).

Actual Heat Load

Table 4 shows the theoretical energy use for the average Missoula house; 666 BTU/DH (British thermal units per degree hour) given 1 ACH. Ideally, this theoretical energy use should be compared to the actual power use data from the same houses. However, the survey included houses from places throughout Montana, many with very different climates from Missoula. Therefore, I obtained cumulative residential electricity and gas consumption figures for June 1979 - May 1980 from Montana Power Company (MPC), and wood use data from the Health Department's 1979-1980 residential woodburning survey (Church 1980).

The raw data from MPC is in Appendix B. The power company also gave me monthly power use streams for 400 randomly selected Missoula houses from January 1979 through December 1980.

Since there was relatively little monthly difference in per customer gas and electric use from June through September (see Appendix B), I defined October through May as the heating season. For appliance consumption I subtracted three times the cumulative June through September electric and gas use from the yearly totals and assumed the rest was used for space heating. This probably understates the appliance load slighty since people burn their lights longer during Missoula's short winter days than during the long days of summer. From the MPC sample of 400 homes I determined that about 4% of the houses with gas hookups aren't heated with gas, 1% being heated with electricity and the other 3% with miscellaneous other fuels indeterminable from the sample. Of the houses without gas hookups about half are heated with electricity. I adjusted the number of gas and electric customers accordingly to arrive at the number of houses heated with gas and electricity respectively, and hence at the average space heating load for each fuel. See Table 5 for a more detailed explanation.

Church (1980) reports that in the 1979-1980 heating season about 60% of Missoula's households burned an average of 2.7 cords of wood apiece. This is equivalent to each of Missoula's households burning 1.6 cords of wood. Missoulians burn a mix of native conifers consisting mostly of douglas fir, western larch, ponderosa pine, and lodgepole pine (Otis 1977). These have an overall specific gravity

Table 5

ACTUAL HEAT LOAD OCTOBER 79 - MAY 80

Total Electricity Used (1)	184,959,265 kwh
Appliance Use (2)	140,614,935 kwh
Space Heat Use	44,344,330 kwh
Number of Houses Heated w/Elec. (3)	2620
Space Heat Use/House (4)	16,925 kwh
	= 57.8×10^6 BTU
Total Gas Used (5)	2,155,295.5 mcf
Appliance Use (6)	813,584.4 mcf
Space Heat Use	1,341,711.1 mcf
Number of Houses Heated w/Gas (7)	16,771
Space Heat Use/House (8)	80.0 mcf
	= 83.8×10^6 BTU
Wood Burned/Woodburning Household (9)	2.7 cords
Wood Burned/House (10)	1.6 cords
	= 33.0×10^6 BTU
Average House Heating Load (11)	113.9×10^6 BTU
Heat to House (12)	61.2×10^6 BTU

1) from Montana Power Company
2) (June through September use) X 3
3) Average monthly Oct.-May elec. customers minus average monthly gas customers divided by 2 plus 1% of the # of gas customers
4) 3413 BTU/kwh
5) from MPC
6) (June through September use) X 3
7) Average monthly Oct.-May gas customers minus 4%
8) 1.048 BTU/mcf
9) Church 1980
10) about 60% of Missoula households burned wood in 1980 (Church 1980)
11) 1/9 (average electric load) + 8/9 (average gas load) + average wood use
12) 100% efficiency for electric baseboard heaters, 50% for woodstoves and gas furnaces

of .48 grams per cubic centimeter (Wood Handbook 1974) and, given the probable collection and storage techniques of Missoula woodburners, a moisture content of 25% (Church 1980). This implies that the average Missoula house burns 33 X 10^6 BTU of wood (5).

In addition to wood, 80 % of Missoulians burn gas for heat, 10% use electricity, and 10% use other fuels such as fuel oil, bottled gas, solar collectors, and coal (MPC sample, Elrick and Lavidge data tape) (6). Since I couldn't quantify the amount of heat obtained from these miscellaneous other fuels, I added 8/9 of the average gas heating load and 1/9 of the average electric heating load to the average wood energy use to derive the total heating load for the composite Missoula house. Assuming wood stove and gas furnace efficiencies of 50% and electric baseboard efficiency of 100%, the average Missoula house used 61 X 10^6 BTU for space heating from October 1979 - May 1980. Again, as was mentioned earlier in reference to ceiling construction, no individual house was heated in such an unusual manner.

Theoretical vs. Actual Heat Use

To compare the theoretical heat load with the actual heat load, I computed the house heat load coefficients predicted by the survey and by MPC's and the Health Department's power use figures. From the survey house description this is 12.3 BTU/SF-DD (7). In order to derive the house heat load coefficient from the power use data, I first had to determine the number of applicable degree days for the

1979-1980 heating season. The traditionally used degree day is based on an indoor balance temperature (the temperature to which the furnace must heat the house) of 65 degrees F (Fahrenheit). ASHRAE (1977) assumes a 72 degree F thermostat setting would result in a 65 degree F indoor balance temperature. It thus seems likely that the average Missoula house, with its thermostat set at 66 degrees F, would have a lower interior balance temperature. To determine what the balance temperature was, I estimated internal and passive solar gains for the Missoula house assuming three people per household (1980 Census of Population and Housing) and one fourth of the window area, i.e. 50 SF, facing in each direction. Table 6 contains the details of the calculations. The total internal gains from people, appliances, and hot water was 83,187 BTU/day; the average solar gains were 43,719 BTU/day. The interior balance temperature is defined as:

$$T\ bal. = T\ set - \frac{QI + QS}{LOAD}$$

where: T bal.= the interior balance temperature
T set = the thermostat setting
QI = internal gains
QS = solar gains
LOAD = the theoretical heat load

For the average house the interior balance temperature is about 58° F (8), implying 5342 degree days during the 1979-1980 heating season (see Appendix C) and a heat load coefficient of 8.8 BTU/SF-DD (9). The actual heat loss was roughly 25% lower than that predicted by the building characteristics.

When optimizing insulation I used the heat load coefficient calculated from the actual power use because that data was Missoula

Table 6

INTERNAL AND SOLAR GAINS

Internal Gains

Internal gains = Heat from people, appliances, and hot water

Heat from people = # of people X Metabolic heat production X Hrs. at home/day
= 3 people X 88 watt-hr. X 3.41 BTU/watt-hr. X 16 hrs. (1)
= 14,404 BTU/day

Appliance heat = Daily appliance electric load
= $\frac{540(12)}{365}$ X 3413 Btu/kwh (2)
= 60,592 BTU/day

Hot Water heat = 100 watt-hr. X 24 hrs./day X 3.413 BTU/watt-hr. (3)
= 8191 BTU/day

Internal gains = 14,404 + 60,592 + 8191
= 83,187 BTU/day

Solar Gains (4)

Solar Gains = [South Window Area + .45(East + West Window Area)](.6) (5) X the yearly sum of: Monthly Solar Insolation at 90° Tilt (6) X Monthly % Heating Season Degree Days

$$= [50\text{ SF} + .45(100\text{ SF})][.6] \times [\underset{\text{Jan.}}{(599\text{ BTU/SF-day})(.187)} + \underset{\text{Feb.}}{(762)(.145)} + \underset{\text{Mar.}}{(927)(.134)} + \underset{\text{Apr.}}{(900)(.087)} + \underset{\text{May}}{(879)(.054)} + \underset{\text{Oct.}}{(1118)(.089)} + \underset{\text{Nov.}}{(837)(.134)} + \underset{\text{Dec.}}{(671)(.171)}]$$

= [95 SF][.6][799 BTU/SF-day]
= 45,543 BTU/day

1) from Ribot and Rosenfield 1982, 1980 Census of Population and Housing
2) from MPC (Appendix A)
3) from Dumont et al. 1982
4) method from Balcomb et al. 1982, Fowlkes 1982
5) depends on clearness factor and solar declination, assumes 2 glazings from Balcomb et al. 1982, Fowlkes 1982
6) 1977-1982 averages, from Fowlkes 1982

specific, and because heat load models and housing surveys tend to overestimate heating requirements (Mike Chapman and Lynda Steele, Department of Natural Resources and Conservation, Helena, MT, personal communication 1983). No one really knows why, but Mike Chapman considers it likely that passive solar gains are greater than expected, even during western Montana's gloomy winters in houses with little thermal mass. Lynda Steele believes that surveys often inadvertently report garage and unheated basement space as part of the heated floor area. On the other hand, wood use could easily have been underestimated. Randomly selected Missoula householders were contacted by phone and asked to approximate how many cords of wood they had burned during the preceeding heating season (1979-1980) (Church 1980). They might have guessed low.

At any rate, using the lower heat load calculated from the power use figures probably understates heating requirements somewhat and, hence, biases the case against conservation. The optimum retrofits presented in the next chapter are conservative.

Footnotes

1) The test is, if X and Y are both independent, normal random variables, and you take large samples of size m from X and size n from Y, then:
$\overline{X} - \overline{Y} +/- 1.96\sqrt{s_x^2/m + s_y^2/n}$ describes a 95% confidence interval for the difference between the actual means of X and Y. If this interval doesn't contain zero then the means are significantly different at the 5% level.
where : $\overline{X} = \sum xi/m$ $\quad s_x^2 = \sum(xi - \overline{X})^2/m$
$\overline{Y} = \sum yi/n$ $\quad s_y^2 = \sum(yi - \overline{Y})^2/n$
For the natural log transformation of floor areas:
Montana sample $\overline{X} = 7.06$ $\quad s = .49$
Missoula sample $\overline{X} = 6.89$ $\quad s = .50$
The 95% confidence interval for the differences between the sample means is the interval (.04 to .30).

2) For example, considering the framing, the R value of the house wall is:
.125(R through the studs) + .875(R through the insulation)
= .125(6.1) + .875(11)
= 10.4 (Petersen 1974, Corbett and Duffield 1982).
The difference between 10.4 and 11 is well within the margin of error in the data.

3) The stack term is the product of the inside/outside temperature difference and a house specific stack constant. The stack constant describes the relative importance of infiltration through the ceiling versus the floor, defines the velocity at which air flows vertically through the house, and accounts for the fact that, given a different temperature inside and out and a vertical temperature gradient within the house, there is a height where the inside/outside pressure difference is zero.
The wind term is the product of the wind velocity and a house specific wind constant. The wind constant measures how protected the house is by trees, other buildings, fences, etc., considers the terrain at the house site vs. the terrain at the nearest weather station, and accounts for the fact that ceilings and floors are more shielded from the wind than walls. (Sherman and Grimsrud 1980).

4) He was thus burning sugar maple, American elm, and red oak (hardwoods) rather than the pines, larch, and douglas fir (softwoods) burned in Missoula. This should make little difference to stove efficiency because the moisture content of all the woods was the same, about 25% (Barnett 1982, Church 1980).

5) Wood with a specific gravity of .48 and 25% moisture content weighs

37.1 lbs./cubic foot. Since moisture content is defined as the weight of the water in the wood divided by the weight of the wood net of the weight of water, this converts to 7.4 lbs./cubic foot water and 29.7 lbs./cubic foot wood (Wood Handbook 1974). Assuming no heat comes from the water, the heat obtained by burning a cord of Missoula mixed conifers is: 29.7 lbs./cubic foot X 80 cubic feet/cord X 8600 BTU/lb. = 20.4×10^6 BTU/cord (Shelton and Shapiro 1976).

6) After this analysis was done the 1980 Census of Population and Housing was released. The Census Bureau reports that 76% of the households in Missoula use gas for primary heat, 18% use electricity, 1% use fuel oil, and 4% use wood. These figures are reasonably close to my estimates from the MPC sample.

7) $$\frac{666 \text{ BTU/DH} \times 24\text{HR/day}}{1300 \text{ SF}} = 12.3 \text{ BTU/SF-DD}$$

8) $$\begin{aligned} T \text{ bal.} &= 66^\circ \text{F} - \frac{128{,}730 \text{ BTU/day}}{666 \text{ BTU/DH} \times 24 \text{ HR/day}} \\ &= 66^\circ \text{F} - 8.1^\circ \text{F} \\ &= 57.9^\circ \text{F} \end{aligned}$$

9) $$\frac{61 \times 10^6 \text{ BTU}}{5342 \text{ DD} \times 1300 \text{ SF}} = 8.8 \text{ BTU/SF-DD}$$

Chapter 3

CONSERVATION RETROFITS

Lifecycle Costing

Equating the cost of fuel to the cost of energy saved by retrofitting defines the cheapest combination of insulation and fuel that will heat the house. Insulation lasts many years, heating fuel only a short time. Therefore, to compare the cost of a one time investment in insulation to the cost of yearly fuel purchases, I converted the lifecycle costs of both into equal annual amounts. Equation 1 was used to annualize insulation prices and equation 2 fuel prices, the difference being that equation 2 accounts for the expected rate of increase in fuel prices during the lifetime of the insulation. Both are standard accounting formulas. Equation 1 has been called the Capital Recovery Factor and equation 2 the Fuel Price Levelization Factor.

$$1)\quad \frac{d(1+d)^n}{(1+d)^n-1}$$

$$2)\quad \left(\frac{1+e}{d-e}\right)\left(1-\left(\frac{1+e}{1+d}\right)^n\right)\left(\begin{array}{c}\text{Equation}\\ \#1\end{array}\right)$$

where : d= the discount rate, or the cost of borrowing money
n= the expected lifetime of insulation
e= the fuel price escalation rate

(Davis 1966, Ruegg 1981, Corbett and Duffield 1982)

Lifecycle costing analysis is fairly sensitive to the discount rate and lifecycle chosen. Ideally, the discount rate reflects the opportunity cost of insulation or, alternatively, the expected rate of return if the money were put to a different but related use. Economists debate what the discount rate should be. Corbett and Duffield (1982) recommend using a 3% real discount rate since banks have historically charged real interest rates near 3% for mortgages and home improvement loans. The Department of Energy (DOE) recommends a 7% discount rate for government-financed alternative energy projects (Ruegg 1981). Nordell (1982) used a 4% discount rate and Dickenson et al. (1982) discount rates of 2.7%, 4.5%, and 7.3% for conservation retrofit projects in northwestern Montana and central Washington, respectively. I used discount rates of 3% and 7% because they bracket the range of values used.

The length of the lifecycle should be the expected lifetime of the project. I used lifecycles of 25 and 10 years; 25 years because it was recommended by Corbett and Duffield (1982) and 10 years because most builders and homeowners expect short pay-back periods. However, since a reasonably well-built house lasts longer than 50 years and, since the average Missoula house is only about 30 years old (1980 Census of Population and Housing), even the 25 year lifecycle is conservatively short.

Table 7 lists the resulting Capital Recovery Factors.

Materials Prices

I obtained prices for insulation, storm windows, and storm doors

Table 7

CAPITAL RECOVERY FACTORS

discount rate	length of lifecycle 10 YR.	25 YR.
3%	.1172	.0574
7%	.1424	.0858

from insulation contractors and building supply stores in Missoula. Because most insulating businesses insist on making on-site inspections before they will give price estimates, I only got one or two price quotes for most of the retrofits. Therefore, I compared these local price estimates with those reported by Nordell (1982), who surveyed twelve insulation contractors in western Montana, northern Idaho, and Spokane, Washington. Nordell's prices were significantly different only in the case of floors.

Blowing cellulose into ceilings is cheaper than adding fiberglass batts. For Missoula, costs were 26 cents/SF for blowing in R 19 insulation, 37 cents/SF for R 30, and 45 cents/SF for R 38 (Lynch Insulation 1982). Nordell reports the price of blown cellulose as \$.01563 + \$.013547R, equivalent to 27 cents/SF for R 19, 42 cents/SF for R 30, and 53 cents/SF for R 38, only slightly higher than the Missoula prices.

The price for blowing cellulose into the wall, assuming a standard 3.5 inch wall cavity, was 55 cents/SF (Lynch Insulation 1982) almost identical to Nordell's 56 cents/SF. Since filling in the wall of the average Missoula house only increases its insulation R value from R 8 to R 11, I also considered rebuilding the wall and adding extra insulation. Corbett and Duffield (1982) describe 29 ways of constructing walls in new houses. Applied to existing houses the cheapest one costs \$1.13/SF; entails adding an extra set of studs, a 3.5 inch fiberglass batt, a vapor barrier, and new drywall; and raises the R value of the wall from R 14 to R 25. Rebuilding walls usually costs about half again what it costs to build from scratch (Fred

Quivick, National Center for Appropriate Technology, Butte, MT, personal communication 1982). Inflating the price accordingly, retrofitting an existing house with a double stud, R 25 wall would cost $1.70/SF.

Because most floors are built with 10-inch joists, the maximum amount of insulation that can practically be installed is 10 inches or R 30. The average Missoula house has less than an inch of floor insulation so it would be possible to add R 30 should that prove cost-effective. The price for attaching fiberglass batts underneath floors was 52 cents/SF for R 11, 87 cents/SF for R 19, and $1.38/SF for R 30 (Intermountain Lumber 1982; Jim Corrigan, Human Resources Development Council, Missoula, MT, personal communication 1982). In this caes, Nordell's price of 53 cents/SF for adding R 19 was the same as the Missoula price for R 11. I called the floor retrofit R 19 when 52 cents/SF was optimum since it is based on more price quotes.

Besides cellulose and fiberglass, urea-formaldehyde foam has often been used for insulating ceilings, walls, and floors. However, it emits fumes to which many people are seriously allergic (Energy User's Report 1 July 1982). Foam also shrinks and cracks after a few years, prompting the United States and Canadian governments to derate its nominal R value from R 5.2/inch to R 3.7/inch and R 3.1/inch respectively (Tsongas 1979). Thus derated, its insulating value is comparable to that of cellulose or fiberglass. In 1982, the Consumer Product Safety Commission banned urea-formaldehyde foam in houses and schools (47 FR 14336 2 April 1982). This ruling has recently been overturned but, because the fumes can make people sick, and because foam insulates no better than either cellulose or fiberglass, I didn't consider retrofitting with it.

Blown cellulose may settle, especially in walls. Petersen (1974) recommends adding 10% for settling and I have done so. However, Tsongas (1979) reports that cellulose doesn't settle significantly so I may have overestimated the cost of insulating both walls and ceilings. Although blowing cellulose is the only relatively inexpensive way to insulate existing walls, one can avoid the possible settling problems in ceilings by installing fiberglass batts. If done by the homeowner this costs about the same as blowing in cellulose (Intermountain Lumber 1982) (1).

It is sometimes stated that insulation shouldn't be backfitted into walls because it lowers the temperature of the outside wall thereby moving the dewpoint from outside the house back into the insulation. Water vapor passing through the interior plaster or drywall will then condense to water in the cold wall cavity eventually causing wood to rot, siding to warp, and paint to peal. Vapor barriers placed between the inside wall and insulation prevent this but are difficult and very expensive to backfit into houses. However, the interior walls can be coated with moisture-resistant paint (Petersen 1974, NRDC 1982). This may or may not be necessary. Seton, Johnson, and Odell (1980) found no evidence of moisture damage, high moisture content, or wood-decaying fungi in the retrofitted walls of seventy-odd houses in Portland. The colder and wetter the climate, the greater the possibility of such damage. Missoula's climate is colder, but dryer, than Portland's. Thus, it is hard to say what the relative chances of moisture damage are here. To be safe, retrofitted walls could be routinely repainted in Missoula. Although I didn't add the cost of paint to the wall retrofit price, the lifecycle cost of insulating the wall is generally so much less than the lifecycle cost of buying heating fuel that wall insulation would be cost-effective anyway.

The average Missoula house has about 25 SF of single pane windows covered with plastic. This could either represent one medium-sized window or two small ones (see Table 1). The Missoula price of a medium-sized storm window was $62.50, the same as Nordell's estimate. Two small storm windows cost $95.60 (Lynch Insulation 1982; Corrigan, personal communication 1982). I used $80.55, the average between the two. The windows of the average house lose 118 BTU/DH and adding 25 SF of storms only reduces this to 111 BTU/DH. Replacing the existing windows with triple panes further cuts the window heating load to 66.7 BTU/DH. However, triple pane windows are expensive. Factory-made ones cost between $7.65/SF and $7.80/SF; custom-made ones cost much more. Although factory-made triple panes usually will fit in the existing wells for casement windows, they usually won't fit in the openings for the double-hung wood sash windows commonly found in older houses (Missoula Glass Company 1982). Provided that factory-made windows fit, backfitting the average house with triple panes would cost $1552.50.

Table 8 summarizes all these prices plus the ones for storm doors. In all cases the prices are for contracted work, the only exception being that I've also listed the price for an owner-installed storm door. Storm doors are relatively easy to hang so many people would probably prefer doing it themselves. Table 8 also lists the annualized marginal costs of the various retrofits using the annualization factors from Table 7.

Fuel Prices

To annualize fuel prices the current price must be multiplied by the fuel price levelization factor which means finding an appropriate escalation rate. Fuel price escalation rates depend on a large number of variables including the past and present prices of the fuel, the prices of alternative fuels, future population growth, and regional economic activity (Berney et al. 1982). The number of interrelationships among these variables is enormous and the future uncertain. Not surprisingly, different economists predict different escalation rates. I used DOE Region 8 (2) escalation rates for electricity, natural gas, and fuel oil (Ruegg 1981). For electricity and gas I also used Montana specific rates (Duffield 1980). For wood I used the escalation rate predicted by Duffield (1980), the only one mentioned in the literature. Table 9 shows levelization factors for these various escalation rates employing the same discount rates and lifecycles used to annualize insulation costs.

Table 10 lists the levelized prices of the four fuels taking furnace efficiency into account as well as the different possible levelization factors. Market prices for electricity and natural gas came from Montana Power Company; the price for fuel oil is the average price quoted by three Missoula fuel oil distributors; and the price of

Table 8

RETROFIT PRICESS

CEILING : Original R 19 insulation, 1300 SF (1)

					Annualized MC		
Add R	Total R	Cost/SF	MC/SF	Total MC	3%,25YR	3%,10YR	7%,25YR
19	38	26¢	26¢	$372	$21.35	$43.60	$31.92
30	49	37¢	11¢	$157	$9.01	$18.40	$13.47
38	57	45¢	8¢	$114	$6.54	$13.36	$9.78

1) Blown cellulose, prices from Lynch Insulation June 1982
added 10% for settling

FLOOR : Original R 2 insulation, 1300 SF (2)

					Annualized MC		
Add R	Total R	Cost/SF	MC/SF	Total MC	3%,25YR	3%,10YR	7%,25YR
11	13	51.5¢	51.5¢	$668.85	$38.39	$78.39	$57.39
19	21	86.5¢	35¢	$455	$26.12	$53.39	$39.04
30	32	$1.38	51.5¢	$688.85	$38.39	$78.39	$57.39

2) Fiberglass batts, prices from HRDC and Intermountain Lumber June 1982

Table 8, Pg 2

WALL : Original R 8 insulation, 1278 SF

Add	Total R	Cost/SF	Total MC	Annualized MC		
				3%, 25YR	3%, 10yr	7%, 25YR
Fill cavity (3)	11	55¢	$211.78(4)	$12.16	$24.82	$18.17
Build in (5)	22	$1.70	$2172.20	$124.70	$253.63	$186.41

3) Blown cellulose, prices from Lynch Insulation June 1982

4) Having R 8 wall insulation in all houses is the same as having R 11 (full cavity) in 72.7% and R 0 (no insulation) in 27.3%. Thus, on average, the cost of filling in the rest of the wall is: (.273)(1278SF)(55¢/SF)=$191.89 plus 10% for settling = $211.78.

5) from Corbett and Duffield (1982)

WINDOWS : Original R 1.7, 200 SF

Add	Total R	Total MC	Annualized MC		
			3%, 25YR	3%, 10YR	7%, 25YR
25 SF Storms (6)	1.8	$80.55	$4.62	$9.44	$6.91
Triple panes (7)	3	$1552.20	$89.10	$181.92	$133.18

6) prices from HRDC, Lynch Insulation 1982

7) prices from Missoula Glass 1982, treated as an alternative first step

DOORS : Original R 2.7, 42 SF

Add	Total R	Total MC	Annualized MC		
			3%, 25YR	3%, 10YR	7%, 25YR
Storm door	3.3	$115 (8)	$6.60	$13.48	$9.87
Storm door	3.3	$100 (9)	$5.74	$11.72	$8.58

8) contractor installed, price from HRDC

9) owner installed, price from HRDC

Table 9

FUEL PRICE LEVELIZATION FACTORS

	Escalation Rate	Levelization Factor 3%,25YR	 3%,10YR	 7%,25YR
Fuel Oil	3.39% (1980-85) (1) 2.82% (1985-90) 4.06% (1990-2005)	1.5288	1.1869	1.4263
Natural Gas	1.76% (1980-85) (1) 3.95% (1985-90) 2.36% (1990-2005)	1.3751	1.1348	1.3012
	7.5% (1980-90) (2) 2% thereafter	1.9541	1.4940	
Electricity	-.02% (1980-85) (1) -2.73% (1985-90) -2.47% (1990-2005)	.8419	.9607	.8767
	2.2% (2)	1.2987	1.1231	
Wood	2% (2)	1.2672	1.1112	

1) from Ruegg 1981
2) from Duffield 1980

wood is an approximate average of prices advertised in the Missoulian "classifieds". Many people cut their their own wood but, given Missoula's air pollution problem, I felt it inappropriate to use a "self-cut" price for wood - estimated at $20/cord by Northern Lights, Incorporated (Cartwright 1982) and $12-$40/cord by Nielsen (1983).

Ideally, the social costs of fuels rather than their market prices should dictate how much insulation is put in houses. However, social costs are generally not available since the values they represent - e.g. the beauty of smoke-free mornings, good health, virgin forests, etc. - can't be measured in dollars and cents (3). Replacement or marginal costs (the price of power from a new thermal generator or gas well, etc.) while not as appropriate as social costs, are better than market prices because they reflect the price of power that will have to be added to the system if houses aren't insulated. Replacement costs can be approximated for electricity and natural gas.

The marginal cost of electricity for Montana Power Company's system is 6.4 cents/kwh - 5.3 cents/kwh for incremental base load cost and the rest for combustion turbine peaking capacity (Mike Lee, Public Service Commission, personal communication 1983; P.S.C. order #'s 4865 and 4865b 1982). The marginal cost of natural gas is equivalent to its current market price because MPC buys most of its gas from Canada at prices linked to the world price for crude oil (Lee, personal communication 1983).

Both wood and fuel oil are sold by many small, independent distributors making it difficult to estimate replacement costs. Few people in Missoula heat with fuel oil and many of those who do are switching to other fuels (Elrick and Lavidge data tape). Thus, finding a marginal price for fuel oil is probably not important. Further, because much of our oil is imported, the price of fuel oil, like that of natural gas, is partially dependent on world prices. Perhaps the market price is close to the marginal price.

On the other hand, many Missoulians heat with wood. Wood smoke contains benzo-a-pyrene and thirteen other known carcinogens, carbon monoxide, and a host of other respiratory irritants (Cooper 1980). Many of these compounds are also found in cigarette smoke which most people agree is unhealthy. Although Missoulians haven't burned wood, and breathed wood smoke, long enough for many of the more serious potential long-term health problems to show up, the Montana Air Pollution Study indicated that the city's winter smog has already harmed school children and adults with chronic breathing problems (Meduic 1981). Wood smoke diminishes psychological well-being, too. Weeks on end of Missoula's natural winter fog can be depressing enough; weeks on end of smog only add to the spiritual gloom. Many suffer from what is jokingly called the "Missoula head cold", an ill-defined and variable combination of sniffles, sore throats, eye irritation, headaches, crabbiness, and general malaise. Probably not serious, adults nevertheless miss work and children school because of it.

Although it seems certain that wood smoke has social costs, it is extremely difficult to put dollar values on such non-marketable items as physical health and psychological well-being. However, Linda

Hedstrom of the Missoula Health Department has completed some preliminary work aimed at determining the social cost of burning wood in the Missoula valley. Such social cost calculations are controversial since they involve quantifying the value of human life, a philosophically as well as technically difficult problem. Because of this, and because the results are preliminary, I decided to use her deliberately conservative low estimate, $100/cord above the market price. This estimate understates the social cost of wood burning since it 1) places a very low value on human life ($200,000), 2) considers only the incremental deaths caused by large particles, ignoring the health effects of small particles and, hence, the carcinogenic potential of wood smoke, and 3) doesn't take into account psychological or aesthetic damage.

Optimum Retrofits

Envelope

To determine the optimum envelope retrofit I had to make several assumptions. First, I assumed that an inch of ceiling insulation saved just as much energy as an inch of wall or floor insulation, neither more nor less. Second, I assumed that the ceiling, walls, windows, and doors lost heat independently of one another. This implies that insulating any one component does not change heat losses elsewhere. Energy savings from each component can then be added to derive the total energy savings for the house. Thus, the optimum level of insulation is the one for which the marginal price of the energy

Table 10

LEVELZED FUEL PRICES

Fuel	Price	BTU/unit	Furnace eff.	$/10^6 BTU	Levelized Price/10^6 BTU 3%,25YR	3%,10YR	7%,25YR
Fuel Oil	$1.16/gal. (1)	1.41X10 BTU/gal	50%	$16.52	$25.26	$19.61	$23.56
Gas, market	$4.01/mcf (2)	1.048X10 BTU/mcf	50%	$7.66	$10.53 $14.97	$8.69 $11.44	$9.97
Gas, marginal	$4.67/mcf (3)	"	"	$8.91	$12.25 $17.41	$10.11 $13.31	$11.59
Elec, market	$.029/kwh (4)	3413 BTU/kwh	100%	$8.50	$7.16 $11.04	$8.17 $9.55	$7.45
Elec, marginal	$.064/kwh (5)	"	"	$18.75	$15.79 $24.35	$18.01 $21.06	$16.44
Wood, market	$55/cord (6)	20.4X10 BTU/cord	50%	$5.39	$6.83	$5.99	
Wood, social	$150/cord (7)	"	"	$14.71	$18.64	$16.35	

1) from Tabish Bros., High Noon Petroleum, Western MT Co-op
2) from MPC : winter rate of $3.50/mcf for first 15 mcf, otherwise $4.67/mcf
MPC records show average house uses 56% gas at lower rate
from Oct.-May
3) from MPC
4) from MPC
5) from Mike Lee, Public Service Commission staff, personal communication
6) from Missoulian, Oct. 1982
7) from Hedstrom 1983
all June 1982 prices unless otherwise noted

saved equals the price of the heating fuel.

In economic terms, this translates to:

$$\frac{\text{MC wall}}{\text{MS wall}} = \frac{\text{MC ceiling}}{\text{MS ceiling}} = \frac{\text{MC floor}}{\text{MS floor}} = \frac{\text{MC windows}}{\text{MS windows}} = \frac{\text{MC doors}}{\text{MS doors}} = \frac{\text{Fuel}}{\text{Price}}$$

where: MC= the cost of the last increment of insulation added
MS= the energy saved by adding that last increment

(Petersen 1974). The MC/MS ratio, hereinafter called cost, is analagous to the fuel price in that it measures the cost of insulation in dollars per million BTU's saved. In reality, since most insulation comes in preformed sizes- e.g. fiberglass batts come in 3.5 and 6 inch thicknesses but not in 4.7 or 8.2 inch thicknesses- the optimal insulation level is the one for which the cost comes closest to the fuel price. I considered storm windows, storm doors, and wall insulation optimal if their cost was close to or less than the price of heating fuel.

Table 11 shows the heating requirements for the average house during a normal weather year given an October through May heating season and a 60° F internal balance temperature. I computed the individual component heat loads by multiplying the total envelope heat load by the proportion of heat loss attributable to each component as determined from the Elrick and Lavidge survey (see Table 4). Table 11 also lists the heat loads for the house, given air change rates of 1.5 ACH or .6 ACH instead of 1 ACH, or a higher balance temperature (65 degrees F instead of 60 degrees F) with a longer, September through June, heating season. I included the latter because the Wisconsin Public Service Commission found that people kept their houses warmer after insulating (cited in Syergic Resources Corporation 1982).

Table 11

HOUSE VARIATIONS

	Case 1 (Base Case)	Case 2 (Draftier)	Case 3 (Tighter)	Case 4 (Warmer)
Heating Season	Oct.-May	Oct.-May	Oct.-May	Sept.-June
Bal. Temp.	60	60	60	65
Degree Days	6110	6110	6110	7620
Infiltration	1 ACH	1.5 ACH	.6 ACH	1 ACH
Envelope Load (1)	48.1	41.7	54.9	60.0
Ceiling	6.2	5.4	7.1	7.8
Wall	12.2	10.6	13.9	15.2
Floor	15.7	13.6	17.9	19.5
Windows	12.4	10.7	14.1	15.4
Doors	1.7	1.5	1.9	2.1
Infiltration (1)	21.8	35.2	15.0	27.2
Total Energy Use (1)	69.9	69.9	69.9	87.2

1) All energy use figures are in 10^6 BTU.

Presumably this happened because people could then afford warmer houses, implying that many who live in uninsulated houses save money (and conserve energy) by turning down their thermostats. The Natural Resources Defense Council (1982) also mentions this as a likely result of insulating.

Tables 12 through 15 list the costs for the various retrofits and house modifications, and Table 16 the optimum retrofits for the various fuels, fuel prices, and fuel price escalation rates. Table 17 shows the optimum retrofits for the average house given either a 7% discount rate or a 10 year lifecycle.

Varying the infiltration rates and indoor temperature changed the optimum retrofit very little. The different escalation rates changed the optima somewhat. Raising fuel prices from market to replacement levels, increasing the discount rate from 3% to 7%, or shortening the lifecycle from 25 years to 10 years all significantly changed the results. Table 18 condenses Tables 16 and 17, rounding insulation R values to the nearest commercially available level, and averaging where there are differences due to the four possible house descriptions. For instance, the optimum amount of ceiling insulation for a gas-heated house varied from R 38 for Case 2 (lower shell losses) using DOE's escalation rate to R 57 for Case 4 (higher interior temperature) using the higher escalation rate, with R 49 being about average. In all cases, the R values listed include what is already in the house, i.e. R 19 in the ceiling, R 11 in the walls, and R 0 in the floors.

For almost all the possible variables R 11 wall insulation (4)

Table 12

COST OF SHELL RETROFITS

CASE 1 - 1 ACH - 6110 DD

CEILING

			MC/MS per 10^6 BTU		
Add R	Total R	MS in 10^6 BTU	3%,25YR	3%,10YR	7%,25YR
19	38	2.9	$7.36	$15.03	$11.07
30	49	.7	$12.87	$26.29	$19.24
38	57	.4	$16.35	$33.40	$24.45

FLOOR

			MC/MS per 10^6 BTU		
Add R	Total R	MS in 10^6 BTU	3%,25YR	3%,10YR	7%,25YR
11	13	8.7	$4.41	$10.05	$6.60
19	21	2.3	$13.35	$23.21	$16.97
30	32	1.3	$29.53	$60.30	$44.15

WALL

			MC/MS per 10^6 BTU		
Add	Total R	MS in 10^6 BTU	3%,25YR	3%,10YR	7%,25YR
Fill	11	2.6	$4.68	$9.55	$6.99
Build in	22	4.2	$29.69	$60.39	$44.38

WINDOWS

			MC/MS per 10^6 BTU		
Add	Total R	MS in 10^6 BTU	3%,25YR	3%,10YR	7%,25YR
storms	1.8	.7	$6.60	$13.49	$9.87
3-panes	3	5.4	$16.50	$33.69	$24.66

DOORS

			MC/MS per 10^6 BTU		
Add	Total R	MS in 10^6 BTU	3%,25YR	3%,10YR	7%,25YR
storm(1)	3.3	.3	$22.00	$44.93	$32.90
storm(2)			$19.13	$39.07	$28.60

1) contractor installed
2) owner installed

Table 13

COST OF SHELL RETROFITS

CASE 2 - 1.5 ACH - 6110 DD

CEILING

Add R	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
19	38	2.7	$7.91
30	49	.5	$18.02
38	57	.3	$21.80

FLOOR

Add R.	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
11	13	7.2	$5.33
19	21	2.1	$12.44
30	32	1.2	$31.99

WALL

Add	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
Fill	11	2.3	$5.29
Build in	22	3.7	$33.70

WINDOWS

Add	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
storms	1.8	.6	$7.70
3-panes	3	4.7	$18.96

DOORS

Add	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
storm(1)	3.3	.3	$22.00
storm(2)			$19.13

1) contractor installed
2) owner installed

Table 14

COST OF SHELL RETROFITS

CASE 3 - .6 ACH - 6110 DD

CEILING

Add R	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%, 25YR
19	38	3.3	$6.47
30	49	.8	$11.26
38	57	.5	$13.08

FLOOR

Add R	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%, 25YR
11	13	9.5	$4.04
19	21	2.8	$9.33
30	32	1.6	$23.99

WALL

Add	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%, 25YR
Fill	11	3.0	$4.05
Build in	22	4.8	$25.98

WINDOWS

Add	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%, 25YR
storms	1.8	.8	$5.78
3-panes	3	6.1	$14.61

DOORS

Add	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%, 25YR
storm(1)	3.3	.4	$16.50
storm(2)			$14.35

1) contractor installed
2) owner installed

Table 15

COST OF SHELL RETROFITS

CASE 4 - 1 ACH - 7620 DD

CEILING

Add R	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
19	38	3.6	$5.93
30	49	.8	$11.26
38	57	.5	$13.08

FLOOR

Add R	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
11	13	10.3	$3.73
19	21	3.0	$8.71
30	32	1.8	$21.33

WALL

Add	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
Fill	11	3.2	$3.80
Build in	22	5.3	$23.53

WINDOWS

Add	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
storms	1.8	.9	$5.13
3-panes	3	6.7	$13.30

DOORS

Add	Total R	MS in 10^6 BTU	MC/MS per 10^6 BTU 3%,25YR
storm(1)	3.3	.4	$16.50
storm(2)			$14.35

1) contractor installed
2) owner installed

Table 16

OPTIMUM RETROFITS - 3%, 25 YEARS

NATURAL GAS - MARKET

Case 1		Case 2		Case 3		Case 4		
low e	high e	low e	high e	low e	high e	low e	high e	
38/49	49/57	38	38/49	49	57	49	57	CEILING
21	21	21	21	21	21	21	21	FLOOR
Fill	Fill	Fill	Fill	Fill	Fill	Fill	Fill	WALL
storms	storms	storms	storms	storms	3-panes	storms	3-panes	WINDOWS
none	none	none	none	none	owner	none	owner	DOORS

NATURAL GAS - MARGINAL

Case 1		Case 2		Case 3		Case 4		
low e	high e	low e	high e	low e	high e	low e	high e	
49	57	38/49	49	49/57	57	49/57	57	CEILING
21	21	21	21	21	21	21	21	FLOOR
Fill	Fill	Fill	Fill	Fill	Fill	Fill	Fill	WALL
storms	3-panes	storms	3-panes	storms	3-panes	storms	3-panes	WINDOWS
none	owner	none	owner	none	storm	none	storm	DOORS

Table 16 - Pg. 2

ELECTRICITY - MARKET

Case 1		Case 2		Case 3		Case 4		
low e	high e	low e	high e	low e	high e	low e	high e	
38	49	38	38/49	38	49	38	49	CEILING
21	21	21	21	21	21	21	21	FLOOR
Fill	Fill	Fill	Fill	Fill	Fill	Fill	Fill	WALL
storms	storms	storms	storms	storms	storms	storms	storms	WINDOWS
none	none	none	none	none	none	none	none	DOORS

ELECTRICITY - MARGINAL

Case 1		Case 2		Case 3		Case 4		
low e	high e	low e	high e	low e	high e	low e	high e	
49/57	57	49	57	49/57	57	57	57	CEILING
21	21/32	21	21	21	32	21	32	FLOOR
Fill	Build in	Fill	Fill	Fill	Build in	Fill	Build in	WALL
storms	3-panes	storms	3-panes	3-panes	3-panes	3-panes	3-panes	WINDOWS
owner	storm	none	storm	storm	storm	storm	storm	DOORS

Table 16 - Pg. 3

WOOD

Case 1		Case 2		Case 3		Case 4		
$55	$150	$55	$150	$55	$150	$55	$150	
38	57	38	49	38	57	38	57	CEILING
21	21	21	21	21	21	21	21	FLOOR
Fill	Fill	Fill	Fill	Fill	Fill	Fill	Fill	WALL
storms	3-panes	storms	3-panes	storms	3-panes	storms	3-panes	WINDOWS
none	owner	none	owner	none	storm	none	storm	DOORS

FUEL OIL

Case 1	Case 2	Case 3	Case 4	
57	57	57	57	CEILING
32	21/32	32	32	FLOOR
Build in	Fill	Build in	Build in	WALL
3-panes	3-panes	3-panes	3-panes	WINDOWS
storm	storm	storm	storm	DOORS

Table 17

OPTIMUM RETROFIT - CASE 1

GAS - MARKET			GAS - MARGINAL			WOOD		
3%,10YR		7%,25YR	3%,10YR		7%,25YR	3%,10YR		
low e	high e		low e	high e		$55	$150	
19	19	19/38	19	19/38	38	19	38	CEILING
21	21	21	21	21	21	2	21	FLOOR
Fill	Fill	Fill	Fill	Fill	Fill	none	Fill	WALL
none	storms	storms	storms	storms	storms	none	storms	WINDOWS
none	none	none	none	none	none	none	none	DOORS

ELECTRICITY - MARKET			ELECTRICITY - MARGINAL			FUEL OIL		
3%,10YR		7%,25 YR	3%,10YR		7%.25YR	3%,10YR/		
low e	high e		low e	high e		7%,25YR		
19	19	19	38	38	38	38	49	CEILING
21	21	21	21	21	21	21	21	FLOOR
Fill	Fill	Fill	Fill	Fill	Fill	Fill	Fill	WALL
none	none	none	storms	storms	storms	storms	3-panes	WINDOWS
none	none	none	none	none	none	none	none	DOORS

Table 18

OPTIMUM RETROFITS - SUMMARY

	3%,25YR R of Insulation Ceiling/Wall/Floor	3%,10YR or 7%,25YR R of Insulation Ceiling/Wall/Floor
Natural gas, market	49/11/19 storm windows	19/11/19 storm windows
Natural gas, marginal	49-57/11/19 storms	19-38/11/19 storm windows
Electricity, market	38-49/11/19 storm windows	19/11/19 no storms
Electricity, marginal	57/11/19 storm door 3-pane windows	38/11/19 storm windows
Wood, market	38/11/19 storm windows	19/11/0 no storms
Wood, social	57/11/19 storm door 3-pane windows	38/11/19 storm windows
Fuel oil	57/22/30 storm door 3-pane windows	38-49/11/19 storm windows
Current house	19/11/0, 1 storm door, most storm windows	

and storm windows turned out to be cost-effective. However, while filling in the rest of the wall cavity and adding the last 25 SF of storm windows is less than optimum, the next step up - to double stud walls and triple pane windows, respectively - requires major rebuilding. Such extensive retrofitting proved economical only when judged against the most expensive heating fuel - fuel oil - and amortized over 25 years at a low interest rate. Since Nordell's (1982) price for R 19 floor insulation was the same as the Missoula price for R 11, 6 inches of floor insulation was probably optimum in most cases. Only for fuel oil was the optimum clearly higher, R 30, and for wood with a 10 year lifecycle was it clearly lower, R 0.

Thus, changing the various parameters really only modified optimum ceiling insulation levels, and determined whether or not adding a storm door was cost-effective. Using the higher escalation rates for electricity and natural gas raised the optimum ceiling retrofit one step. Using marginal prices similarly increased the optimum ceiling insulation level and made storm doors cost-effective. Decreasing the lifecycle to ten years generally had the same effect as raising the discount rate to 7%, dropping optimum ceiling insulation levels one or two steps and making storm doors uneconomical.

Infiltration

Infiltration accounts for about 30% of the heat load of the average house (see Table 4). Dickenson et al. (1982) estimate that extensive caulking and weatherstripping, "house doctoring", reduces infiltration 20% - 40%. However, infiltration rates must be measured on-site before and after retrofitting to know precisely how much energy was saved. No on-site measurements were made in Missoula but I assumed house doctoring would cut infiltration losses 20% - 40%.

Among other things, house doctoring entails applying caulk along the sill plate and around fuse boxes, chimneys, and flue pipes, taping heating system ducts, stuffing fiberglass into large cracks in the foundation, and weatherstripping attic doors (Harrje et al. 1980, Dickenson et al. 1982). Such extensive leak-plugging is quite cheap if done by the homeowner. In fact, none of the Missoula contractors I talked to could quote prices for house doctoring. Most said the work was so easy to do that people did it themselves. Since it was difficult to estimate how much caulk, weatherstripping, etc., would be needed to seal the average house, I used the cost of materials reported by Dickenson et al. (1982) for houses in Midway, Washington - $120 in 1980. I increased this to $200 to account for two years of inflation and for Missoula's leakier houses. Even so, $200 probably overestimates weatherizing costs. Nordell (1982) used $150 and considered that estimate conservatively high. Table 19 shows marginal weatherization costs for a 3% discount rate, a ten year lifecycle, and three possible original air change rates. House doctoring is economical in all cases for all possible heating fuels.

It is generally claimed that storm windows and doors not only reduce envelope losses but also cut infiltration (Petersen 1974, Konigsberg 1980, Dickenson et al. 1982). Wall insulation, especially cellulose, also may reduce infiltration significantly (Seton, Johnson, & Odell 1980). Storm windows and wall insulation are cost-effective in

Table 19

HOUSE DOCTORING

	Original Infiltration Load	Infiltration Reduction	Energy Saved	MC/MS 3%, 10YR
Case 1	$21.8X10^{6}$ BTU	20%	$4.36X10^{6}$ BTU	$5.38
		40%	$8.72X10^{6}$ BTU	$2.69
Case 2	$35.2X10^{6}$ BTU	20%	$7.04X10^{6}$ BTU	$3.33
		40%	$14.08X10^{6}$ BTU	$1.66
Case 3	$15.0X10^{6}$ BTU	20%	$3.00X10^{6}$ BTU	$7.81
		40%	$6.00X10^{6}$ BTU	$3.91

	Original ACH	Infiltration Reduction	New ACH
Case 1	1	20%	.8
		40%	.6
Case 2	1.5	20%	1.2
		40%	.9
Case 3	.6	20%	.5
		40%	.3

all cases considering envelope losses alone. Storm doors aren't. They might be if they also reduce infiltration. Adding storm windows and doors to the houses at Midway reduced infiltration 14%. However, the houses there had no storms to begin with, making extrapolation to Missoula difficult.

Weatherizing attics is especially important. Without extensive leak-sealing warm air enters the attic, bypassing the insulation, and reducing by as much as half the possible savings from attic insulation. However, leaks to the attic are easily sealed and after this has been done the attic insulation will perform as predicted (NRDC 1982, Harrje et al. 1980).

There is some concern that thorough house tightening may reduce natural ventilation so effectively that without an air-to-air heat exchanger the house could become stuffy and smelly, humidity could build up causing paint to peal and water to condense on windows, and concentrations of radon, formaldehyde, carbon monoxide (CO), nitrogen dioxide (NO_2), and particulates could reach health-threatening levels. Radon, a chemically inert radioactive gas, may or may not be present in soil, bricks, concrete, and tap water from underground wells. It decays with a half-life of about four days producing products which are potentially carcinogenic in combination with air-borne particulates. If it accumulates indoors it could be dangerous. Background radon levels vary with geographic location, however, and are often too low to create problems even in very tight houses. Furniture and many building materials outgas formaldehyde which may cause allergies and cancer (Energy Users Report 1 July 1982, Offermann et al. 1981, Sherman 1980).

Extensive house doctoring of 12 houses in Midway led to only moderate increases in ambient concentrations of formaldehyde and radon, and no measurable increases in NO levels (Offermann et al. 1981). Applying these results to Missoula is difficult. The houses at Midway were originally so tight, averaging .4 ACH, that if the levels of radon and formaldehyde were going to exceed recommended standards, they would probably have done so before house doctoring. Also, because they were all heated with electricity and none had gas cook stoves, NO_2 concentrations were, not surprisingly, low. By contrast, tightening up Missoula's much draftier, gas and wood heated houses could cause more significant increases in indoor air pollutants, especially of combustion products such as NO_2, CO, and particulates. (The latter two were not measured at Midway.) Also, radon concentrations are higher in the mineral soils of western Montana than in central Washington (Bonneville Power Administration 1983). Even so, a heat exchanger probably wouldn't be needed in Missoula after thorough house tightening. It is generally felt that unless air exchange rates fall below .5 ACH natural ventilation will prevent indoor air contaminants from reaching toxic concentrations (Balcomb 1980, Shelton and Shapiro 1976, NRDC 1982). Weatherstripping and caulking the average house here would probably not reduce infiltration to below .5 ACH in most cases (see Table 19).

Gas Furnaces

About 80% of Missoula's houses have gas furnaces. Since these average only 50% efficient a lot of heat blows up Missoula's chimneys each winter. Lowering the burn rate until the furnace burns almost continuously in cold weather, increasing the fan speed, and cleaning filters and ducts all cost little or nothing and increase furnace efficiency somewhat (McGrew et al. 1979).

Replacing the existing furnace with a properly-sized, 96% efficient pulse heater saves even more gas and, as shown in Table 20, is cost-effective over the expected 25 year lifetime of the furnace (Lanham Heating 1982). Installing a more efficient furnace essentially lowers the price of delivered gas, thereby reducing the optimum retrofit for the house to R 19 ceilings, R11 walls, and R 19 floors. Storm windows and extensive house doctoring are still cost-effective. Storm doors aren't unless they reduce infiltration significantly.

Woodstoves vs. Insulation

To compare the cost of insulating to the cost of backfitting with a woodstove, I computed the annual cost of the optimum conservation retrofit for each fuel, with a 3% discount rate and 25 year lifecycle, and compared this to the annual cost of retrofitting with wood. I used the higher electricity price escalation rate predicted by Duffield (1980) because it is closer to a third estimate for the Northwest used by Dickenson et al. (1982), i.e. 1% to 3%. I used the lower gas price escalation rate predicted by DOE (Ruegg 1981) because

Table 20

GAS FURNACE REPLACEMENT

Cost : $2000

Saves : 58.7 X 10^6 BTU

	3%,25YR	7%,25YR
Annualized price furnace	$114.80	$171.60
Cost/10^6 BTU	$1.96	$2.92
Levelized price of gas		
Market, low e	$5.49	$5.19
Marginal, low e	$6.38	$6.04

it too is similar to a third estimate , 1.2% to 3.7% (Energy Analysis and Planning 1982). The average house currently derives $16.5X10^6$ BTU of heat from wood. Any of this not provided by insulation would have to be bought from the power company or a fuel oil distributor. However, in all cases the optimum retrofit saved at least this much energy. The average price of a woodstove was adapted from Cartwright (1982) who surveyed woodstove dealers in northwestern Montana and northern Idaho . (Details of the woodstove calculations are in Appendix D.) The results are summarized in Table 21. I didn't include the costs or fuel savings from house doctoring.

Judged against the market price of wood, retrofitting with insulation is cheaper than retrofitting with wood for houses heated with electricity or natural gas and more expensive for houses heated with fuel oil. Judged against the minimum social cost of wood, $150/cord, it is universally cheaper to insulate.

Summary

Briefly, the average house in Missoula currently has about R 19 insulation in the ceiling, R 11 in the walls, and no insulation under the floor. All but 25 SF of its 200SF of windows are double pane and one of its two outside doors has a storm.

For all heating fuels the average house is less than optimally insulated. Optimal levels are very similar for houses heated with natural gas and electricity, i.e. about R 49 in the ceiling, R 11 in the wall, and R 19 under the floor. Storm windows are also

Table 21

WOOD VERSUS INSULATION RETROFITS

CASE 1 - 3%,25 YRS.

ELECTRICITY - MARKET, high e

Insulation Retrofit	Price	Savings
R 49 Ceiling	$30.36	3.6 X10^6 BTU
R 11 Wall	12.16	2.6
R 19 Floor	64.51	11.0
windows	4.62	.7
	$111.65	17.9 X10^6 BTU

ELECTRICITY - MARGINAL, high e

Insulation Retrofit	Price	Savings
R 57 Ceiling	$36.90	4.0 X10^6 BTU
R 11 Wall	12.16	2.6
R 19 Floor	64.51	11.0
3-panes	89.10	5.4
storm door	6.60	.3
	$209.27	23.3 X10^6 BTU

NATURAL GAS - low e

Insulation Retrofit	Price	Savings
R 49 Ceiling	$30.36	3.6 X10^6 BTU
R 11 Wall	12.16	2.6
R 19 Floor	64.51	11.0
windows	4.62	5.7
	$111.65	17.9 X10^6 BTU

Table 21 - Pg. 2

NATURAL GAS - low e

Furnace Retrofit	Price	Savings
Furnace	$114.80	58.7 X10^6 BTU
R 11 Wall	12.16	2.6
R 19 Floor	64.51	11.0
windows	4.62	.7
	$196.09	73.0 X10^6 BTU

FUEL OIL

Insulation Retrofit	Price	Savings
R 57 Ceiling	$36.90	4.0 X10^6 BTU
R 22 Wall	133.22	6.8
R 30 Floor	102.90	12.3
3-panes	89.10	5.4
storm door	6.60	.3
	$368.72	28.8 X10^6 BTU

WOODSTOVE RETROFIT

stove	$57.40	(see Appendix D)		57.40
maintenance	100.47	(see Appendix D)		100.47
wood, market	112.70		wood, social	$307.56
	$270.57			$465.43

cost-effective. Optimal ceiling insulation levels for wood heated houses are lower - R 38. Optimal levels for houses heated with fuel oil are higher, approaching superinsulation (5). All houses should be extensively weatherstripped and caulked. Judged against the marginal/social prices of fuels, optimal ceiling insulation levels are increased to R 57 for houses heated with electricity and wood. Triple pane windows and ten inches of floor insulation are cost-effective in some cases.

An alternative retrofit for gas heated houses is replacing the furnace, and then adding less insulation to the floor, and none to the ceiling. This costs considerably more than retrofitting alone - $197/year rather than $112/year, exclusive of house doctoring - but also saves much more energy, $73.0X10^6$ BTU instead of $17.9X10^6$ BTU for an overall cost of $2.69 compared to $6.24. Both retrofits are cheaper than the delivered cost of gas. Both are also cheaper than retrofitting with a woodstove. Insulating an electrically heated house also costs less than becoming a woodburner. Only for fuel oil heated houses is woodburning cheaper than insulating.

At this point a few provisos are in order. First, arriving at both the average house description and the optimum retrofits neccessitated making many assumptions about such uncertain factors as air exchange rates, discount rates, and fuel price escalation rates. It also meant making numerous calculations based on equally uncertain house dimensions and insulation levels derived from the Elrick and Lavidge survey. As it turned out, varying many of the different parameters made little difference in the predicted optimum retrofit. Possibly the errors inherent in the calculations tended to cancel each other out rather than compound one another. At any rate, the predicted optima should be taken as approximations only. For this reason, I have rounded insulation levels to the closest commercially available amount. Being any more specific would be an example of what Ehrlich (1981) calls "trying to determine the circumference of a roughly circular field...by asking the village idiot to guess its diameter and then multiplying his answer by 'pi' taken to 50 decimal places" (p.31).

The floor heat load calculations are especially doubtful. I used a "fudge factor" reported by Shelton and Shapiro (1976) which inflates the R value of the floor's structural components to 6.7 and ignores any basement insulation (6). It is a quick and dirty method designed to account for the fact that ground temperatures are greater than air temperatures during winter. It assumes that the house has either an unvented crawl space or an unheated basement. This may or may not be the usual case in Montana. One cannot tell from the survey data (7). The HOTCAN program (Dumont et al. 1982) calculates foundation heat losses precisely but requires more detailed information on floors and basements than was collected.

Second, the average house doesn't exist. No house in town has 89% of its ceiling insulated with one third of an inch of foam covered with three inches of fiberglass and three inches of loose fill, nor does any house derive 8% of its heat from electricity, 65% from natural gas, and 27% from wood. Houses are generally built in much simpler ways, and they are all slightly different. Therefore, they all need somewhat different retrofits. To indiscriminantly add R 30 insulation to every ceiling in Missoula would save far less energy than bringing all ceilings up to R 49. Even that is not truly optimum, however. People live differently. Those who leave home often and wear wool sweaters and socks indoors don't need as much insulation in their houses as those who stay home more and prefer not to bundle up inside. In fact, judging from the MPC sample, who lives in a house seems to be the most important factor in explaining how much heat the house uses. But calculating a house and people specific internal balance temperature for every home in Missoula, and then optimizing accordingly, would be extremely time-consuming, very expensive, and ill-advised. Over half of Missoula's houses are rented and even owner-occupied homes change hands relatively frequently.

Third, the retrofits considered are not universally applicable to all houses. For instance, because cellulose is blown into walls through holes drilled in the siding, it can generally only be backfitted into houses with wood siding. Except for adding storms and house doctoring, none of the retrofits discussed apply to trailers, 5% of Missoula's housing stock (1980 Census of Population and Housing). Retrofitting trailers entails removing the roof and siding, adding a vapor barrier and insulation, and then putting the roof and siding back on. A similar proceedure is used for insulating floors. The annualized cost of retrofitting, given a 10 year lifecycle, (the average lifespan of a trailer is only about 20 years) is $\$15.65/10^6$ BTU (Nordell 1982), cost-effective only against fuel oil, the replacement price of electricity, and the social cost of wood.

Finally, because insulation in south-facing walls may perform better than ASHRAE test values (Tsongas 1979), optimum insulation levels for the south wall may be lower than R 11. To say for sure, south wall insulation performance needs to be measured in Missoula houses.

Footnotes

1) The costs of owner installed fiberglass batts are 26 cents/SF for R 19, 41 cents/SF for R 30, and 52 cents/SF for R 38 (Intermountain Lumber 1982).

2) DOE Region 8 is the Rocky Mountain west, including Montana.

3) Duffield (1980) suggests social costs are about three and a half times current market prices.

4) Optimum wall insulation was computed assuming a wood frame house. However, the optimum levels for brick houses are about the same despite the fact that brick has a somewhat higher R value than wood (Goldstein et al. 1980).

5) Houses are generally called superinsulated if they have at least R 50 insulation in the ceiling, R 40 walls (R 19 for south-facing), R 30 floors, and triple pane windows (Corbett, Hansen, and Sesso 1980). Except for the wall, the optimum retrofit levels for fuel oil heated houses are this high.

6) The average basement insulation for the Montana sample is R 3.5 (Elrick and Lavidge data tape).

7) The survey reports that 18% of the houses in the sample have full crawl spaces, 42% have full basements, 7% are built slab-on-grade, and the other 33% have foundations that are various unspecified hybrids of the three. The survey doesn't say what proportion of the basements are heated (Elrick and Lavidge vol. 1 1980).

Chapter 4

POLICY IMPLICATIONS

Why are Houses Underinsulated?

There are many possible reasons why Missoula's houses are underinsulated (see, for instance, Duffield 1977, NRDC 1982). Some of the commonly mentioned ones are:

1) People lack sufficient information about which retrofit measures are cost-effective, how to implement them, and/or who to hire to do the work. I believe this is a minor reason. The benefits of insulation, caulking, weatherstripping, storm windows, etc. have been widely broadcasted in Missoula. Conservation has been touted in bill stuffers from the power company, in newspaper articles, at public meetings, and on the public radio station. Books and pamphlets on conservation are available from the power company, the public library, and the Human Resources Development Council (HRDC), to name a few. There are several pages of insulation contractors listed in the Missoula yellow pages. Granted, people probably wouldn't know what optimum insulation levels are; few other than government agencies and economists compute lifecycle costs. But it seems unlikely that anyone wouldn't know that insulation is relatively cheap and saves money on fuel bills. It also seems unlikely that anyone wouldn't know that Missoula has an air pollution problem caused by woodburning. The Missoula Health Department has put on an excellent public education

campaign during the past two years, and our winter air smells like a campfire and scratches in our throats like sandpaper.

2) Financing is unavailable for all except the wealthy few who qualify for bank loans, or for the very frugal with large savings accounts. McNairy (1983) feels this explains why many Montanans haven't insulated their houses. Banks generally lend money for home improvements at high interest rates and short terms, often requiring second mortgages as collateral. Such stringent requirements discourage many people.

In Missoula, however, loans and grants are available to most people. Homeowners qualify for Montana Power Company's conservation loans, up to $2000 of no-interest retrofit money. MPC provides complete financing for measures which pay back in seven years or less; these usually include weatherstripping, caulking, storm windows and doors, R 38 attic insulation, and R 19 floor insulation. The power company will make prorated loans for measures with longer pay back periods. Loans have to be repaid in four years. Occasionally, but not usually, the power company requires a lien on the house. In the approximately four years since MPC started this program, only about 1000 Missoula households have taken advantage of it (Don Mourich, Montana Power Company, personal communication 1983). Low income people, homeowners and renters alike, qualify for the Human Resource Development Council's Low Income Home Weatherization Program. This program pays outright for caulking, weatherstripping, R 19 floor insulation, and R 30 ceiling insulation. So far, HRDC has retrofitted 2300 homes in Missoula, Mineral, and Ravalli Counties (Corrigan, personal communication 1983). Both programs will also pay for replacing broken windows, broken doors, and rotten thresholds. Both will occasionally pay for blowing cellulose into walls.

Between the two programs, retrofit loans and/or grants are available to everyone except middle and high income renters. Even landlords qualify for the MPC program if their buildings have four units or less, 60% of the rental housing in Missoula(1980 Census of Population and Housing). Very few landlords have insulated to date (Phil Smith, Montana Power Company, personal communication 1983).

3) Fuel prices are deceptively low. This would explain why houses are underinsulated in relation to marginal or social costs, but not why they are underinsulated with respect to current market prices. Raising prices to their marginal costs would be impossible, inequitable, and impractical. Impossible because utilities are regulated monopolies required to set prices at average costs; inequitable because the utilities would make unreasonably high profits at the expense of those least able to insulate, i.e. low-income people, renters, and the elderly; and impractical because people would most likely respond by burning more wood instead of insulating.

4) About 52% of Missoula's residences are rented (1980 Census of Population and Housing). Often the tenant, rather than the landlord, pays for space heat. This is a classic prescription for an underinsulated house; the landlord must approve and finance conservation retrofits but the tenants reap the benefits in decreased fuel bills. Although economic theory would predict that landlords could charge more rent for tight, well-insulated houses than for leaky

ones with R 4 walls, tenants do not always inspect houses for insulation and caulking before renting. So far the possibility of increased rent hasn't been enough to motivate landlords to insulate (NRDC 1982, Smith, personal communication 1983; Dana Peck, Portland (OR) Energy Office, personal communication 1982).

5) People expect their investments to pay back in a very short time. Lopreato and Cunningham (1977) found that people in middle to upper income brackets expected a $500 investment in insulation and storm windows to pay off in 4.5 years; low income people expected a 1.5 year payback on the same investment. Similarly, Hausman (1979) reports that people's purchases of room air conditioners implied a real discount rate between 5% and 89%. Not surprisingly, poor people had the highest implied discount rates but even people with annual incomes of $25,000 had discount rates well above market interest rates. (In other words, if the energy efficient model didn't conserve enough fuel to recoup its additional purchase price within a few years, few bought it.) Both a high discount rate and a short lifecycle make insulation look relatively expensive and heating fuel relatively cheap.

Some say that a short payback period is reasonable because people move, and sell their houses, about once every seven years. However, an insulated house should theoretically sell for more than an uninsulated one, provided prospective homebuyers value energy efficiency.

6) Finally, many people enjoy gathering and chopping wood and sharing a fire with family and friends. By comparison, one cannot bask in the glow of an R 50 ceiling on a cold winter evening, and it is

messy and often difficult to backfit a house with insulation. Further, many see burning wood both as energy conservation (trees are renewable resources if not over-harvested) and as a declaration of independence from the power company. Such non-economic reasons could very well explain Missoula's love of woodburning better than the economic ones mentioned above.

Justifying a Public Insulation Program

Whatever the reason, the average house in Missoula is underinsulated. Knowledge alone will not convince people to insulate their houses. According to Lopreato and Cunningham (1977), the more educated people are the more likely it is that they will understand the problem. But understanding does not neccessarily lead to action. It seems equally unlikely that market forces alone will prompt people to retrofit their houses to appropriate levels. During the past decade, in fact, the market has instead encouraged people to burn wood. Wood is abundant in the hills surrounding Missoula and firewood can easily be had for a few days' work and the price of several tanks of gasoline. Market forces cannot solve the problem because air is a public good. Everybody uses it but nobody owns it; nobody pays to breathe it or to dump garbage (wood smoke) in it. The private cost of burning a cord of wood, $55/cord, greatly understates the collectively shared costs of decreased physical, psychological, and aesthetic well-being associated with burning that same cord. Equivalently, the private benefits of reduced fuel bills outweigh the private costs of each person's decreased well-being. From an individual citizen's perspective woodburning is a bargain; from a community perspective it is anything but.

Ethically, one could argue that no one has a right to use the air as a private garbage dump to the detriment of all, that burning wood bespeaks a lack of social and environmental manners. The community should simply insist that such anti-social behavior cease by banning woodburning. People who now heat with wood could either insulate or buy more fuel from the power company, accepting the extra cost as their contribution to the common good.

Practically, this wouldn't work. Although many Missoulians find the city's smoky winter air unbearable enough that they are willing to limit woodburning, many feel otherwise. In fact, this past winter many woodburners testified at public hearings and wrote letters to the <u>Missoulian</u> asserting that any limitation on their freedom to burn wood whenever and however they pleased infringed on their rights as free citizens of a free country. All this furor was ignited by the Missoula Health Department's proposed new woodburning regulations. These regulations did not suggest banning woodburning. Rather they would have required people to purchase low-emission stoves within five years and lowered the particulate levels at which burning restrictions would take effect. A ban on woodburning would be impossible to enact here, let alone enforce.

Politically, it would be far more practical to devise a publicly-financed insulation program. There are also ethically sound reasons for doing this. The cumulative social benefits of clean air are high. Optimally insulating every house in Missoula would save the equivalent of over 11,800 cords of wood annually. This is over one third the number of cords currently burned (Steffel 1983). If one accepts $150/cord as the social cost of wood, the annualized savings in decreased health and fuel costs are over two million dollars (calculations are in Appendix E). And there are many reasons favoring a public conservation program which, in the long run, are just as important as eliminating wood smoke pollution. To name a few:

1) Conserving energy "reduces the rate at which society turns resources into rubbish" (Ehrlich 1981, p. 31) both decreasing environmental disruption and ensuring that resources last longer. The pollution caused by insulation manufacture is ecologically benign compared not only to woodburning but also to the possibilities of coating Arctic tundra with spilled oil, chasing the last grizzly bears out of the northern Rockies exploring for gas, flooding sacred sites and riparian ecosystems with hydroelectric dams, and sterilizing midwestern lakes and forests with acid rain from coal-fired electric generators.

2) Energy produced by conservation is decentralized, and therefore more secure than either electricity or natural gas. It is less vulnerable to accidental breakdowns or sabotage. Because the technology is simple and dispersed, it can be controlled locally by the people who use it rather than by corporate bureaucrats or a "remote preisthood of technical experts" (Daly 1979).

3) Conservation not only matches fuel quality to end use, but also can be tailored exactly to local climates and fuel prices. For

instance, R 60 attic insulation could be backfitted into gas heated houses in Duluth, R 49 in Missoula, and R 30 in electrically heated houses in Seattle. (Except for Missoula the numbers are arbitrary.)

4) Finally, a community insulation program would create many local jobs and ultimately keep more money at home by decreasing the dollars sent to Canada for natural gas, to the Mideast for oil, and to BPA for electricity.

I think all these social benefits justify using public money to insulate private homes. Homeowners who had already insulated might legitimately complain that they were being asked to pay for insulating other people's houses, yet no one had helped pay to insulate their houses. A public program could take this into account, perhaps by rebating part of the costs to these people.

A public insulation program will not be cheap. Considering market fuel prices the cost, in 1982 dollars, of insulating a gas or electrically heated house to the optimum level is about $2000. For the combination gas furnace/insulation retrofit the price is $3000, for a fuel oil heated house over $6000, and for a wood heated house nearly $1500. Considering marginal/social prices, the optimum retrofit for both wood and electrically heated houses costs over $3500. If the city were to spend an average of $2000 per house, the total bill would be close to thirty million dollars. These figures do not include the cost of energy audits which would be necessary before retrofitting. Jim McNairy (1983) details possible ways of raising conservation funds, including utility ratebasing, extending the terms on existing power company programs, setting up a reserve fund to guarantee conservation loans made by local banks, establishing a secondary money market to finance the loans outright, or creating a Community Development Corporation.

Insulating to Appropriate Levels

So far, I have defined optimum conservation retrofits according to what is either personally or (approximately) socially cheapest. But picking the least expensive combination of insulation and heating fuel begs the real question, i.e. Do we want to live in a society powered by renewable energy or by fossil fuels? Daly (1979) calls this a choice between "permanent solar income economics" and "geocapital consumption economics", and argues for explicitly deciding what sort of world we want, and then setting our energy policy accordingly. Lovins (1977) agrees, stating that values, "though fuzzy and unscientific...are the beginning and end of any energy policy. The most important, difficult, and neglected questions of energy strategy are not mainly technical or economic but rather social and ethical" (p.95).

Others echo and expand upon this. For example, Wendell Berry (1981), "... energy is not just fuel. It is a powerful social and cultural influence. The kind and quantity of the energy we use determine the kind and quality of the life we live" (p.128). Similarly, Tom Power (1980), "The energy system we choose is not some neutral technical gadget we build and set off in a corner somewhere to serve us. That energy system is intimately intertwined with our economic, social, and political organization in a way which allows it to change and mold the way we live" (p.9-2).

Further, Daly (1979) asserts, our values determine fuel prices and, therefore, comparing the price of insulation to the price of natural gas is inappropriate. Fossil fuels often look like a bargain compared to insulation or solar systems because we have implicitly valued resources in the ground at zero. Hence the prices of fossil fuels represent only the costs of extraction and delivery. In Missoula we have similarly set the value of clean, healthful winter air at zero. Paraphrasing Mishan (1971), optimum insulation levels for wood heated houses are relatively low here because we are "entitled" to use the air as a private garbage dump and must be bribed to cease doing so. If, on the other hand, we were "entitled" to breathe smoke-free air and had to cajole our neighbors into allowing us to pollute, optimum insulation levels would be much higher.

The conservation retrofits presented earlier simply make shift with things as they are. They are optimum within the context of "geocapital consumption economics". As it turns out, even in terms of this system, biased as it is against energy conservation, houses in Missoula need more insulation. We are being inefficient even according to the rules dictated by the status quo. As a community, we need to decide whether we want to continue burning wood and fossil fuels or whether we would rather depend on renewable energy. Either way we need to insulate.

Chapter 5

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Appendix A

DAVIES' COEFFICIENT OF SKEWNESS
source: Davies and Crowder 1933

If $\frac{[\ln LQ + \ln UQ - 2 \ln MQ]}{[\ln UQ - \ln LQ]} < .15$

then the distribution is log normal.

where: LQ = the value in the n+2/4 position or the lower quartile
MQ = the value in the n+1/2 position or the middle quartile
UQ = the value in the 3n+2/4 position or the upper quartile
ln = the natural logarithm
n = the sample size

when the sample values are ranked in order of increasing magnitude.

For the Montana sample, Davies' coefficient is:

$$\frac{\ln 900 + \ln 1500 - 2 \ln 1147}{\ln 1500 - \ln 900}$$

$= .05$

For the Missoula sample:

$$\frac{\ln 750 + \ln 1272 - 2 \ln 996}{\ln 1272 - \ln 750}$$

$= -.06$

Appendix B

MISSOULA RESIDENTIAL POWER USE - JUNE 1979-MAY 1980

Source : Montana Power Company

	June 79	July 79	Aug 79	Sept 79	Oct 79	Nov 79
KWH sold	11,924,055	11,809,895	11,393,574	12,044,121	13,070,549	18,253,998
# Cust.	21,678	21,737	21,770	21,975	22,033	22,305
KWH/cust.	550.1	543.3	523.4	548.1	590.5	818.4
MCF sold	80,111.8	56,405.6	56,675.6	78,001.8	137,420.7	270,525.5
# Cust.	17,103	17,101	17,093	17,228	17,403	17,516
MCF/cust.	4.68	3.30	3.32	4.53	7.90	15.44

	Dec 79	Jan 80	Feb 80	Mar 80	Apr 80	May 80
KWH sold	20,655,750	19,834,537	20,878,508	15,998,966	14,950,495	14,145,817
# Cust.	22,333	22,372	22,450	22,396	22,385	22,513
KWH/cust.	924.9	886.6	930.0	714.4	667.9	628.3
MCF sold	312,977.8	324,192.0	330,262.8	224,658.0	161,534.4	122,529.5
# Cust.	17,529	17,437	17,515	17,469	17,443	17,444
MCF/cust.	17.85	18.59	18.85	12.86	9.26	7.02

Appendix C

58°F DEGREE DAYS

Oct. 1979 - May 1980

monthly degree days = (balance T - average monthly T) X #days/month

Month	Average T (1)	# Degree Days
Oct.	47.1° F	338
Nov.	27.5° F	915
Dec.	30.8° F	843
Jan.	17.2° F	1265
Feb.	30.0° F	812
Mar.	33.1° F	772
Apr.	48.9° F	273
May	54.0° F	124
		5342

1) source: U.S. Weather Service

Appendix D

ANNUALIZED WOODSTOVE COSTS at 3%, 25 YEARS

Source : Cartwright 1982

Stove Cost:

$570 to $1625 for a well-insulated 1000 SF house
$570 to $1825 for a well-insulated 1600 SF house

used : $1000 for modestly-insulated 1300 SF Missoula house
annualized: $57.40

Maintenance:

chimney cleaned and gasket replaced : $35/yr.
annualized : $73.26

wall pipe to exhaust flue replaced : $50/every 5 yrs.
annualized : $16.84

sideplates and baffles replaced : $100/every 20 yrs.
annualized : $10.37

total annualized maintenance : $100.47

Appendix E

SOCIAL SAVINGS DUE TO RETROFITTING

Total savings = energy savings/house X # houses X cost of wood

energy saved/house = $\frac{16.87 \times 10^{6} \text{ BTU } (1)}{20.4 \times 10^{6} \text{ BTU/cord}}$

\# houses = 14,351 (2)

social cost of wood = $190/cord (3)

Total savings = $2,254,866

1) weighted average from Table 21
2) from 1980 Census
3) levelized price, from Table 9