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Mobile Home Weatherization Measures: A Study of Their Effectiveness

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CONTENTS

CONTENTS (Conclusion)

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The Solar Energy Research Institute (SERI) was funded by the Department of Energy's Office of Buildings and Community Systems (DOE OBCS) in FY 1987 and 1988 to investigate cost effective ways to weatherize mobile homes constructed prior to the enactment of HUD Thermal Standards in 1976. In FY 1987 SERI studied the effectiveness of a variety of infiltration-reducing retrofits by monitoring 20 units in the field before, during, and after application of air tightening measures. In FY 1988 we began studying measures intended to reduce envelope conduction losses. These measures included storm windows, insulated skirting, and wall, roof, and floor insulation. This part of the project resulted in the development of a short-term testing method for measuring the thermal impact of individual conduction-reducing retrofits.

Major conclusions from the air leakage portion of the study were:

- the locations of primary infiltration sites are different in pre-HUD-Standard mobile homes than in conventional site-built, single family detached (SFD) residences
- primary leakage sites were:
  - furnace closets
  - heat distribution and return air ducts
  - water heater closets
  - envelope penetrations for plumbing, wiring, ducts, vents, and flues
  - broken windows and operator mechanisms
  - swamp cooler chases (for units having swamp coolers)
- using a blower door was essential in locating many of these infiltration sites
- air-sealing weatherization measures typically used for site-built houses would have been ineffective on these mobile homes
- the average reduction in infiltration rate was about 40% under Denver climate conditions
- the average reduction in annual heating energy use, due to the reduced infiltration rate, was about 15% in the Denver climate.

1.0 INTRODUCTION

There are roughly three to five million mobile homes nationwide that were built prior to the enactment of the HUD Thermal Standards in 1976 (1,2). These homes consume from 1.25 to 2 times the energy per square foot of comparable conventional single family detached (SFD) houses. Currently, weatherization services spend about $1,000 - $1500 to retrofit each of these units. However, very little data exists on the effectiveness of retrofit measures in mobile homes. Most weatherization services and programs freely admit a lack of knowledge concerning the retrofit of mobile homes. Many weatherization services simply apply those measures which are believed to be cost effective in site-built housing. The construction details in manufactured buildings are quite different from those in site builts. With a potential national cost of approximately 5 billion dollars to weatherize these units, it would appear prudent to put some effort into ascertaining the most cost effective techniques for retrofit.

This report is an account of work conducted by the Solar Energy Research Institute in 1987 and part of 1988 on the weatherization of mobile homes. The report is divided into two main sections, one on the monitoring of infiltration reducing measures, and one on the development and testing of a short-term method to monitor envelope conduction reducing measures.

2.0 BACKGROUND

In 1979 SERI was asked by DOE to manage its Manufactured Buildings Program. Through this program, SERI gained considerable experience working with the manufactured buildings industry which produces new mobile homes.

In 1985, SERI began studying weatherization problems related to mobile homes constructed prior to the enactment of the HUD Thermal Standards in 1976. This was under auspices of the DOE Building Energy Retrofit Research Program (BERR). The findings from that effort were used by DOE for multiyear planning purposes in December 1985 (3).

Three areas of research were identified in the multiyear plan which related specifically to pre-HUD-Standard mobile homes:

1. option-specific monitoring to ascertain the contribution of retrofit measures currently used, or being considered for use in weatherization delivery programs,
2. evaluation of new materials and retrofit techniques, and
3. evaluation of innovative energy equipment options.

The work described in this report concentrates in the first area which was deemed the highest priority by state and local weatherization organizations.

SERI began the project in 1987 by informally surveying state and local weatherization agencies, subcontractors, and suppliers to determine what retrofit measures were commonly being used on qualifying mobile homes. Most weatherization programs emphasized retrofit measures that reduce infiltration (called "general heat waste" by many weatherization services). The air-sealing strategies were essentially identical to those used for conventional site-built units, i.e., caulking and weatherstripping around doors, windows, and joints. A few weatherization programs had tried, or considered using, retrofit procedures specially adapted to the construction details common in mobile homes. These included floor, wall, and roof insulating techniques, skirting, and improved air leakage reduction methods. The weatherization services expressed a need for hard data on the thermal effectiveness of these various retrofit options. Based on this survey, SERI designed a research program to focus on infiltration-reducing retrofits in 1987, and conduction-reducing retrofits starting in 1988.

For the infiltration portion of the project, SERI collaborated with Sunpower Consumer Association, a non-profit cooperative with an excellent reputation in Colorado for conducting furnace tune-up, and house-nurse programs. The Westside Energy Association which provides weatherization services to Denver County, funded Sunpower to retrofit 20 mobile home units in accordance with the Colorado Division of Housing guidelines. SERI contracted with Sunpower to collect data on the 20 units. The data included a complete physical description of the mobile home units, blower-door test results taken before, during, and after installation of the retrofits, and complete retrofit cost data.

SERI provided Sunpower with two carefully calibrated blower doors, and data collection forms. SERI trained the Sunpower crews in the proper use of the blower doors, and provided an on-site researcher for the first six mobile home units. The SERI researcher observed and assisted the Sunpower crews until they were able to collect high quality data on their own. The SERI researcher did not try to influence the crews on which retrofits to perform, but did instruct the crews on how to interpret the blower door readings. SERI encouraged the crews to use the blower door as a diagnostic tool during the retrofit process.

Sunpower completed their contracted work in April 1987. At that time we conducted two debriefing meetings with Sunpower personnel. Based on those meetings the Sunpower crew recorded their qualitative impressions of the retrofit of older mobile homes and the use of the blower door as a diagnostic tool (these impressions are included later in this report).

Sunpower transferred all the raw data to SERI at the conclusion of the contract. We (SERI) began the data reduction phase of the project. The physical description data and the cost data were entered into Lotus, a computerized spreadsheet program. This allowed rapid statistical analysis of the data. The analysis enabled us to define a "typical," pre-HUD-Standard mobile home unit, and average costs for each retrofit option from our sample set of 20 mobile homes.

We then wrote two computer programs, one to transform blower door data into "leakage-area" data, and one to transform "leakage-area" data into location-dependent, air-change-per-hour (ACH) data (4). (Computer listings or diskettes are available on special request from SERI.) These programs helped us define a pre- and post-retrofit average infiltration rate for our sample set.

The final step in the data analysis process was to create input files for the SERI Residential Energy Simulator (SERIRES) building-energy computer program which mathematically represented the "typical" mobile home unit, before and after retrofit. Computer runs were executed using four representative weather locations to determine the bottom-line energy savings attributable to the retrofit options. The energy savings data, retrofit cost data, and fuel cost data were used to determine the "simple payback" for various retrofit options and combinations.

In late 1987, SERI began working on measuring the effect of conduction-reducing weatherization options. A short-term monitoring technique was developed which involved moving a mobile home into a warehouse, and maintaining quasi-steady state conditions for the test. Heater power in the mobile home was measured, along with mobile home-to-warehouse temperature differences to extract the effective overall conductance of the unit. Theory indicated that this could be done on consecutive single nights of testing with different weatherization measures installed during the daytime. Two series of tests were conducted to try the method. The first was done in Jackson, Wyoming, in conjunction with a Wyoming State Weatherization Workshop. The second set of tests was done in Glenwood Springs, Colorado, in conjunction with the Colorado

Division of Housing's Weatherization Program, and Colorado Mountain College. The test results suggested several improvements to the technique including:

- o tighter control of the warehouse environment
- o a larger warehouse-to-mobile home temperature difference
- o a 36-hour test period instead of a 12-hour test period.

3.0 OBJECTIVE

The primary objective of this research is to determine the impact of infiltration- and conduction-reducing retrofits on energy consumption, and to establish base line data on the infiltration and conduction characteristics of older mobile homes. We decided to treat the infiltration and conduction issues separately because of the intrinsic differences in the monitoring approaches required for these two modes of heat transfer.

4.0 APPROACH

The approaches used in this research involved a combination of direct measurement and the use of calculational "models". For the infiltration problem, we measured reduction in the infiltration leakage area using a device commonly referred to as a "blower door". Once the leakage area was obtained with the blower door, a mathematical model was used to predict infiltration rates under average seasonal meteorologic conditions in four typical climate zones (4). These infiltration rates were used as input to a building energy analysis simulation (BEAS) program. The BEAS allowed calculation of the impact of the retrofits on energy consumption for a typical pre-HUD-Standard mobile home unit. The typical unit was defined by analyzing the physical description information obtained from auditing the 20 mobile homes in our test sample. Some readers may question why we did not directly measure the leakage reducing, and energy reducing effects of the retrofits.

Several methods of directly measuring infiltration have been attempted by various researchers. Among these are included short-term tracer gas measuring techniques (5), and long-term tracer gas techniques. Tracer gas techniques allow direct measurement of the infiltration rate, whereas, the blower door requires a model to calculate the infiltration rate from the leakage area. However, tracer gas tests are very sensitive to transient climate conditions, and yield different infiltration rates depending on wind speed, orientation, and temperature differences. These are conditions which are unlikely to remain constant throughout the retrofit of a unit. Thus, with tracer gas it would be difficult to determine what portion of a change in infiltration rate was due to the retrofit, and what portion was due to a change in microclimatic conditions. Long-term tracer techniques such as the perflourocarbon tracer (PFT), developed at Brookhaven National Laboratory (6), present similar problems and would require the occupants consent to be exposed to the PFT.

The blower door was chosen because it is relatively insensitive to changing climatic conditions as long as wind velocity is less than 5 mph. The blower door can also be used as a diagnostic tool to determine where leaks occur and should be highly accurate in measuring differences in leakage area.

An alternative method for determining the energy impact of the retrofits is to submeter the units, or use the "Princeton Scorekeeping Method" (PRISM) to analyze utility bill data. This could be done for both the infiltration and conduction retrofits, obviating the need for modeling. However, this approach requires a much larger sample size (preferably about 100 per retrofit). It would also require at least two years of study, the first to establish the baseline performance of the units and the second year to establish the performance of the retrofits.

The larger sample size is necessary because changes in tenants, lifestyle, or operation can strongly effect the energy performance of the units, thereby masking the effects of the retrofits. In this type of testing the measured results only apply to the climate or climates where the testing is done. If we wish to extrapolate the results to other climates we again here to rely on calculational models. Others who have tried these approaches have achieved uncertain results (7,7a). Also, funding limitations make this approach impractical for our project.

We did complete a before- and after-utility-bill study on the 20-unit test sample using the PRISM analysis method (7b). Our experience with this method confirmed the need for large sample sizes, especially with the transient nature of the occupant group.

The approach used here, a combination of short-term direct measurements and modelling, may not give very accurate "energy magnitude" results, but should be sufficiently accurate in terms of energy differences. Since our primary interest is the energy savings from various retrofit options, we believe the approach to be justified. However, realize that this approach cannot account for the effect of individual human behaviour patterns. In this sense, our results are analogous to an EPA gas mileage test. They indicate the savings due to weatherization measures under a set of assumed standard operating conditions.

More detail on the conduction monitoring technique is provided in Section 6.0 of this report.

5.0 MONITORING OF INFILTRATION REDUCING WEATHERIZATION MEASURES

5.1 Infiltration Analysis Process

Infiltration is the rate of uncontrolled air exchange in a building through cracks and other openings. The rate of air flow is a function of crack opening area, the dynamic pressure of the wind, and the buoyant pressure of inside-outside temperature differences. Some infiltration is desirable since it is a means of diluting indoor air contaminants. A large infiltration rate is undesirable due to the energy losses associated with heating or cooling the outdoor air.

The rate of infiltration is often expressed in air changes per hour (ACH). This measure can be made indirectly by using a device called a "blower door". A blower door test determines the cumulative area of cracks in the building shell by measuring the blower door air flows necessary to maintain a series of pressure differences between the inside and the outside of the building. Once leakage area is determined, location-specific wind speeds, indoor-outdoor temperature differences, and the relative position of leakage areas in the building shell are used to calculate the air infiltration rate for that building under those conditions.

The final step in the analysis is to relate ACH to energy use. This is done by defining a typical mobile home (based on audit data from our test sample) at various stages of weatherization, modeling the unit in a simulation program, and analyzing the effect of conservation measures on the energy load. Climate effects both the air infiltration rate, and the energy impact of a reduction therein. The performance of our typical mobile home was, therefore, modeled using several different typical meteorological year (TMY) data sets. A TMY is an hour by hour annual record of weather conditions based on historical data for a given geographical location. TMYs exist for many cities in the United States. Using TMYs for Denver, Phoenix, Miami, and Madison, Wisconsin, to determine the energy impact of the infiltration reducing weatherization measures in the climate zones represented by those cities.

The procedure used to analyze the effects of infiltration on energy load included:

Mobile Home Audits
- o Conduct audits to collect thermophysical data on units
- o Run blower door tests and determine leakage area
- o Weatherize and repeat blower door tests

Define Typical Mobile Home
- o Assemble audit data
- o Calculate ACH based on typical leakage area and climatic conditions

Model Typical Mobile Home
- o Define heating, cooling, and ventilation control strategies
- o Define natural ventilation capacity/schedule
- o Define internal gains/schedule
- o Define typical unit thermal conductance and capacitance characteristics

Simulation
- o Run simulations in four locations while varying weatherization conditions

Economics
- o Determine the impact of infiltration on energy loads
- o Calculate simple payback periods for each measure in each location, based on the cost of the measures and fuel costs.

5.2 Selecting and Calibrating the Blower Doors Used for Testing

The blower door is a relatively new monitoring device and there is considerable controversy among researchers and users as to what constitutes good standard practice in its manufacture and operation. Currently, different testing standards are being developed by the ASHRAE Air Leakage Testing Committee, the ASTM E779 Committee, the Canadian General Standards Board, ASME, and various state committees. At the outset of the project, SERI possessed two "fan-rpm" blower doors, among the first produced by the Harmax Company and the Gadsco Company.

Because our data would depend on the accuracy of the instruments used in the project, we were particularly interested in testing several blower door brands and types. We were able to collaborate with the Colorado Thermal Improvement Association (CTIA) to test a number of blower doors in their State Certification Testing Chamber at Red Rocks Community College in Golden, Colorado. Based on those tests, we chose to use two "current vintage" blower doors of the "calibrated orifice" type, manufactured by Infiltec Corp. and by Minneapolis Blower Door Corp. These instruments measured a series of known leakage areas in the test chamber to within 5%. Complete test results are available on request. (We did not test all currently available brands. Other blower doors may be as accurate or more accurate than those we selected.)

5.3 Defining the Characteristics of the Typical Mobile Home

Table 1 shows key data extracted from the Audit and Blower Door forms filled out by Sunpower for each of the 20 mobile homes in our test sample. The mobile home code numbers are shown across the top of the table, and tabulated characteristics are listed vertically under each code number. One of the headings is listed as "Typical." The data under this heading is averaged from the data for 17 of the individual units. Three of the units listed were eliminated from consideration because of their atypical nature. These three units were travel or vacation trailers as opposed to conventional mobile homes. Data from the travel trailers was not used in determining the average characteristics of the typical mobile home because these units tend to be smaller and differently constructed than conventional mobile homes. Some of the major characteristics of the typical mobile home before weatherization are listed below:

- Floor area: 555 ft^2 (11.4 ft × 48.7 ft)
- Height: 7 ft
- Volume: 3872 ft^3
- Surface area: 1947 ft^2
- Wall construction: 2 in. × 2 in. stud wall 16 in. O.C.
- Wall insulation: 1.2 in. glass fiber batt
- Roof insulation: 1.2 in. glass fiber batt
- Belly insulation: 1.3 in. glass fiber batt
- Window area: 73 ft^2.

5.3.1 Leakage Area

Listed in the table for each mobile home are leakage area values expressed as ELA-LBL and ELA-C. These values represent Effective Leakage Area (ASME standard) and Equivalent Leakage Area (Canadian standard), respectively. These two measures are similiar in that they represent the equivalent amount of open area that would have the same air flow as the actual leakage area. The main difference between them is that ELA-LBL assumes the equivalent open area to have a rounded edge, while ELA-C assumes a sharp edge. Also, the reference pressure is 4 pascals for ELA-LBL and 10 pascals for ELA-C. The CTIA blower door test chamber used sharp-edged orifice plates. The two blower doors used in this project predicted ELA-C to within about 5% of the known sharp-edged orifice plate areas.

TABLE 1 PART 1
DENVER MOBILE HOME DATA

UNIT #		D1	D2	D3	D5	D7	D8	D9	D10	D11
BEFORE WEATHERIZATION										
ELA-LBL		106	100	277	88	63	73	73	53	268
ELA-C		188	178	481	155	114	138	133	99	477
% LEAK CEILING		45	30	20	45	55	30	65	65	45
% LEAK FLOOR		35	40	45	20	30	45	25	20	25
ACH		1.67	1.30	2.82	0.93	0.85	1.04	1.18	0.84	2.92
AFTER WEATHERIZATION										
ELA-LBL		52	53	124	69	36	50	46	37	82
ELA-C		96	101	213	125	70	97	86	69	157
% LEAK CEILING		20	10	10	15	15	35	15	15	15
% LEAK FLOOR		15	30	15	15	10	15	15	10	20
ACH		0.93	0.87	1.26	0.80	0.58	0.77	0.80	0.59	1.06
WIDTH	FT	9.75	12	12			12	12	10	12
LENGTH	FT	46.2	46	55			50	40	52	56
HEIGHT	FT	7	7	7			7	7	7	7
VOLUME	FT3	3153.2	3864.0	4620.0	4620.0	3850.0	4200.0	3360.0	3640.0	4704.0
SURFACE AREA	FT2	1684.2	1916	2258	2258	2010	2068	1688	1908	2296
WALL SURFACE AREA	FT2	783.3	812	938			868	728	868	952
WALL TYPE										
Interior		PANELING	PANELING	PANELING			PANELING	PANELING	PANELING	PANELING
Exterior		AL SIDNG	AL SIDNG	AL SIDNG			AL SIDNG	AL SIDNG	AL SIDNG	AL SIDNG
INSULATION										
Type		FG BATT	FG BATT	FG BATT			FG BATT	FG BATT	RW BATT	FG/RW BT
Amount Before										
wall	IN	1	1	1.5			1	1	1	1.5
roof	IN	1	1	2				1	1	1
floor	IN			3.5			1	2	3.5	1.5
Amount After										
wall	IN	1	1	1.5			1	1	1	1.5
roof	IN	1	1	2				1	1	1
floor	IN	5+	5+	3.5	5+		1	7	3.5	1.5+
WINDOW AREA										
Total	FT2	49.8	73.7	56.9		77.8	98.5	80	86.4	93.5
BEFORE										
wndw/wall area	FT2	0.064	0.091	0.061			0.113	0.110	0.100	0.098
% Double glaz			49.7	0.0		95.9		56.9	100.0	
% Single glaz			50.3	100.0		4.1		43.1	0.0	
Front	FT2	5.8	5.6	5.6		28.1		25.4		15.6
double glaz	FT2		0	0		28.1		0		
single glaz	FT2		5.6	5.6		0		25.4	0	
Side 1	FT2	19.1	36.6	27.8		31		24.1		48.7
double glaz	FT2		18.3	0		31		15		
single glaz	FT2		18.3	27.8		0		9.1	0	
Back	FT2	5.8	5.6	5.6		9		8.9		4.5
double glaz	FT2		5.6	0		9		8.9		
single glaz	FT2		0	5.6		0		0	0	
Side 2	FT2	19.1	25.9	17.9		9.7		21.6		24.7
double glaz	FT2		12.7	0		6.5		21.6		
single glaz	FT2		13.2	17.9		3.2		0	0	
AFTER										
% Glaz added		0		90		7	0	20	0	

TABLE 1 PART 2
DENVER MOBILE HOME DATA

UNIT #		D12	D15	D17	D18	D19	D20	A64	A86	TYPICAL
BEFORE WEATHERIZATION										
ELA-LBL		100	68	66	102	224	122	149	85	119
ELA-C		176	121	123	180	426	216	276	156	214
% LEAK CEILING		30	40	25	15	25	15	20	25	35
% LEAK FLOOR		35	30	15	20	65	40	65	30	34
ACH		1.58	1.05	1.20	1.20	2.76	1.58	1.77	1.50	1.54
AFTER WEATHERIZATION										
ELA-LBL		57	44	41	60	130	90	102	56	66.4
ELA-C		107	85	75	116	230	163	185	105	122.4
% LEAK CEILING		15	15	10	10	15	10	10	15	15
% LEAK FLOOR		20	15	10	10	20	30	45	40	20
ACH		1.07	0.84	0.73	0.91	1.29	1.26	1.15	1.16	0.95
WIDTH	FT	11.3		10	12	12	12	12	10	11.4
LENGTH	FT	39.5		44	50	60	46	56	41	48.7
HEIGHT	FT	7		7	7	7	7	7	7	7.0
VOLUME	FT3	3124.5	3220.0	3080.0	4200.0	5040.0	3864.0	4704.0	2870.0	3872.3
SURFACE AREA	FT2	1603.9	1670	1636	2068	2448	1916	2296	1534	1947
WALL SURFACE AREA	FT2	711.2		756	868	1008	812	952	714	840.8
WALL TYPE										
Interior			PANELING	PANELING	PANELING	PANELING	PANELING	PANELING	PANELING	PANELING
Exterior			AL SIDNG	AL SIDNG	AL SIDNG	AL SIDNG	AL SIDNG	AL SIDNG	AL SIDNG	AL SIDNG
INSULATION										
Type		FG BATT	FG BATT	FG BATT	FG BATT	FG BATT	FG BATT	FG BATT	FG BATT	FG BATT
Amount Before										
wall	IN	1.5		1.5	1	1	1			1.2
roof	IN	2		1	1	1	1	1		1.2
floor	IN	1.5			1		1			1.3
Amount After										
wall	IN	1.5		1.5	1	1	1			1.2
roof	IN	2		1	1	1	1	1		1.2
floor	IN	6.5		5+	6	5+	6	BLOWN		6.3
WINDOW AREA										
Total	FT2	54.2		41	64.4	110.9	65.1	91.9	51.4	73.2
BEFORE										
wndw/wall area	FT2	0.076		0.054	0.074	0.110	0.080	0.097	0.072	0.086
% Double glaz		74.4		33.7	100.0	24.3	62.4	100.0	40.1	61.4
% Single glaz		25.6		66.3	0.0	75.7	37.6	0.0	61.9	38.7
Front	FT2	5.6		9.2	16.6	24	6.1	21	6.3	13.5
double glaz	FT2	0		9.2	16.6	0	6.1	21	0	
single glaz	FT2	5.6		0	0	24	0	0	6.3	
Side 1	FT2	22.2		16.2	16.6	41	28.8	32.1	21.1	28.1
double glaz	FT2	13.9		0	16.6	6.1	20.5	32.1	9.5	
single glaz	FT2	8.3		16.2	0	34.9	8.3	0	12.6	
Back	FT2	5.6		0	16.6	9	5.6	8.9	3.2	6.8
double glaz	FT2	5.6		0	16.6	0	5.6	8.9	3.2	
single glaz	FT2	0		0	0	9	0	0	0	
Side 2	FT2	20.8		15.6	14.6	36.9	24.6	29.9	20.8	21.7
double glaz	FT2	20.8		4.6	14.6	20.8	8.4	29.9	7.9	
single glaz	FT2	0		11	0	16.1	16.2	0	12.9	
AFTER										
% Glaz added		17		66	0	9	39	0		19

Table 1 shows the percentage of leakage area found in the ceilings and in the floors of the mobile home units. This information is necessary in order to calculate ACH from the leakage area. The sensitivity to wind-induced or stack-induced infiltration is strongly dependent on the distribution of crack area on the different surfaces of the building shell. Unfortunately, leakage distribution cannot readily be measured and is, therefore, dependent on the judgement of the tester. This information was recorded by Sunpower during the blower door tests. SERI instructed the Sunpower crews to judge the leakage distribution as best they could by depressurizing the building and feeling for leakage sites. The Sunpower estimates were compared to independent estimates made by two SERI researchers for six of the mobile homes. The SERI and Sun Power estimates showed reasonable agreement.

The ACH values reported in Table 1 are yearly average values calculated with a program resident in the Infiltec portable computer. That program consists of a highly simplified algorithm:

$$\text{Annual Average ACH} = \text{ACH at 50 Pa}/20$$

These values were not used to determine the ACH in the typical mobile home. A more detailed model, developed at Lawrence Berkeley Laboratory by Sherman and Grimsrud, was used to determine the before- and after-infiltration rate for the typical unit. The use of that model is described in a later section.

5.3.2 Dimensions

The dimensions of the typical mobile home were based on the arithmatic average of the dimensions of the 17 units in our test sample. The volume of the typical unit was also based on these dimensions.

5.3.3 Insulation

Wall and roof insulation thicknesses and R-values for the typical unit were found from the average amounts in those units which had this information available from the audit data (see Table 1 for details). Fourteen of the units had 5 in. of glass fiber-batt belly insulation added to them, though not as part of the infiltration reduction study. The typical base-case floor resistance was averaged from the resistances found in those 14 units before the extra belly insulation was added.

5.3.4 Windows

Window areas for the two long and two short sides of the typical unit were based on average values. These areas were summed and compared to the total window area, calculated from the average window/wall area ratio. The two values differed by only 1 ft^2. The window/wall area ratio was then used to properly distribute the window area on the four walls of the typical unit. This was done so that the ratio of heat transfer through the walls and the radiation gain through the windows would be representative of our sample group. The range of window/wall ratios varied from 5% to 11%, with smaller units tending to have smaller ratios. The typical mobile home, based on the average, had a window/wall ratio of 8.5%. For the energy simulations, the unit was assumed to be oriented 45° off the cardinal directions. This was done so that the results would include an "average" solar effect.

Most of the units had at least some storm windows already installed. The area and location of storm windows on the mobile homes before weatherization were determined from the audit sheet schematics. A storm/non-storm window area ratio was determined and distributed to the window areas on the four walls of the typical unit by area weighting. The area of storm windows added during retrofit was determined from the itemized materials provided by Sunpower. All storms added to the mobile homes were made of plexiglass. The specific windows to which the storms were added could not be identified. However, the same area weighting strategy was used to distribute the additional storm window area on the four walls of the unit.

5.4 Modeling the "Typical" Mobile Home

To calculate the energy impact of the retrofits, the thermal performance of the "typical" mobile home unit was modeled using the SERIRES building energy analysis simulation program (8). SERIRES is a detailed dynamic thermal analysis program using time steps of less than one hour. The mathematical representation of the building is a thermal network with non-linear, temperature-dependent controls. The mathematical solution technique includes forward finite differencing, Jacobian iteration, and constrained optimization.

All building energy simulation programs require certain input information. Wherever possible we used audit data from our test sample of 20 mobile home units to derive these inputs. Some input sets were quite straightforward, such as averaging physical dimensions to determine the floor area of the typical unit. However, others were either not available from the audit data, or difficult to determine. Parameters involving human behavior (i.e., the operation of thermostats) were typically the most difficult to ascertain. For these kinds of inputs we attempted to find some commonly accepted reference to assist us in selecting reasonable average values. It is important to remember that the simulation results are very sensitive to these input assumptions. For example, the cost effectiveness of most of the retrofits would have gone up had we assumed a higher heating thermostat set point. We have carefully documented our input assumptions below. SERIRES input files for the before- and after-weatherization cases are available on request.

5.4.1 Infiltration

The equivalent and effective leakage areas, before and after weatherization, were determined for each mobile home from the blower door tests. The averages of each of these values for the stationary units were used to depict the typical unit. Leakage area is a weather independent parameter. However, to model infiltration with the SERIRES program, the air infiltration rate (measured in air changes per hour) must be provided as an input. An infiltration model based on the ELA-LBL, monthly average wind speed, monthly indoor-outdoor temperature differences, and relative location of the leakage areas was used (4) to calculate the average hourly infiltration rate for each month of the year. This was done for each of four climate locations. The monthly infiltration values were then used as input to the SERIRES program.

The equations and parameters used in the calculation are presented in Table 2. The spreadsheet shown was completed using Phoenix weather data as an example.

TABLE 2
Typical Mobile Home
ACH Monthly Calculations
Phoenix Wind Data

Input Parameters

site terrain parameter	y	0.2
site terrain parameter	a	0.85
wind site terrain param	y'	0.15
wind site terrain param	a'	1
wind site height	H'	30
structure height	H	9
structure volume	V	3872
shielding coefficient	C	0.24
ceil+floor leak ratio		
R=(%leak floor + %leak ceil)/100		
before	R1	0.69
after	R2	0.35
ceil-floor leak ratio		
X=(%leak ceil - %leak floor)/100		
before	X1	0.01
after	X2	-0.05
reduced wind parameter		
fw=C*(1-R)^1/3*(a*(H/10)^y/a'*(H'/10)^y')		
before	fw1	0.108
after	fw2	0.138
reduced stack parameter		
fs=(1+R/2)/3*(1-(X^2/(2-R)^2))^3/2*(g*H/T)^1/2		
before	fs1	0.448
after	fs2	0.391
air changes per hour		
ACH=((fw*Asurf*v')^2+(fs*Asurf*(Tin-Tout)^1/2)^2)^1/2 / V		

Before weatherization	
ELA-LBL	119
% leakage ceiling	35
% leakage floor	34
After weatherization	
ELA-LBL	66.4
% leakage ceiling	15
% leakage floor	20

Month		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Yearly
Ave inside temp	F	69	69	69	69	69	69	69	69	69	69	69	69	69
Ave outside temp	F	52.3	54.2	61.5	68.1	78.7	88.4	93.0	90.3	85.0	72.8	60.7	51.8	71.4
Ave wind speed	MPH	6	6.8	7	5.6	7.1	6.3	8.5	7.5	7.2	6.2	5.8	6.4	6.7
Natural vent ACH		10.7	12.2	12.5	10.0	12.7	11.3	15.2	13.4	12.9	11.1	10.4	11.5	12.0
Before Weatherization														
Qwind	ft3/hr	2829	3207	3301	2641	3348	2971	4008	3537	3395	2924	2735	3018	3160
Qstack	ft3/hr	4040	3803	2711	936	3074	4350	4833	4560	3951	1922	2842	4092	1528
ACH		1.27	1.28	1.10	0.72	1.17	1.36	1.62	1.49	1.35	0.90	1.02	1.31	0.91
After Weatherization														
Qwind		2020	2290	2357	1886	2391	2121	2862	2525	2424	2088	1953	2155	2256
Qstack		1967	1851	1320	456	1497	2118	2353	2220	1923	936	1384	1992	744
ACH		0.73	0.76	0.70	0.50	0.73	0.77	0.96	0.87	0.80	0.59	0.62	0.76	0.61

The table lists the natural ventilation capacity and monthly infiltration ACH for the typical mobile home before and after weatherization in Phoenix.

5.4.2 Heating, Cooling and Ventilation Control Strategies

The control strategies and schedules developed for heating, cooling, and ventilation were designed to reflect normal occupant behavior in controlling comfort conditions. The heating and cooling set points were assumed to be 69°F (20.5°C) and 79°F (26°C), respectively, as recommended by ASHRAE (5).

Many occupants will open windows under overheated conditions. However, no consistent pattern was determined to characterize this behavior. To assume that windows were never opened would show unjustifiably large cooling savings for some retrofits. Therefore, we had no alternative but to make some assumptions concerning this effect.

To simulate the occupant opening and closing the windows, the ventilation set point was scheduled seasonally. In the months when only heating was necessary, it was assumed that occupants would open windows if the temperature equalled or exceeded 79°F. In the months when only cooling was required, it was assumed that window ventilation would be used when the temperature was greater than or equal to 71°F and the outside temperature was less than the inside temperature. For those months with both heating and cooling loads, window ventilation was assumed to start when the temperature equalled or exceeded 75°F, and an outside cooling resource existed. These assumptions are conservative in the sense that failure to adhere to this control strategy would result in greater heating and cooling loads. This would, in turn, make the retrofit strategies appear more cost effective. For example, if a constant window ventilation control temperature, set midway between the heating and cooling set points, had been used throughout the year then heating and cooling loads would have increased. During the heating season this would have been due to the relatively low venting set point, reducing potential daytime energy storage. For the cooling season this would have been caused by the relatively high venting set point, allowing the unit to store unwanted heat before venting began.

5.4.3 Calculating Natural Ventilation Capacity from Windows

The capacity for natural ventilation is limited by the available open window area, inside to outside temperature difference, and wind speed. Several different techniques for calculating this effect exist. One of the more detailed methods was developed by Aynsley (9), and one of the more simplified approaches was developed by Olgyay (10). In previous work this author demonstrated close agreement between these two methods for simple building geometries (11). Thus, the simplified method of calculation was used to determine monthly average natural ventilation from window openings in four climate zones. The equation used was:

$$ACH = 60 \times E \times A \times v$$

where E = factor dependent inlet area to outlet area ratio
A = inlet window area (ft^2)

v = on-site wind velocity normal to the opening face (mph)
ACH = ventilation capacity in air changes per hour

For the calculation, it was assumed that half the window area was available as a natural ventilation opening. Half of this available area carried inlet air flow and half outlet air flow. The results for Phoenix are presented as an example in Table 2. These results were used as input to the SERIRES model.

5.4.4 Internal Gains

Internal gains are heat contributions to a space from such activities as cooking, bathing, using appliances, and lighting. These gains have two components, a sensible and latent contribution. Due to daylength and household activity differences, internal gains vary through the year (12). Typically, more gains are experienced in winter than in summer. In winter these gains are not wasted since they contribute to heating the unit. In summer, the cooling load is increased by these internal heat gains.

Due to the effect of internal gains on heating and cooling loads, the fluctuations of the gains throughout the year needed to be accounted for in the SERIRES model. The schedule for internal gains was based on the deviations of non-heating consumption from the average over the year. The average sensible gain was based on average daily use in the Denver area for lights and appliances (3). Latent gains were assumed to be 30% of the calculated sensible gains. Both average gain values were then subject to monthly deviations in the derivation of the annual internal gains schedule for input to the SERIRES model.

5.4.5 Windows and Orientation

The orientation of the typical unit was specified such that one of the short walls faced 45° east. The window areas in a mobile home are not typically equal on each of the short walls or on each of the long walls. But, in order to eliminate a bias in regard to solar orientation, it was assumed that the window areas were equal on both short walls and both long walls. These areas were calculated from the average window areas of the long and short walls, respectively.

5.4.6 Mobile Home Construction

The modeling of the shell for the typical mobile home was based on a review of mobile home construction methods, and on field observations made by the Sunpower crew and SERI researchers. The actual SERIRES simulation input file was not necessarily realistic from a structural point of view, but it was a realistic model from a thermal point of view. The exterior finish of the mobile home consisted of a thin, aluminum sheet. The wall frame was 2 in. × 2 in. studs, 16 in. on center. The interior wall material was 1/4 in. paneling. The roof of the unit was comprised of a 1/2 in. plywood base, an air space of 6 in., bowstring trusses, and an exterior finish of galvanized metal. The floor was constructed of 1/2 in. plywood and joists. The underside of the trailer was covered with a rodent barrier. The pre-retrofit wall, roof, and floor sections were assumed to contain glass fiber batt insulation of 1.2, 1.2, and 1.3 in., respectively.

Mobile homes are of very lightweight construction. However, we accounted for the thermal mass effects of the structural wood frame in our simulation. Interior mass was also modeled, assuming 1200 lb of wood cabinets and furniture and 900 lb of metal appliances and plumbing fixtures.

5.4.7 The Weatherization Measures

The weatherization techniques described below were those favored by the Sunpower crew. They may not be representative of methods used by other weatherization groups. The description of the methods provided below does not represent an endorsement by the Solar Energy Research Institute for any specific method or material. Occasionally, we mention alternative methods and materials. However, this section is not intended to be a comprehensive treatment of alternative methods. The purpose of this section is to describe what the Sunpower crews did to weatherize the mobile homes in our test set.

The observations made by Sunpower regarding the condition of the mobile homes are listed in Table 3. The three leakiest points for each unit are presented in the table. A rating of "1" indicates the worst point. An "X" denotes that the problem was present, although it was not one of the top three problems.

TABLE 3 PART 1
DENVER SAMPLE
LEAKAGE MEASURES

UNIT #	D1	D2	D3	D5	D7	D8	D9	D10	D11
INFILTRATION LEAKAGE POINTS									
Swamp cooler	2	2	1		1		1	1	2
Windows	1		X	2		1			3
Storms (3+)	X		X	X			X		X
Cold air return									
Ductwork						X			X
Furnace Closet	3	3		X	2	2		3	X
HWH Closet			3	1			2		X
Plumbing penetr	X	X	X	2	3	3	3	2	1
Doors wthrstrp	X	X	2	X				X	
Floor penetr			X				X		X
BLOWER DOOR DATA AVAILABLE	YES	YES				YES			YES
OTHER INFORMATION									
Belly insltd	X	X		X	X	X	X		X
Plumbing leaks							X		X
Roof leaks	X		X			X		X	
Wall fan present	X	X	X	X					X
Vented walls			X			X			
HWH type	GAS	GAS	GAS	GAS	ELEC	GAS	GAS	GAS	GAS
Doors repl	(1)		(2)		(1)			(1)	
Leveled							X		

TABLE 3 PART 2
DENVER SAMPLE
LEAKAGE MEASURES

UNIT #	D12	D15	D17	D18	D19	D20	A64	A86	TYPICAL
INFILTRATION LEAKAGE POINTS									
Swamp cooler	2	2	2						
Windows			X	X			X		
Storms (3+)			X	X		X	X		
Cold air return					1			1	
Ductwork								3	
Furnace Closet	3	3	1	2	X	2	X	2	2
HWH Closet	1	1	3	1	2	1			3
Plumbing penetr	X	X	X	3	X	X	1	X	1
Doors wthrstrp		X	X	X	X			X	
Floor penetr				X	3	3	X		
BLOWER DOOR DATA AVAILABLE			YES		YES		YES	YES	
OTHER INFORMATION									
Belly insltd	X	X	X	X	X	X	X	X	
Plumbing leaks			X			X	X		
Roof leaks		X							
Wall fan present						X	X		
Vented walls									
HWH type	GAS	GAS	GAS	GAS	GAS	GAS	ELEC		
Doors repl		(1)			(1)		(1)		
Leveled									

The other information provided indicates the conservation measures and repairs which were completed by Sunpower. The typical mobile home is also rated for leakage problem areas. The rating was based on a weighted average of the three leakiest points from the 17 units in our test group. These leakage points were, in order of importance, plumbing penetrations, furnace closet and heat distribution system leaks, and gas water-heater closet.

1) Plumbing and Electrical Penetrations:
These commonly occurred through the floor or wall. Frequently, a 2-3 in. diameter hole had been drilled at the factory for a 1/2 in. outer diameter (O.D.), or smaller pipe. Much larger openings were sometimes found where sloppy plumbing or electrical repairs had been made in the past. Weatherization consisted of plugging these openings with expanding foam, silicone with backerod, or 6 mil polyethylene sheet and construction adhesive.

2) Furnace Closet and Heating System:
The furnace closet was found to be a source of air leakage in every mobile home in the project. Leakage areas were found where the flue penetrates the ceiling and where the combustion air duct penetrates the floor and rodent barrier. The flue penetration was sealed with sheet metal, high temperature caulk, and/or silicone. The combustion air duct was sealed

with silicone, open cell foam, sheet metal, and/or expanding foam depending on the size, shape, and accessibility of the opening.

Mobile homes typically use a furnace with a sealed combustion chamber. Combustion air is supplied from under the mobile home through ductwork, or from above, through a downdraft air channel fabricated as part of the furnace flue. Other combustion air sources are not necessary, as long as the sealed combustion path is operating properly and there are no cracks in the heat exchanger. Nevertheless, a carbon monoxide test should always be conducted after any work on the furnace or furnace closet.

Most mobile home furnaces use a register in the furnace closet door as the cold air return. In two of the mobile homes a separate return air system was found between the floor and the rodent barrier. Such systems are extremely leaky and generally unnecessary because of the small volume of single-wide mobile units. Weatherization consisted of sealing the return air floor registers and the return air chase at the base of the furnace with plastic and construction adhesive. A large register was then installed into the furnace closet door to accomodate the cold air return.

Another important source of air leakage in the heating system was at the junction of the hot air delivery plenum and the floor heating register sleeves. These vertical sleeves were often poorly connected to the longitudinal plenum via a loose friction fit. These and other holes in the heat distribution ducts can best be observed with a mirror and a flashlight aimed from a floor register. Such leaks were sealed with aluminium tape, silicone, and/or expanding foam. Access to these leaks is difficult. In general, only major leaks in this system were repaired.

Leaks in the heating distribution ducts have two very different effects, depending on whether the furnace fan is on or off. With the fan off, extra infiltration leakage paths exist from the under floor area through the ducts and up through the floor registers into the living space. With the fan on, the heated distribution air leaks out into the under floor space and then to the outside environment. Thus, the overall efficiency of the heating distribution system is decreased.

3) Gas Water Heater Closet:
In most of the mobile homes the gas water heater was found to be in a separate closet, outside the intentionally heated space of the unit. The water heater is located so that combustion air is supplied from outside the living area. This closet area proved to be a major source of air leakage. Leakage sites in the hot water closet were also among the least accessible for correction. Several of these closets opened directly into bathroom cabinets, built-in drawers, or under-sink and under-tub areas. Where possible, these points were sealed with 1/8 in. hardboard and silicone. For less accessible areas, 6-mil polyethylene sheet and construction adhesive sometimes worked. For smaller penetrations, expanding foam or silicone and backerod were effective. Other's have tried stuffing large openings with batt insulation, then sealing them off with an insulating foil membrane.

These kinds of problems are not generally found in units using electric water heaters, where the heater can safely be located within the conditioned space.

Occasionally, we find a gas water heater drawing combustion air from inside the mobile home. In such cases we recommend isolating the closet from the interior of the mobile home and installing an outside combustion air opening in the closet. Such appliances should be carefully checked for backdrafting and spillage with a CO meter.

4) Evaporative Cooler:
About half of the mobile homes in the test sample had roof-top evaporative coolers, sometimes called "swamp coolers". These units were rarely operational. Nonetheless, the cooler chase was a major source of air leakage. Cooler covers made of reinforced vinyl and fastened with screw clips are commercially available. A technique favored by the Sunpower crews was to cut a slightly oversized plug from open cell foam wrapped in 6-mil polyethylene sheeting, then pressure fit it into the interior side of the chase. This allows the occupant the option of removing the plug in summer without climbing on the roof.

5) Windows:
Every mobile home in the test group had some air leakage from the windows. The mobile homes in our study were constructed with awning or jalousie type windows. Although these windows are by nature less tight than a sliding window, they did not constitute a major air leakage problem unless they were damaged. The most common failure of this type of window was due to malfunctioning of the operator mechanism, rendering tight closure impossible. The second most common problem was due to degradation of the seals between panes. Additionally, cracked, broken, and missing panes were frequently found. Occasionally, cable TV lines, antennae wire, and anti-freeze tapes were routed through the windows, preventing tight closure of the assembly.

Storm windows were found on some of the windows in every mobile home. For windows with storms, remaining air leakage was primarily from the crack between the interior window trim and lip of the interior wall rough opening. Storm windows were only added to those windows which had significant leakage.

Weatherization of the windows consisted of several different methods. Operating mechanisms were repaired where possible to facilitate tight closure of the window. Broken panes of glass were replaced with plexiglass. Damaged windows, judged not necessary for ventilation purposes, were replaced with site-fabricated plexiglass fixed-pane assemblies. Damaged seals at awning and jalousie pane edges were repaired or replaced with weatherstripping. TV lines, antennae, etc. were rerouted through the floor or wall. The crack between the window trim and interior wall was sealed with siliconized acrylic caulk.

Windows judged necessary for summer ventilation, were replaced with insulated sliding units if badly damaged. For less severe damage, such as non-repairable operator mechanisms, site-fabricated plexiglas storm windows were installed. If no storm frame existed, the plexiglass was cut slightly oversized with weatherstripping glued to the plexiglass perimeter. Storm clips were installed to pressure fit the storm to the inside wall surface. Plexiglass was favored by Sunpower because of the savings in cost and labor. However, the long term durability of the plexiglass may be less than that for glass storm and replacement windows.

Storm windows reduce energy consumption by reducing infiltration, and by reducing conduction losses. In the infiltration portion of the study, we had no way of directly measuring the conduction-reducing effect of the storm windows. However, we did calculate this effect using the SERIRES computer program so that we could compare this effect to the measurements we anticipated taking on storms in the conduction portion of the study (those results are discussed in section 6).

6) Doors:
Doors were not a major source of air leakage in these mobile homes. For those doors which did show significant air leakage, conventional weatherizing devices such as jamb seals and door-sweeps were not appropriate because mobile home doors open outward. They rely on a seal created by weathersripping on a flange which surrounds the door perimeter. The flange is pressed against the outer wall at the door frame when the door is closed. Some weatherization personnel have tried attaching door weatherstripping "jamb-up" kits to the mobile home door itself.

Common problems and appropriate repairs determined by the Sunpower crews for mobile home doors were:

1) Replace damaged, missing, or degraded weatherstripping on door flanges.
2) Repair or adjust damaged latch or lock mechanisms which prevent tight sealing of the door.
3) Damaged door flange preventing a pressure fit of the weatherstripping upon closure. Replace the door.
4) Damaged window in the door. Remove the window and replace with rigid insulation sheathed in mobile home siding.
5) Door does not fit properly in the door frame. This can be corrected by levelling with jacks and installing supplementary support pylons. However, leveling often creates as many problems as it solves. Doors and windows which previously sealed may cease to do so. Leveling is a last resort solution.

7) Kitchen Vent Fans:
Air leakage through kitchen vent fans was a problem in only a few of the mobile homes in our study. When in proper working condition the vent dampers provided a sufficient seal. However, the fans are prone to certain failures over time. Broken pull-chain fan operators cause the fan damper to remain open and the fan to run continuously. This is a straightforward repair. Damaged dampers require replacement of the fan unit. Degraded damper seals should be replaced.

8) Rodent Barrier:
Rodent barriers are commonly constructed of relatively fragile fiber board materials. Holes and loose seams in the rodent barrier allow air infiltration through the floor and around the heating distribution ducts. This

air flow also short-circuits whatever insulation may be in the underfloor area. Small openings were sealed with expanding foam. Large openings were repaired with 6-mil polythylene sheet and construction adhesive.

9) Exterior Walls:
The exterior walls of a mobile home tend to be vented due to the vertical ridges in the aluminium skin. Air leakage past the exterior skin penetrates the interior finish materials via seams, joints, and electrical outlets. None of these individual leakage sites are great, but their cumulative effect is fairly significant. This was generally the lowest priority area for the weatherization crews because of the diffuse nature of the leakage problem. In general, unless an occupant identified a drafty spot, or a large leakage source was found with the blower door, these sites were not sealed. This would have to be addressed to achieve significantly greater reduction in air leakage than was attempted in this project.

10) Leakage Ratio:
The leakage ratio is the area of crack opening per 100 ft^2 of exterior surface of a building. The measure is useful because it allows a partially normalized comparison between buildings of different types and geometries. In this study the average pre-retrofit leakage ratio was 11 $in.^2/100\ ft^2$. The average post weatherization leakage ratio was reduced to 6.3. The floor area was assumed to be part of the exterior surface of the building in calculating these ratios. This is not particularly tight by comparison to many site built houses. However, the small volume of most mobile homes raises the question of how tight is too tight with respect to health, safety, and moisture accumulation issues.

For comparison, a superinsulated, super tight site-built house might have a leakage ratio of about 2.0. A poorly maintained, older site-built house might have a leakage ratio of about 9.0. Most site-built houses would probably have leakage ratios of around 5.5. The ASHRAE proposed Standard 119P suggests that houses with leakage ratios less than 2.0 be provided with continuous mechanical ventilation. Kitchen and bathroom fan vents are suggested for houses with leakage ratios from 2.0 to 5.5.

11) Belly Insulation:
Floor insulation was not specifically part of the infiltration study. However, Sunpower did insulate the floors of 18 of the units in the study. This was done after all infiltration reducing work and all final blower door tests were completed. We had no way of directly measuring the effect of the floor insulation in the context of this study. However, we did calculate the effect of floor insulation using the SERIRES computer model. This was done so that we could compare the calculated result with the direct measurements we would be taking in the conduction study (see Section 6).

Sunpower attempted a somewhat unique method for installing belly insulation. Most methods involve blowing loose-fill insulation in the cavity between the rodent barrier and the floor. Instead, Sunpower installed 5 in. of 5 ft-wide, vinyl-backed glass fiber roll insulation below the rodent barrier. To do this a grid of 16 gauge wire was formed below the main steel support beams of the mobile home. Nails were driven into the rim joists 16 in. on center (O.C.). Wires were secured to the nails and pulled tight across the width of the unit. The grid hangs 6-8 in. below the rodent barrier and supports the insulation. The insulation was cut to appropriate sizes and fit between the structural supports of the steel framing member. The pieces were oversized by 8-12 in. in both dimensions to achieve a tight fit and less leakage past the vinyl vapor barrier at the seams. After the insulation was installed, additional wires were strung the length of the unit for extra support.

This method has thermal advantages over blown-in insulation. However, the durability of such installation remains to be proven, especially if the unit is moved. Also, the relative costs for a highly experienced crew to do a belly-wrap versus a blown-in technique are not known.

5.4.8 Simulation Runs

The four locations chosen to represent various climates in the United States were Denver, Madison, Miami, and Phoenix. For each location, four simulations were run. The typical mobile home was modeled in various weatherization stages. These were:

1. Initial condition before any weatherization (Base Case)
2. Decreased infiltration rate from infiltration retrofits (including the tightening effect of storm windows, but not their added resistance)
3. Decreased infiltration rate + storm windows added (accounts for the theoretical reduction in shell conductance due to the added resistance of the storm windows)
4. Decreased infiltration rate + storm windows added + belly insulation added (accounts for the theoretical increase in resistance due to added belly insulation; no additional reduction in infiltration is attributed to the belly retrofit).

From the simulation results, the effect of air infiltration, storm windows, and belly insulation on energy loads was determined for each location. Cooling loads were calculated even though none of the mobile homes in our sample actually had a vapor compression air conditioner. This was done both to approximate the effect of the retrofits on summer comfort and to assess these weatherization measures for other locations where air conditioners would be used.

The cooling load was assumed to include both sensible and latent components. SERIRES calculates the sensible component based on the energy balance of the zone. Enough cooling is supplied to maintain the set point temperature. The latent component results from the dehumidification of the return air when it is cooled below its saturation temperature by the cooling coil. The amount of moisture removed is dependent on the humidity ratio of the zone air and the temperature of the conditioned, supply air. SERIRES allows the user to set the cooling coil temperature. For this study, the temperature was set at 55°F, a reasonable value for residential unitary equipment.

The heating and cooling energy values calculated with SERIRES are actually envelope loads. These quantities do not include mechanical equipment efficiencies. In order to determine simple paybacks for the weatherization measures, it was necessary to make some assumptions about these efficiencies. The seasonal furnace efficiency was assumed to be a constant .61 (13). This value was based on the RCS (Residential Conservation Service) default heating system efficiency for a gas furnace with a pilot light and no vent damper. This figure is, of course, highly variable depending on such factors as furnace sizing, blower size, blower control settings, thermostat setting, heat exchanger effectiveness, and heating duct delivery efficiency.

The air conditioner SEER (Seasonal Energy Efficiency Rating) was assumed to be 6.5 Btu/Wh (13). This value is recommended by RCS for air conditioners manufactured between 1972-1976. SEER is intended to represent the average operation of air-conditioning equipment over an entire cooling season. It is derived from a standardized test that considers one cycling rate at one outdoor temperature for dry conditions. SEERs provide a rough idea of the seasonal cooling efficiency of a residential air conditioner. Because this measure does not consider the effects of moisture removal on equipment operation, SEER values will suggest a higher than actual performance in humid conditions. When moisture is removed from the air, condensation occurs on the cooling coil. The water layer decreases the efficiency of heat transfer across the coil between the air and the coolant. The SERIRES simulation accounted for the extra energy required to condense moisture out of the air at the evaporator coil; but neither it, nor the SEER, considers the decrease in efficiency due to exterior surface wetting of the coil.

RCS has addressed the effect of location on SEER, but only in terms of crankcase heater energy. Otherwise the SEER is assumed constant for a given piece of equipment throughout the country (14).

5.5 Quantitative Results from the Infiltration Study

Figure 1 shows infiltration rates in four representative climates before and after installation of infiltration reducing retrofits on our typical mobile home unit. These can also be regarded as average infiltration rates for the 17 units used in our study. On average the effective leakage area, which is independent of climate, was reduced from 119 to 66 in.^{2}, a reduction of 44%. The average leakage ratio was reduced from 11 to 6.13 in.^{2}/100 ft^2. The lowest leakage ratio achieved was 3.38 (Table 4).

Reduction in infiltration rate is climate dependent. From Figure 1, it is apparent that the colder climates show a relatively larger reduction in infiltration for a given reduction in leakage area. Average annual temperature differences and wind speeds were used to calculate the infiltration rates.

Figure 2 shows the average change in heating and cooling envelope loads in four climates before and after weatherization of the 17 mobile homes. In this case, weatherization refers to all retrofit measures combined, including infiltration and the added resistance of storm windows and belly insulation. The negative and positive bars represent cooling and heating, respectively. It is evident that these retrofits have very little effect on cooling loads regardless of climate. It is also clear that the reduction in heating loads is insignificant in warm climate zones. As we would expect, the colder the climate, the greater the reduction in heating load.

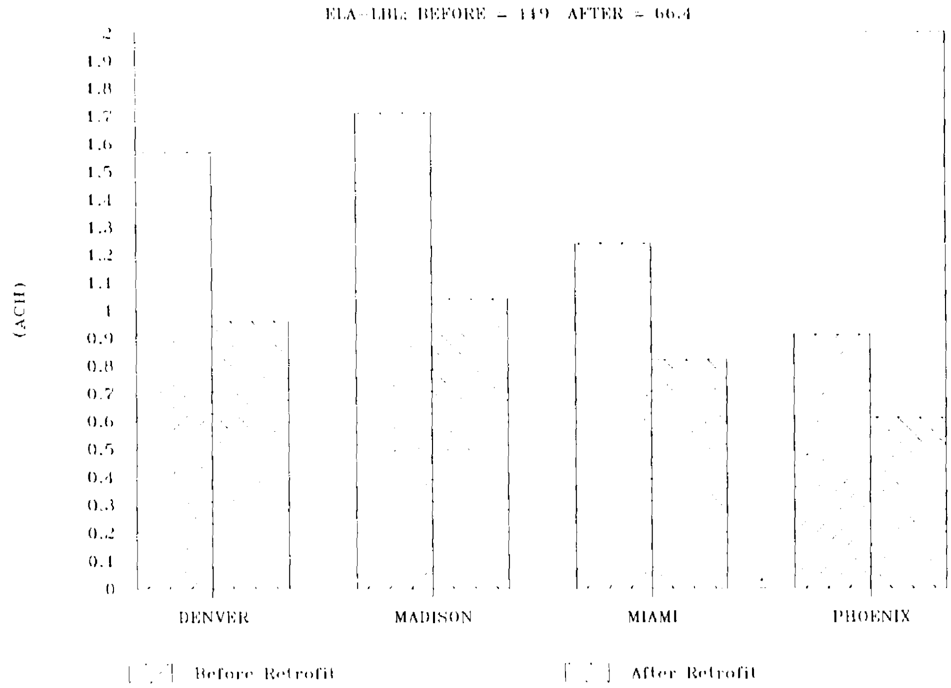

Figure 1. Typical Infiltration Rate

TABLE 4
LEAK RATIO &
ACH AT 50 PA

UNIT	ACH AT 50 PA BEFORE	ACH AT 50 PA AFTER	LEAK RATIO BEFORE	LEAK RATIO AFTER
D1	29.79	16.95	12.41	6.42
D2	26.19	17.54	9.29	5.31
D3	56.58	25.34	21.29	9.44
D5	18.74	16.15	6.87	5.53
D7	17.11	11.67	5.69	3.48
D8	19.50	14.50	6.91	3.38
D9	23.73	16.11	7.89	5.09
D10	16.80	11.80	5.22	3.62
D11	61.52	22.41	21.41	7.02
D12	31.61	21.57	10.99	6.65
D15	21.15	16.90	7.23	5.09
D17	24.06	14.68	7.51	4.59
D18	24.12	18.27	8.70	5.60
D19	55.20	25.82	17.39	9.41
D20	31.61	25.29	11.25	8.50
A86	30.00	23.21	14.18	6.83
A64	37.08	24.38	12.39	8.29
AVERAGE	30.87	18.98	10.98	6.13
ST DEV	13.63	4.62	4.90	1.88
MAX	61.52	25.82	21.41	9.44
MIN	16.80	11.67	5.22	3.38

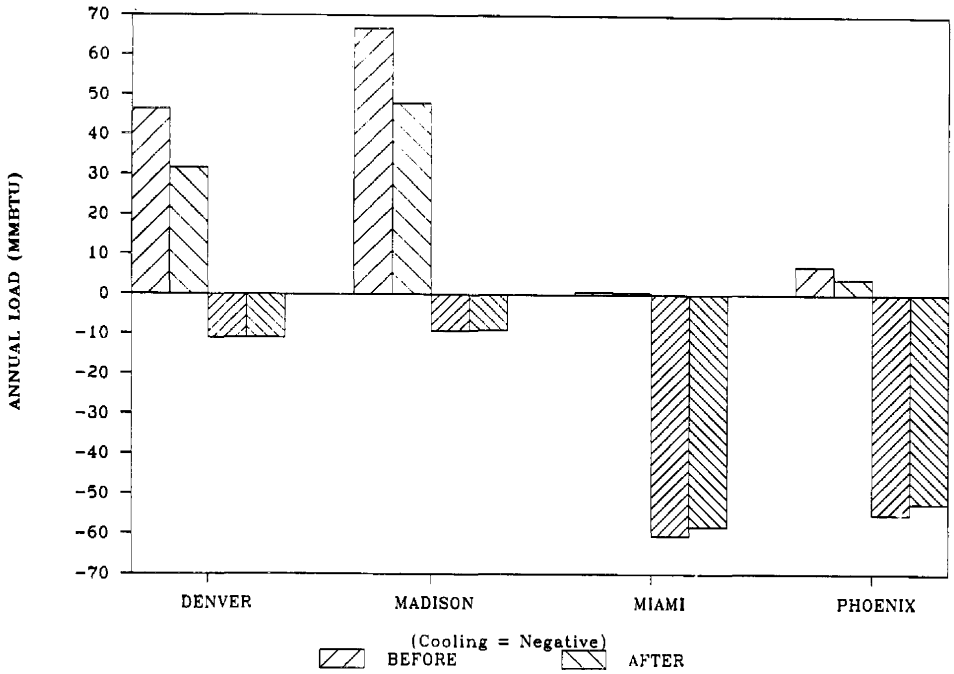

Figure 2. Heat and Cool Shell Loads, Before and After Weatherization

Figure 3 shows average component heating and cooling envelope load savings in the representative climates before and after weatherization. INFIL refers to savings from all infiltration measures including the infiltration reducing effect of the storm windows. INSUL refers to the savings attributable to belly insulation. STORMS refers to the savings from the conduction reducing effect of storm windows. The savings shown for the belly insulation and STORMS are based on SERIRES simulations. They are completely theoretical. In Section 6.0 we will describe a study to directly measure the thermal effect of such resistance-augmenting retrofits as belly, wall, and roof insulation, and storm windows. The savings shown for infiltration are based on a combination of blower door measurements and calculations as explained in Section 4.0.

The savings shown for STORMS are somewhat deceptive in Figure 3. On average only about 16.8 ft^2 of new storm window was added per mobile home. Thus, the savings shown is for the conduction reducing effect of the additional 16.8 ft^2. The relative efficacy of storm windows will be better shown in the economic analysis tables. Infiltration reduction and belly insulation appear to be about equally effective in reducing heating loads in both the Denver and Madison climates.

The small negative cooling savings for some of the retrofit measures in Denver and Madison indicates that in these climates cooling loads stem primarily from internal heat generation. Some retrofit measures hinder the dissipation of this internally generated heat to the outside, and actually cause a slight increase in cooling load. More importantly, however, the effect of these weatherization measures on cooling in the Denver and Madison climates is negligible.

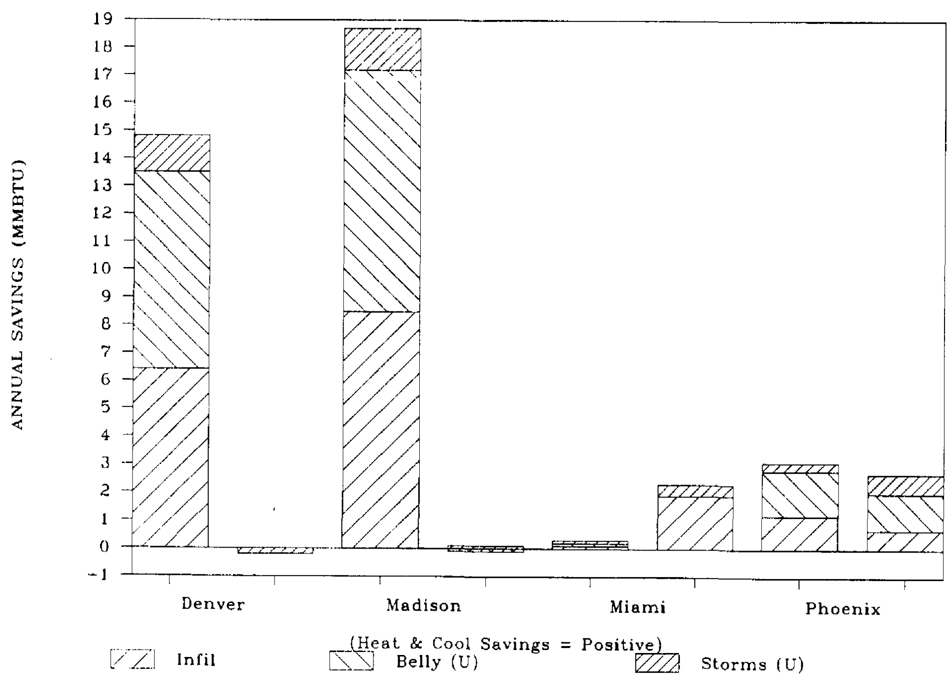

Figure 3. Disaggregated Savings (Shell Load)

In Miami, the weatherization measures have practically no effect on heating loads. This is due to the fact that there is little heating load in this climate. The cooling load savings in Miami is due exclusively to infiltration reduction and storm windows. There is no savings from the belly insulation. This is due to the fact that cooling loads in Miami are primarily from internally generated heat, solar gains, and moisture. The floor insulation inhibits dissipation of internal heat to about the same degree that it resists inward flowing heat. Thus, on average, the effect of the belly insulation is nil. The storm windows reduce cooling load mainly because the extra pane reduces solar transmissivity of the window assembly. In practice, however, this function would be defeated by opening windows for natural ventilation. Shading could be much more effectively achieved through other means (i.e., with awnings, exterior shades, shutters, or proper placement of trees and bushes).

In Phoenix, the modest summer and winter savings are about equal. Dry-bulb summer temperatures are much more extreme in Phoenix than in Miami. In Phoenix, therefore, the average temperature difference between inside and outside is similar in winter and summer. The storm windows are more effective in summer than in winter because of the solar effect. As in Miami, this is misleading because better shading strategies exist. Floor insulation and air tightening are less effective in summer than winter because part of the benefit from resisting inward heat flow is cancelled by the inhibited dissipation of internally generated heat.

The before and after heating and cooling loads, and savings for each retrofit in each of the climates, are itemized in Table 5. The quantitities in Table 5, and in all the figures shown so far have not been adjusted to account

TABLE 5
TYPICAL UNIT SHELL LOADS & SAVINGS

	DENVER	MADISON	MIAMI	PHOENIX
ENERGY LOADS (10E6 BTUs)				
Before Weatherization				
heating	46.5	66.7	0.7	7.1
cooling	11.0	9.1	60.4	55.1
total	57.5	75.8	61.1	62.2
After Weatherization				
-with storms and belly insulation				
heating	31.7	48.0	0.4	4.0
cooling	11.0	9.0	58.1	52.4
total	42.7	57.0	58.5	56.4
-with storms and no belly insulation				
heating	38.8	56.7	0.5	5.6
cooling	11.0	8.9	58.1	53.7
total	49.8	65.6	58.6	59.3
-no storms and no belly insulation				
heating	40.1	58.2	0.6	5.9
cooling	11.2	9.1	58.5	54.4
total	51.3	67.3	59.1	60.3
ENERGY LOADS SAVINGS (10E6 BTUs)				
-due to decrease in infiltration				
heating	6.4	8.5	0.1	1.2
cooling	-0.2	0	1.9	0.7
total	6.2	8.5	2	1.9
-due to belly insulation				
heating	7.1	8.7	0.1	1.6
cooling	0	-0.1	0	1.3
total	7.1	8.6	0.1	2.9
-due to storms				
heating	1.3	1.5	0.1	0.3
cooling	0.2	0.2	0.4	0.7
total	1.5	1.7	0.5	1
-due to all measures				
heating	14.8	18.7	0.3	3.1
cooling	0	0.1	2.3	2.7
total	14.8	18.8	2.6	5.8

for seasonal furnace efficiency, or air conditioner SEER. These are envelope-load savings, not purchased-fuel savings. The purchased-fuel savings will, of course, be much greater than the envelope load savings. Equipment efficiencies will be accounted for in the economic analysis section of this report.

5.5.1 Economic Analysis

The energy savings calculated with the SERIRES simulation program was used, with the cost data kept by Sunpower, to calculate the simple payback of each retrofit. The costs for completing the conservation measures for each of the mobile homes are listed in Table 6. The average cost of weatherization for the 17 units in our study group was $801. This included costs for materials and labor, based on prices charged by Sun Power during the winter months of 1987.

Table 7 shows the purchased heating and cooling energy savings for each retrofit across all climates. These figures include a seasonal furnace efficiency of .61 and an air conditioner SEER of 6.5. Also displayed are local costs for gas (1985) and electricity (1986) for the four representative cities used in the study, and cost savings for purchased heating and cooling fuel (15, 16). Finally, at the bottom of the table, simple paybacks are given for each retrofit measure in each city.

It should be noted that payback periods are extremely sensitive to costs. These costs are highly variable for different locations and weatherization groups. Sunpower's costs for storm windows were at the low end of the cost spectrum while their costs for belly insulation and air tightening were relatively high. Table 8 shows the effect of this cost variability on payback in Denver and Madison (17).

Another important factor is the assumed seasonal furnace efficiency. We used .61 for the calculations in this study because that quantity was suggested in an RCS publication. However, recent studies suggest that the combined furnace and delivery duct efficiency may commonly be as low as .3 to .4, where ducts pass through unheated spaces (18). Since ducts in these mobile homes run through the belly area, it is likely that the delivered heat efficiencies for these units are not nearly as high as .61. If, for example, the efficiency is really .4, then payback periods would decrease by about 33%. Also, certain retrofits such as belly insulation, rodent barrier repairs, heating duct repairs, and furnace tune-ups may increase the combined furnace and heat delivery efficiency. This effect, which we have not accounted for in this study because of lack of data, would have an even greater impact on the economic analysis. For these reasons, the payback periods should not be interpreted too literally. More important are the general trends indicated by the paybacks.

The payback figures in Table 7 clearly indicate the futility of these weatherization measures in predominantly warm climates such as Miami and Phoenix. The only retrofit which appears favorable in these climates is the storm window. However, as previously explained, this is a deceptive result. The savings from the storm windows are primarily due to reducing solar gain. For hot climates, weatherization measures aimed at solar load avoidance will be much more effective.

TABLE 6
COST BREAK DOWN

WEATHERIZATION COSTS ($)

UNIT	D1	D2	D3	D5	D7	D8	D9	D10	D11	D12	D15	D17	D18	D19	D20	A64	A86	TYP
TOTAL COST	811	595	910	778	799	168	1056	270	981	578		813	775	977	1000	533	811	801
TOTAL LABOR COST	405	180	465	350	365	140	670	185	565	300		460	395	370	600	365	405	390
TOTAL MATERIAL COST	406	415	445	428	434	28	386	85	415	278	440	353	380	607	400	168	406	411
MATERIAL COSTS																		
INSULATION	278	330	0	383	324	0	284	0	188	237	294	272	347	420	324	95	278	284
STORMS	0		72	0	6	0	25	0	50	9	25	42	0	10	38	0	0	17
OTHER	128		373	45	104	28	77	85	177	32	121	39	33	177	38	73	128	110
LABOR COSTS																		
INSULATION													140					170
STORMS																		5
OTHER																		215

TRAVEL TYPE

UNIT	D4	D6	D13
TOTAL COST	582	588	630
TOTAL LABOR COST	315	420	465
TOTAL MATERIAL COST	267	168	165
MATERIAL COSTS			
INSULATION	199	0	
STORMS	27	0	
OTHER	41	168	

Note: -Total Cost Calculations for the Typical Mobile Home are based on the the average of costs of those units which had belly insulation added. Unit A64 was excluded since its insulation installation method was different from the others.
-Material Costs for insulation and storm windows for the Typical Mobile Home are based on actual material unit prices.
-Labor costs for insulation and storm windows for the Typical Mobile Home are based on SUNPOWER estimates.

TABLE 7 PAYBACKS BASED ON SUNPOWER COSTS FURNACE EFFICIENCY = .61

		DENVER	MADISON	MIAMI	PHOENIX
EFFICIENCY INFORMATION					
Gas Furnace Efficiency = .61					
AC SEER = 6.5 Btu/WH					
ENERGY SAVINGS (MMBtus or KWH)					
	Infiltration				
	heating	10.49	13.93	0.16	1.97
	cooling	-30.77	0.00	292.31	107.69
	Belly insul				
	heating	11.64	14.26	0.16	2.62
	cooling	0.00	-15.38	0.00	200.00
	Storms				
	heating	2.13	2.46	0.16	0.49
	cooling	30.77	30.77	61.54	107.69
	All Measures				
	heating	24.26	30.66	0.49	5.08
	cooling	0.00	15.38	353.85	415.38
ENERGY COST SAVINGS ($)					
LOCAL COST INFORMATION					
	Gas ($/10E6 Btus)	5.11	6.39	7.33	6.66
	Electricity ($/KWH	0.072	0.095	0.089	0.073
	Infiltration				
	heating	53.61	89.04	1.20	13.10
	cooling	-2.22	0.00	26.02	7.86
	total	51.40	89.04	27.22	20.96
	Belly insul				
	heating	59.48	91.14	1.20	17.47
	cooling	0.00	-1.46	0.00	14.60
	total	59.48	89.67	1.20	32.07
	Storms				
	heating	10.89	15.71	1.20	3.28
	cooling	2.22	2.92	5.48	7.86
	total	13.11	18.64	6.68	11.14
	All Measures				
	heating	123.98	195.89	3.60	33.85
	cooling	0.00	1.46	31.49	30.32
	total	123.98	197.35	35.10	64.17
SIMPLE PAYBACK					
	Infiltration	6.09	3.52	11.50	14.93
	Belly Insul	7.82	5.19	386.97	14.50
	Storms	1.75	1.23	3.44	2.07
	All Measures	6.46	4.06	22.82	12.48

TABLE 8 COST AND PAYBACK VARIABILITY

	COST		DENVER PAYBACK (years)		MADISON PAYBACK (years)	
	SUNP	OTHER	SUNP	OTHER	SUNP	OTHER
INFIL	$325	$225	6	4	3.5	2.5
STORM	$22 ($1.31)	$46 ($2.75/FT²)	1.5	3.5	1	2.5
BELLY	$454	$300	7.5	5	5	3

In Table 8, for Denver and Madison, the storm windows appear most cost effective. This is primarily due to the strategy that Sunpower used, applying storm windows only where they were obviously needed. Many weatherization programs apply storms to all windows regardless of the condition of existing windows. This is much less cost effective. Sunpower reported remarkably low costs for the storm windows. Other professionals in weatherization have expressed skepticism about those costs. Sunpower site-fabricated frameless, gasketed storm windows from 1/8 in. plexiglas and weatherstripping. The durability of this system is unknown. This is also true for more expensive commercial storm windows in the sense that occupants may break or remove the storms and fail to replace them. Storm windows still appear cost effective even when more typical commercial prices are assumed, as long as they are only applied where really needed.

The air-tightening package and the belly insulation appear about equally cost effective in Table 8. Air tightening shows 6 and 3.5 year paybacks, respectively, in Denver and Madison. However, it is likely that experienced crews equipped with blower doors could reduce the tightening cost considerably (this was the first mobile home weatherization project attempted by the Sunpower group). Using costs reported by some other weatherization groups the paybacks in Denver and Madison would have been reduced to 4 and 2.5 years, respectively. Durability is an important unkown with respect to this retrofit. Air leakage may begin to increase over time due to client interaction (failing to replace a swamp cooler chase plug after the summer), physically moving the unit, foundation settling, expansion and contraction, moisture, and/or general degradation of sealants. Will the air tightening retrofits outlive the payback period? At this point, the answer is not known.

The belly retrofit appears to be about as cost effective as the air-tightening measures in Denver and Madison. Some groups report costs below $300 for installing belly insulation. If the rodent barrier is sound, blown-in floor insulation can probably be considered a fairly permanent retrofit, and not subject to significant degradation. It is also likely that belly insulation may increase heating system efficiency by insulating the heating ducts and by reducing air leakage out of the duct when the furnace fan is on. No data currently exists on this effect and it is not accounted for it in these tables.

As previously mentioned, it is likely that furnace efficiencies in older mobile homes are considerably less than assumed in Tables 7 and 8. Table 9 shows paybacks in Denver, assuming a heating system efficiency of .4 instead of .61.

5.6. In Their Own Words: Observations Made by the Sunpower Crews

Two debriefing sessions were held with the Sunpower crews at the close of the infiltration study. The crew supervisors also noted their observations in writing, based on the experience of weatherizing the 20 mobile homes in our study group. Here, we record the most significant of those observations from the individuals who actually did the work.

- "The application of traditional weatherization techniques on mobile homes has not been very effective. These traditional weatherization techniques include interior caulking, door sweeps, and door jamb-ups. These techniques are not as effective on mobile homes because the areas which they weatherize are not the areas of the greatest amount of air infiltration. Mobile homes possess unique infiltration problems which require a more in-depth analysis of the major air leakage points."
- "The use of the blower door during the weatherization process allows the weatherization team to check the progress of their work. Other leakage areas can be found as the larger holes are successfully sealed. The amount of follow-up work is reduced since the weatherization work is continually reviewed."
- "Many of the air leaks found with the blower door would not have been found by just a physical inspection."

TABLE 9 PAYBACK IF
FURNACE EFFICIENCY = .4

DENVER

PAYBACK (YEARS)

	SUNPOWER COSTS	OTHER GROUP COSTS
INFILTRATION	4	2.6
STORM	1	2.3
BELLY	5	3.3

- "The decision to weatherize specific air leakage points is based on the observations made while the blower door is running. Installing a predetermined set of weatherization measures on every mobile home will most likely not result in a satisfactory reduction in heat loss."

5.7. Conclusions from the Infiltration Study

- The locations of primary infiltration sites are different in pre-HUD-Standard mobile homes than in conventional site-built single family detached (SFD) residences
- Most air-sealing weatherization measures typically used for site-built houses would have been ineffective on these mobile homes
- Primary leakage sites were:
  - envelope penetrations for plumbing, wiring, ducts, vents, and flues
  - furnace closets
  - heat distribution and return air ducts
  - water heater closets
  - swamp cooler chases (for units having swamp coolers)
- Using a blower door was essential in achieving significant reductions in infiltration rate
- The blower door also helped to ensure air quality by allowing the weatherization workers to determine if they were making the unit too tight for health and safety considerations
- The average reduction in infiltration rate was about 40%
- The average reduction in annual heating energy use due to the reduced infiltration would be about 15% in a climate similar to that in Denver
- Storm windows appear to be a very cost effective retrofit in cold climates assuming that:
  - they are only installed where they are really needed
  - they are durable enough to outlive their payback period
  - they are reasonably maintained and used by the occupants.

6.0 MONITORING OF CONDUCTION REDUCING WEATHERIZATION MEASURES

Most weatherization agencies emphasize infiltration reducing measures when retrofitting mobile homes. However, increasing insulation levels in mobile homes would also be extremely desirable. As a point of general comparison the building load coefficient (BLC) for a pre-HUD-Standard mobile home is about 12-16 Btu/ft^2-HDD; for a comparable conventional house roughly 7-10 Btu/ft^2-HDD; and for an energy conserving passive solar house, about 4 Btu/ft^2-HDD. A few individuals and agencies have tried, or proposed, adding insulation to the shell of the mobile home. Some of these retrofits are:

- Wall insulation. Remove the windows, doors, and sheathing panels. Fill the wall cavity with fibreglass batts. Wrap the outside of the insulation with Tyvek. Reassemble the skin, doors, and windows.

- o Roof cap. Install rigid board insulation on top of the existing mobile home roof. Cover the insulation with an elastomeric roof membrane. Plug attic vents.
- o Belly insulation. Fill the cavity between the floor and the rodent barrier with blown-in, chopped fibreglas insulation.
- o Skirting, and insulated skirting.
- o Storm windows.

All these retrofits have a number of major and minor variants in terms of materials and installation techniques. For example, some individuals advocate blowing insulation into the bow-string truss cavity instead of capping over the roof. Others suggest wrapping, instead of blowing, the belly. Some of these measures can be quite costly. It is, therefore, important to determine if their thermal effectiveness justifies the cost. It is also necessary to make sure that a technique will not cause moisture damage to the building structure.

6.1 Approach for Conduction Monitoring

A different kind of testing technique was needed for measuring the effectiveness of conduction-reducing retrofits, than for air-tightening measures. The blower door was a convenient instrument for directly measuring reduction in leakage area. It could be used on occupied mobile homes in the field. However, no analogous device exists for directly measuring the effectiveness of weatherization measures intended to reduce building shell conduction. A number of different long- and short-term methods have been proposed, or tried with little or no success.

The most obvious of these is to submeter the building heating and cooling energy usage before and after installation of a given retrofit measure or set of measures. This can be done with either occupied or unoccupied buildings. The advantage of this kind of test is that the quantities of interest, namely heating and cooling energy, are directly measured. However, the practical difficulties of such tests are numerous. Generally, long term tests of this kind require about two years for pre- and post-retrofit data collection. The data must then be normalized because weather differences between the two years can bias the results. Finally, if occupied buildings are used, then a very large sample is needed to remove behavioral bias. In practice, attempts at these kinds of tests rarely, if ever, yield unambiguous results.

Several different short-term testing methods are also suggested by various researchers (18a). These usually involve test periods of from one night, to several days, during which the buildings are kept unoccupied. Such tests, while potentially quite useful, are not yet sufficiently developed. The range of uncertainty for this type of test is probably about 15% to 25% of the building load coefficient (18b). This would not have been accurate enough to determine the effects of individual weatherization measures in our study, where savings might be expected to range around 10% of the pre-weatherization building load coefficient (BLC). For these reasons we decided to develop a different short-term method. It is a variant of what is termed a "co-heating" test. The method takes advantage of the happy coincidence that a mobile home is, in fact, mobile.

6.2 Description of the Test Method

Our short-term monitoring technique involves moving a mobile home into a warehouse. We then maintain a constant "warehouse-to-mobile-home" temperature difference by maintaining constant temperatures in the warehouse and mobile home until quasi-steady state is attained. Generally, the warehouse and mobile home are kept at about 50° and 80°F, respectively, so that work can be done in relative comfort. However, the signal-to-noise ratio can be improved by increasing the temperature difference. Electric resistance heaters are installed in the unit to maintain the desired temperatures. The electric heater power in the mobile home is measured under the quasi-steady state condition to extract the effective overall conductance of the unit. This can be done on consecutive single nights of testing with different weatherization measures installed during the day. More reliable results can be obtained if at least 36 hours are allowed for the test. The effect from any single retrofit is the difference in overall conductance, with and without the retrofit.

Each weatherization measure will have both an infiltration and a conduction reducing component. To separate these components, a tracer gas test is conducted under the steady state condition for each case. The energy associated with the steady state infiltration is subtracted from the overall conductance to yield the shell conduction component. In general terms:

1) $Q_b = U_bA \times \Delta T_b$

2) $U_bA = Q_b/\Delta T_b$

3) $U_rA = Q_r/\Delta T_r$

4) $(U_b-U_r)A = \text{SAVINGS}_{\text{effective conductance}}$

5) $U_bA = (U_bA)_{\text{cond}} + \text{INFIL}_b$

6) $(U_bA)_{\text{cond}} = U_bA - \text{INFIL}_b$

7) $(U_rA)_{\text{cond}} = U_rA - \text{INFIL}_r$

8) $[(U_b-U_r)A]_{\text{cond}} = \text{SAVINGS}_{\text{cond}}$

9) $\text{INFIL}_b - \text{INFIL}_r = \text{SAVINGS}_{\text{infil}}$

10) $\text{SAVINGS}_{\text{effective conductance}} = \text{SAVINGS}_{\text{cond}} + \text{SAVINGS}_{\text{infil}}$

Where:

Q: Measured heater power or heat flow at steady state
UA: Conductance (A = area)
ΔT: Measured temperature difference between mobile home and warehouse
cond: Solid shell conduction
INFIL: Heat flow due to infiltration at steady state
b: Base case
r: Retrofit case

6.2.1 Tracer Gas Test

Several different types of tracer gas tests are documented in the literature including decay, constant concentration, and constant flow approaches. In our testing method we used the decay approach. The monitoring instrument was a

Foxboro Analytical Miran 101 Specific Vapor SF6 Infrared Analyzer. The test was conducted according to the following protocol:

1) Initial reading to establish zero-point of instrument
2) Introduce gas via a gas distribution manifold fabricated from non-absorbent Tygon tubing; allow 10 minutes for mixing; aim for an initial concentration of approximately 170 PPM
3) Take 12 readings at 5-minute intervals
4) Take outside (warehouse) reading to establish zero-drift of instrument (The warehouse was large enough that the concentration of gas in the warehouse was not measurable immediately after the test.)

The concentration decay curves are linearized and converted to infiltration rate as follows:

1) $C_t = C_i e^{-(Q/V)t}$
2) $\mathrm{Ln}(C_i/C_t)/t = Q/V$
3) $Q/V = I$
4) $\mathrm{Ln}(C_i/C_t)/t = I$

Where:

C_i: Initial concentration for each interval.
C_t: Concentration at time (t).
Q: Volumetric flow rate (ft^3/hr).
V: Volume of mobile home (ft^3).
t: Time (hours).

6.3 Description of the Data Acquisition System

The heart of the data acquisition system is a Fowlkes SAM 8.12.4 data logger. In its most basic form, this data logger allows for eight analog-input and four digital-output channels. However, up to four SAM terminal boxes may be ganged together to quadruple channel capacity. The logger contains a 12-bit analog-to-digital converter which yields a resolution in temperature measurement of about .1°F. It is relatively inexpensive, easily transportable, and has proven to be extremely reliable in the field. The data logger contains a small NEC computer which can be programmed to execute control functions as well as log, reduce, and store data. In our current configuration the logger reads two vertical rakes of three air temperature sensors in the mobile home and in the warehouse. The twelve AD-590 temperature sensors are shielded with concentric double-cylinder infrared radiation shields. The logger also controls, via solid state relays, the operation of four Titan 1.5 kW electric resistance heaters to maintain the specified temperatures. An FW Bell watt transducer (.5% accuracy) is wired between each heater and the data logger. The logger reads the output of the watt transducer to record heater power. Each channel is read about every 15 seconds. The readings are averaged and stored hourly. Two 10-watt, 100-cfm muffin fans are run continuously inside the mobile home to minimize stratification. The heater fans also help to discourage stratification.

6.4 Description of the Tests (Jackson & CMC)

Two series of tests were conducted to assess the method. The first was done in Jackson, Wyoming, in conjunction with a Wyoming State Weatherization Workshop. The second set of tests was done in Glenwood Springs, Colorado, in conjunction with the Colorado Weatherization Service and Colorado Mountain College.

For each test, the inside of the mobile home was maintained at approximately 80°F and the warehouse temperature was maintained at about 50°F, long enough for steady state to be approached. The electric heater power necessary to maintain the 30°F temperature difference was measured under this quasi-steady state condition. All results are shown in units of Btu/h°F. The heater energy was divided by the actual measured temperature difference each hour to obtain this normalized figure. The figure can be thought of as the building load coefficient (effective UA), where infiltration is included, and the building conductance (UA), where infiltration heat losses are subtracted from the effective UA.

6.4.1 Analysis Process for the Conduction Tests

The analysis process consisted of data reduction and a comparison between measured and calculated savings. The data reduction procedure was as follows:

1) Transfer hourly temperature and heater power data from Fowlkes logger to LOTUS spreadsheets
2) Scan spreadsheets for anomalous readings, or holes (none were observed)
3) Average the six mobile home air temperature readings to define an interior hourly bulk-air temperature, and average the warehouse channels to define an exterior hourly bulk-air temperature; subtract these two quantities to determine the hourly bulk-air temperature differences between the mobile home and the warehouse
4) Sum the heater power channels and convert to Btu/h; divide the summed hourly heater power by the hourly bulk-air temperature difference to give UA in Btu/h°F
5) Plot the hourly UAs and select those time intervals where quasi-steady state appears to have been reached; average the quasi-steady state UAs to determine the UA for each case
6) Enter the tracer gas readings into a LOTUS spreadsheet
7) Convert tracer monitor voltage outputs to gas concentrations in PPM according to the calibration fourth order polynomial:

   $$PPM = -1.77 + (224.613v) - (36.64v^2) + (111.412v^3) - (48.899v^4)$$

   Where: v = volts
8) Make zero-drift corrections to concentrations; convert concentration curves to infiltration in air changes per hour
9) Calculate the hourly heat loss associated with the infiltration rate using the average bulk-air temperature difference during the quasi-steady state

time intervals chosen in step 5; correct for actual barometric pressure during test

10) Subtract the hourly infiltration heat loss from the UAs calculated in step 5 to determine the solid conduction component of the UA overall.

The comparison between calculated and measured savings also had several steps. First, a detailed audit of the mobile home was conducted during which dimensions, material thicknesses, and wall, window, floor, and roof section details were recorded. Next, an ASHRAE steady-state heat loss calculation was done based on the audit information. Finally, the measured solid conduction UA was compared to that calculated for each case.

6.4.2 Jackson Test

Our first attempt at applying the test method was not very successful for determining the energy savings of retrofits. However, we did learn a great deal about the practical problems of conducting these kinds of tests in the field.

Our primary difficulty had to do with the conflicting scheduling requirements of our tests versus those of the weatherization workshop. The original intent had been to monitor three retrofits in four nights of testing as indicated:

Night 1	Base Case
Night 2	Wall Insulation
Night 3	Insulated Roof Cap
Night 4	Belly Insulation

However, the weatherization agencies preferred a two, instead of three day workshop due to budgetary constraints. Thus, when we started our second night of monitoring, it was no longer possible to distinguish the effects of one retrofit from another, because three different retrofit measures were in various states of completion.

In spite of the scheduling problems, we still managed to learn a great deal about how to improve our monitoring approach. For the Jackson test we used amp clamps to measure the heater power. We found that line voltage in the warehouse electrical supply was too unstable to obtain accurate readings via this technique. Subsequently, we switched to watt-hour transducers for this measurement. We observed that stratification in the mobile home was much greater than expected. This led us to increase the number of temperature sensors used in the mobile home from two at mid-height, to two vertical rakes of three sensors each. We likewise increased the number of temperature sensors used in the warehouse from two to six. In the Jackson tests, we used a blower door, but no tracer gas, to measure infiltration. For subsequent tests we decided to use both a blower door and tracer gas.

One positive aspect of the Jackson tests was the quality of the warehouse in which the tests were conducted. The warehouse was well insulated, large in volume, and maintained extremely stable temperatures throughout the tests. Despite the previously mentioned shortcomings, it was still possible to get a good measurement of the cumulative effect of the weatherization measures. The initial and final BLC's were 354 and 286 Btu/h°F, respectively, including the effect of stack-induced infiltration occurring during the tests. This 19% reduction was primarily due to blown-in floor insulation and a roof-cap.

6.4.3 Colorado Mountain College (CMC) Test

For the CMC tests, we attempted to correct those problems found during the Jackson experiment. Firm schedules were established with those running the training sessions, allowing only one retrofit to be installed each day. We also instituted the previously mentioned hardware improvements to our monitoring kit. One unforeseen difficulty was the poor condition of the warehouse provided by CMC. The walls were composed of a single layer of uninsulated corrugated metal with numerous holes to the outside. The roof was of uninsulated plywood. This introduced uncertainties into our measurements that are described later in this section.

The CMC tests involved a collaboration between Colorado Mountain College, Colorado Division of Housing, and SERI. The college was primarily interested in the training aspect of the project, while SERI and the Division of Housing were interested in the testing aspect. The Division of Housing was particularly curious about the thermal effectiveness of storm windows, insulated skirting, and belly insulation. The tests were sequenced as indicated below.

Base Case

Storm	Skirt	Belly
		Wall
		Roof

Night 1) Base Case: Mobile home as it was found originally.

Night 2) Storms: Base Case + Storm windows installed.

Night 3) Skirt: Base Case + Insulated Skirting installed (storm windows removed).

Night 4) Belly: Base Case + Blown-In Belly Insulation (skirting removed).

Night 5) Wall: Base Case + Belly Insulation + Wall Insulation.

Night 6) Roof: Base Case + Belly Insulation + Wall Insulation + Insulated Roof Cap.

6.4.3.1 Description of the CMC Mobile Home and Retrofits

Major characteristics of the CMC mobile home are listed below. All dimensions are for the interior of the unit.

Dimensions:
- o Length: 57 ft
- o Width: 11.25 ft

o Average Height: 7.5 ft
o Floor Area: 641 ft^2
o Volume: 4809 ft^3
o Window Area: 115 ft^2
o Opaque Wall Area: 977 ft^2
o Carpet Area: 250 ft^2

Wall Section 2 in. × 3 in. Studs 16 in. O.C.:
o .25 in. interior panelling
o 1.5 in. fiberglass batt
o 2 in. void cavity
o 1 in. × 2 in. horizontal lath 24 in. O.C.
o .25 in. foam core
o Exterior aluminium skin panels

Floor Section 2 in. × 6 in. Joists 16 in. O.C.:
o .5 in. plywood floor
o 4 in.+ void cavity (some bowing observed in rodent barrier)
o 1.5 in. fiberglass batt
o .5 in. rodent barrier

Roof Section Bowstring Trusses 24 in. O.C.:
o .5 in. mineral board ceiling
o 6-mil polyethylene vapor barrier
o 1.5 in. fiberglass batt
o avg. 6 in. bowstring cavities
o .25 in. foam core
o galvanized roof panels.

Details of the mobile home are shown in Appendix I. Characteristics of the weatherization measures installed on the mobile home appear below:

Retrofit Measures:
o Storms: single glass storm windows added.
o Skirt: 1 in. polystyrene insulation, laminated to mobile home skin panels
o Belly: 4 in. + shredded fibreglas blown in
o Wall: 2 in. fiberglass batt added, .25 in. foam core removed, Tyvek wrapped
o Roof: 3 in. rigid board polystyrene added + Hypalon roof membrane

6.5 Conduction Test Results

To properly interpret the results shown in this section, it is helpful to remember that savings does not have exactly the same definition for each case. This is because it was quite easy to remove such retrofit measures as storm windows and skirting, but it would have been impractical to remove the belly, wall, and roof insulation, once installed. Thus savings for the storm windows, skirt, and belly retrofits are the differences between each of those cases and the Base Case. Savings for the wall and roof are defined as:

Wall Savings = difference between belly and wall cases.

Roof Savings = difference between wall and roof cases.

In all cases we define percent savings as:

Figure 4 shows the total measured effective UA, or building load coefficient (BLC), for the Base Case and each retrofit. This quantity includes both the envelope heat loss and the heat loss due to stack-induced infiltration. The Base Case BLC was about 380 Btu/h°F.

Figure 5 shows the measured reduction in the BLC due to each retrofit measure. The storm windows and the belly insulation each have the largest effect, followed by the wall and roof retrofits. The insulated skirting shows only a very minor effect. Keep in mind that the effects of the wall and roof cases are somewhat smaller than they would if it was possible to compare them directly to the Base Case. This would have required removing all previous retrofits, and was not practical for this series of tests. Note also that insulated skirting may be unfairly penalized by this particular test since the warehouse ground temperature was warmer than the outside ground temperature, and wind protection effects are not accounted for. Also, this retrofit may require a season to store sufficient heat in the ground to show significant benefit. Finally, this test will not credit belly insulation with any improvement to the heating system efficiency. We are currently developing a test to account for this effect.

Figure 6 shows the savings in building UA associated with the envelope conduction heat loss component for each case. The bars on the left are based on the measured data. The bars on the right are based on ASHRAE steady state heat loss calculations as defined in the 1985 ASHRAE Handbook of Fundamentals. Most of the comparisons appear quite close, except for the roof. The measured data and the calculations show about an equal decrease in building UA for the storms, belly, and wall weatherization measures. Theory predicts that the roof retrofit should have a larger effect, however, this does not show in the data, perhaps because the attic vents were mistakenly left open by the student

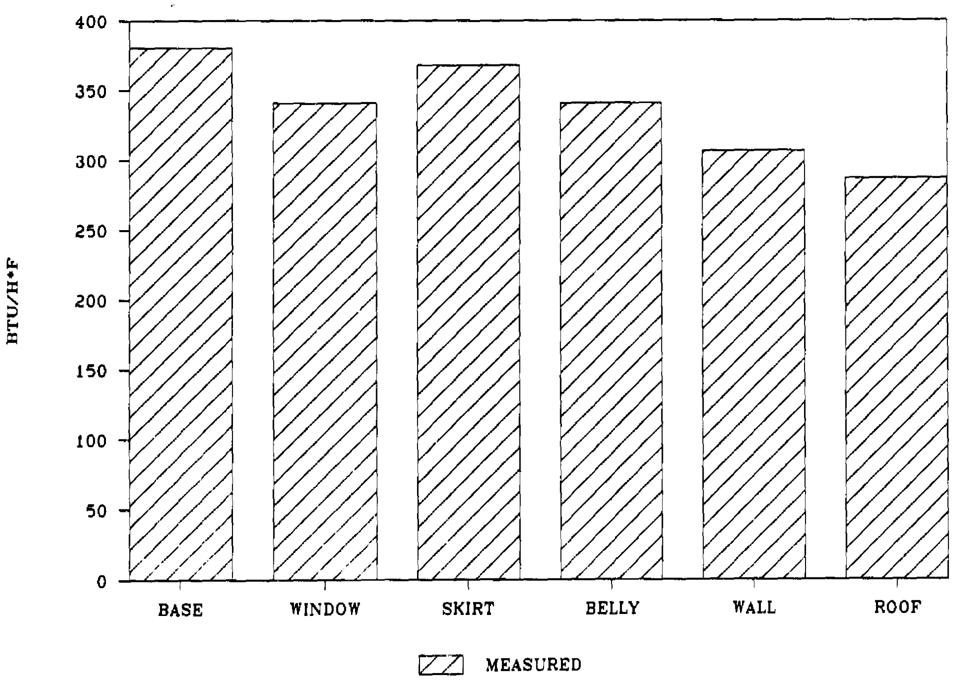

Figure 4. CMC Total Measured UA (Including Infiltration)

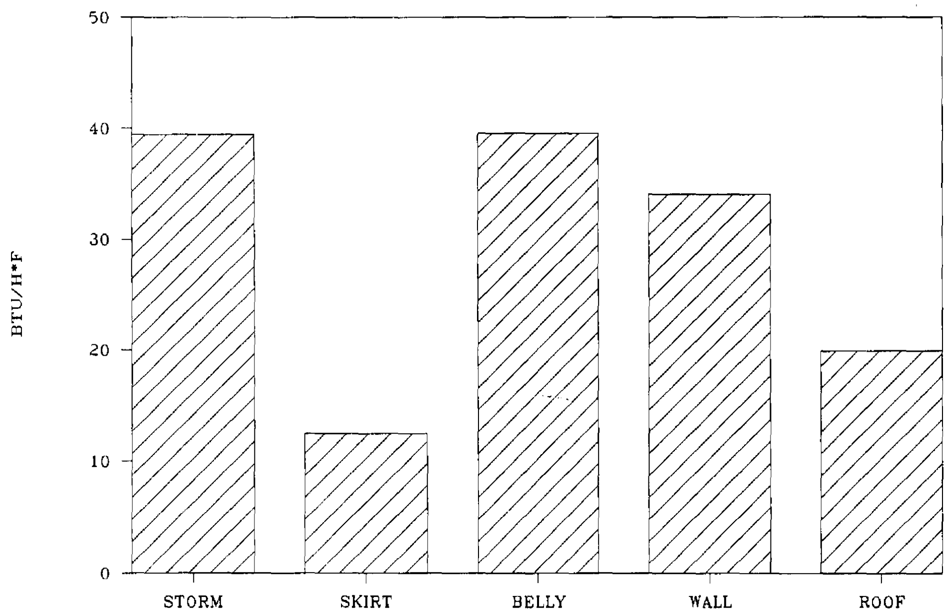

Figure 5. CMC Total Measured Savings (Including Infiltration)

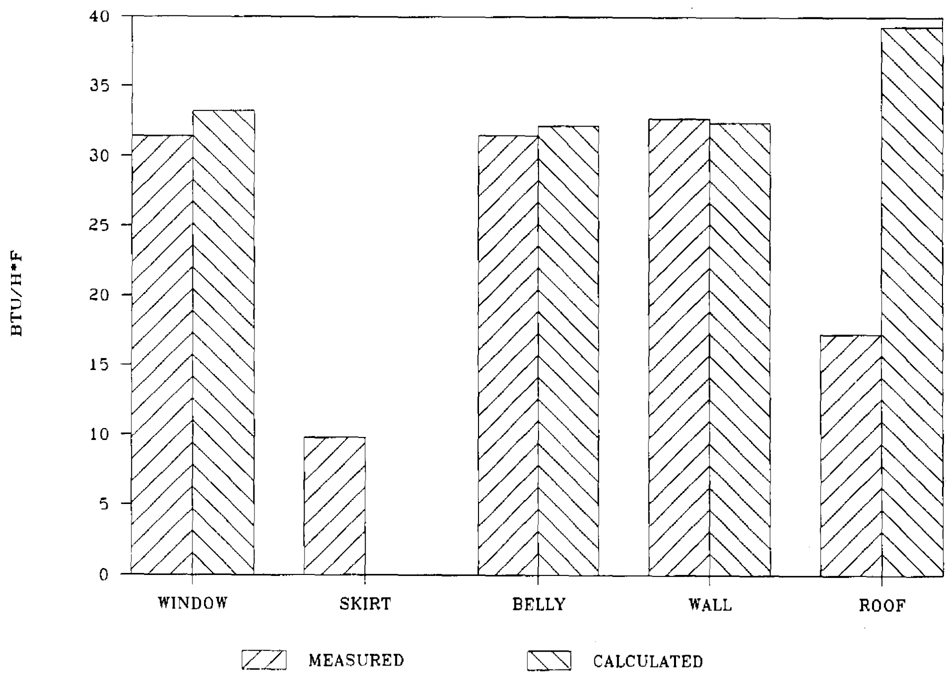

Figure 6. CMC Measured vs. Calculated Conduction Savings (No Infiltration)

workers. We did not do an ASHRAE calculation for the skirting case because there is no satisfactory ASHRAE method for the conditions of that case.

Understand that the close agreement between measured and calculated results could be coincidental. There were many instances in reducing the data, and in doing the calculations, where the judgement of the researcher was required. Large uncertainties were introduced in the measured data due to the lack of insulation in the warehouse. This made it difficult to maintain tight temperature control and exacerbated the effects of both spatial and temporal radiant asymmetries from the warehouse surfaces. Also, the savings we calculated, based on ASHRAE, are very much dependent on what we assumed as the initial condition of the unit. In the field, it is often difficult to assess the insulating properties of the existing materials which compose the unit. Also, ASHRAE leaves a wide margin for judgement concerning the R-values of batt and loose-fill insulating materials. For example, the R-values reported for fiberglass batts range from 2.75/in. to 3.7/in., a difference of 29%. Uncertainty in the R-values of loose-fills are even greater due to variations in packing tightness as it is blown in. We tried to deal with these problems by selecting average values, and by maintaining consistency once a value was chosen. Table 10 summarizes the ASHRAE calculations. Tables 11 through 15 show the assumptions made for the calculations. Additional testing under more highly controlled conditions than those possible in the CMC warehouse will be necessary before more definitive conclusions can be drawn.

TABLE 10 CMC MOBILE HOME MEASURED VS CALCULATED THERMAL PERFORMANCE

MEASURED SAVINGS

	UA-TOTAL BTU/H*F	DELTA-UA TOTAL BTU/H*F	TRACER (ACH)	INFILTR ENERGY BTU/H*F	UA-COND BTU/H*F	DELTA UA-COND BTU/H*F	DELTA %
BASE	380.38		0.82	54.75	325.63		
STORM	340.95	39.42	0.70	46.74	294.21	31.41	-9.65
SKIRT	367.91	12.46	0.78	52.08	315.83	9.79	-3.01
BELLY	340.85	39.52	0.70	46.74	294.11	31.51	-9.68
WALL	306.80	34.05	0.68	45.40	261.40	32.72	-11.12
ROOF	286.89	19.91	0.64	42.73	244.16	17.24	-6.60

ASHRAE STEADY STATE HEAT LOSS CALCULATIONS

	COMPONENT UA BEFORE	COMPONENT UA AFTER	DELTA-UA	TOTAL-UA	DELTA %
BASE	342.33			342.33	
WINDOW	98.90	65.65	33.25	309.08	-9.71
SKIRT					
BELLY	62.94	30.75	32.19	310.14	-9.40
WALL	114.12	81.71	32.41	277.73	-10.45
ROOF	66.37	27.08	39.29	238.44	-23.12

TABLE 11 BELLY
ASHRAE SAVINGS CALCULATION

TITLE: BELLY

JOISTS		BEFORE	AFTER	AREA
FILM-R		0.92	0.92	60.00
CARPET		0.40	0.40	
.5"-PLY		0.62	0.62	
2X6 JOIST R1.23/"		6.76	6.76	
.5"-RODENT BARRIER		1.32	1.32	
FILM-R		0.92	0.92	

NOTE:Carpet on 40% of floor thus R=.5.

TOTAL R		10.94	10.94	

CAVITIES				
FILM-R		0.92	0.92	581.00
CARPET		0.40	0.40	
.5"-PLY		0.62	0.62	
AIR-GAP 4.5"		1.12		
1.5"-BATT R3.208/"	1.50	4.81	4.81	
.5"-RODENT BARRIER		1.32	1.32	
FILM-R		0.92	0.92	
4"-GLAS LSE FILL R2.57/"	4.00		14.00	

TOTAL R		10.11	22.99	

BEFORE	R	U	A	UA	SAVINGS
JOIST	10.94	0.09	60.00	5.48	
CAVITY	10.11	0.10	581.00	57.46	
TOTAL				62.94	

AFTER					
JOIST	10.94	0.09	60.00	5.48	32.19
CAVITY	22.99	0.04	581.00	25.27	
TOTAL				30.75	

TABLE 12 WALL
ASHRAE SAVINGS CALCULATION

TITLE: WALL

STUDS		BEFORE	AFTER	AREA
FILM-R		0.68	0.68	98.00
.25"-PLY		0.31	0.31	
2X4 STUD R1.23/"		4.30	4.30	
.25"-FOAM CORE R5/"		1.25	1.25	
FILM-R		0.68	0.68	
TOTAL R		7.22	7.22	

CAVITIES		BEFORE	AFTER	AREA
FILM-R		0.68	0.68	879.00
.25"-PLY		0.31	0.31	
1.5" BAT R3.208/"	1.50	4.81		
AIR GAP		1.01	0.00	
.25"-FOAM CORE		1.25	0.00	
FILM-R		0.68	0.68	
3.5" BATT			11.23	
TOTAL R		8.74	12.90	

BEFORE	R	U	A	UA	SAVINGS
STUD	7.22	0.14	98.00	13.57	
CAVITY	8.74	0.11	879.00	100.55	
TOTAL				114.12	

AFTER	R	U	A	UA	SAVINGS
STUD	7.22	0.14	98.00	13.57	32.41
CAVITY	12.90	0.08	879.00	68.14	
TOTAL				81.71	

TABLE 13 ROOF
ASHRAE SAVINGS CALCULATION

TITLE: ROOF

TRUSSES		BEFORE	AFTER	AREA
FILM-R		0.61	0.61	40.00
.5"-MIN FIBREBOARD		1.47	1.47	
4"-TRUSS R1.23/"		4.92	4.92	
AIR-GAP 3.5"		0.90	0.90	
.25"-FOAM CORE		1.25	1.25	
FILM-R		0.61	0.61	
TOTAL R		9.76	9.76	

CAVITIES				
FILM-R		0.61	0.61	601.00
.5"-MIN FIBREBOARD		1.47	1.47	
1.5" BATT R3.208/"	1.50	4.81	4.81	
AIR GAP 3.5"		0.90	0.90	
.25"-FOAM CORE		1.25	1.25	
FILM-R		0.61	0.61	
3" EXT POLYSTYR SMOOTH			16.50	
TOTAL R		9.65	26.15	

BEFORE	R	U	A	UA	SAVINGS
TRUSS	9.76	0.10	40.00	4.10	
CAVITY	9.65	0.10	601.00	62.27	
TOTAL				66.37	
AFTER					
TRUSS	9.76	0.10	40.00	4.10	39.29
CAVITY	26.15	0.04	601.00	22.98	
TOTAL				27.08	

TABLE 14 WINDOWS
ASHRAE CALCULATIONS
CMC MOBILE HOME

BEFORE	U (Btu/h*ft²*F)	
Flat Single Glass, Clear	1.1	*(from 1985 Fundamentals chapter 27 Table 13 part A)*
Adjustment Factor for small metal frame windows	1.1	*(from part C)*
	$U * A_f = 1.21$	
Conversion from 15 mph wind to still air	*U = .86*	*(from Table 14)*
Window Area = 115 ft²	*UA = 98.9*	*(btu/h*F)*

AFTER

Flat Single Glass + indoor storm sash: U=.5
$A_f = 1.4$
$U*A_f = .7$
Still air adjustment: U = .5709

UA = 65.65

SAVINGS = 33.25 (btu/h*F)

TABLE 15 INFILTRATION SUMMARY DATA CMC MOBILE HOME

	ELALBL IN2	FLOOR IN2	WALL IN2	ROOF IN2	BLOWDOR ACH	SF6 ACH	DELTA T DURING SF6 TEST
BASE	163.1	63.6	63.5	36	1.33	0.82	30.317
STORM	132.5	63.6	32.9	36	1.11	0.7	30.033
SKIRT	149	49.5	63.5	36	1.255	0.78	32.3
BELLY	134.7	35.2	63.5	36	1.13	0.7	32.8
WALL	126	35.2	54.8	36	1.09	0.68	33.967
ROOF	128.4	35.2	54.8	38.4	1.04	0.64	29.5

	DELTA % SF6	DELTA% BLOWER DOOR	DELTA % ELALBL
BASE			
STORM	-14.6	-16.5	-19
SKIRT	-4.8	-5.6	-8.5
BELLY	-14.6	-15	-17
WALL	-2.8	-3.5	-6
ROOF	-5.9	-4.6	2

Figures 7 and 8 show the hourly BLCs recorded throughout each test. They indicate the degree to which steady state was achieved. In theory, once steady state is reached the lines should all be horizontal, meaning that effective UA was equal for each hour. In Figure 7 we see the curves generally approaching steady state by about 1 a.m. However, in Figure 8, which is a magnification of part of Figure 7, we observe considerable noise in the quasi-steady state period. In fact, the noise is similar in magnitude to the savings we are trying to measure. This makes it difficult to reliably determine a measured UA for each case. In the wall retrofit, for example, it appears that steady state was never reached. Had there been more time, the wall UA might have leveled off lower than displayed at hour 7 on the graph. Thus, the wall retrofit may be more effective than our test indicated. The Base Case and skirt lines are noisy enough so that they actually cross in some places. However, we know that the insulated skirting should not cause energy use to increase in this situation.

As mentioned above, we believe the noise to be primarily due to the poor quality of the warehouse. This is supported by the fact that the Storm BLC's are quite steady. On that night cloudy conditions minimized surface radiant effects. Also, steady outside temperatures encouraged steady warehouse temperatures.

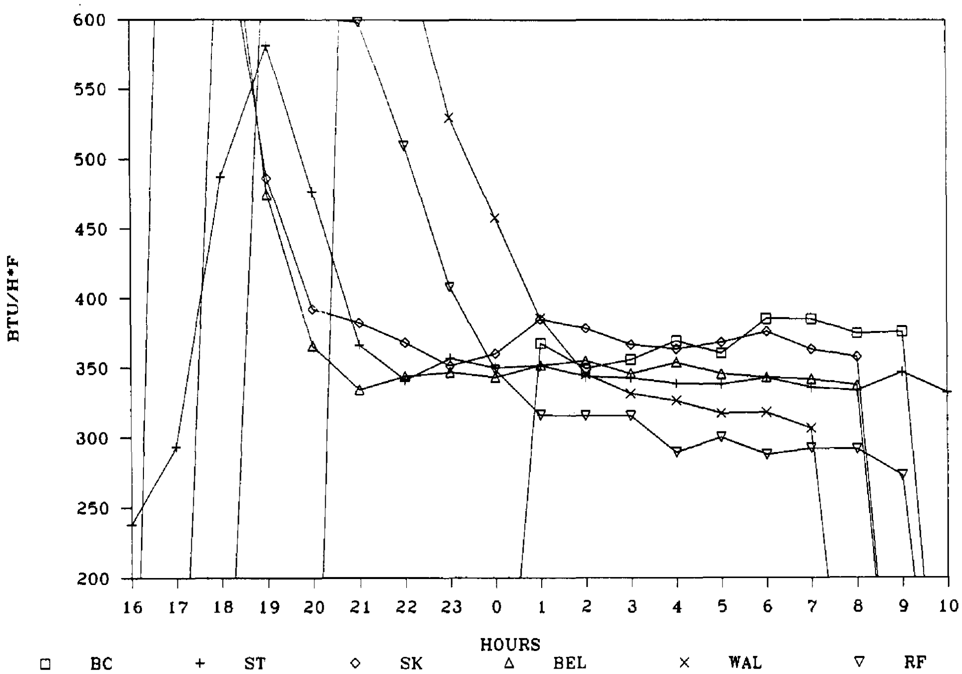

Figure 7. CMC (Q/Delta T) Progression to Steady State, 4 p.m.-10 a.m.

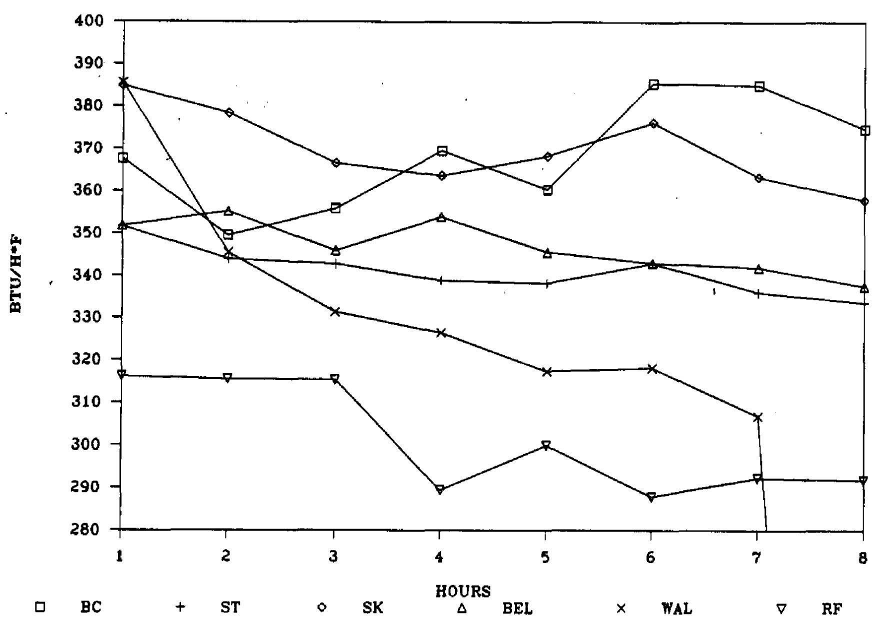

Figure 8. CMC (Q/Delta T) Steady State Uncertainty, 1 a.m.-8 a.m.

Figure 9 shows the noise and uncertainty associated with the tracer gas test. In theory the infiltration rate should be equal at each five-minute reading as long as the temperature difference between the mobile home and the warehouse remains constant. In other words the data points should cluster closely around a horizontal line. In fact, we see infiltration rates ranging from about .43 to .9 ACH. This occurred primarily because of 0-drift problems in the Foxborough SF6 Infra-Red Analyzer and because of the poor quality of the warehouse. The 0-drift problems might be reduced by using a more accurate instrument, building a device to allow continous 0-correction of the instrument, allowing the test to continue longer, and injecting higher concentrations of SF6, thereby using the instrument's high range (0-2500 PPM) rather than the low range (0-250 PPM).

In general, the noise problems can be solved by using a well insulated warehouse with very tight environmental control, allowing each test more time to come to steady state, and increasing the temperature difference. The only warehouse that was available to use at CMC was, unfortunately, entirely uninsulated and represented a worst-case test condition.

6.5.1 Payback Calculations for the Conduction Retrofits

It would be unwise to draw any definitive conclusions about retrofit measures from the CMC mobile home tests. Nevertheless, we thought it would be interesting to calculate simple paybacks for the belly and storm window retrofits based on the measured savings from those tests. We were curious to see if these would be at all similar to our calculations in the infiltration study (Section 5.5.1).

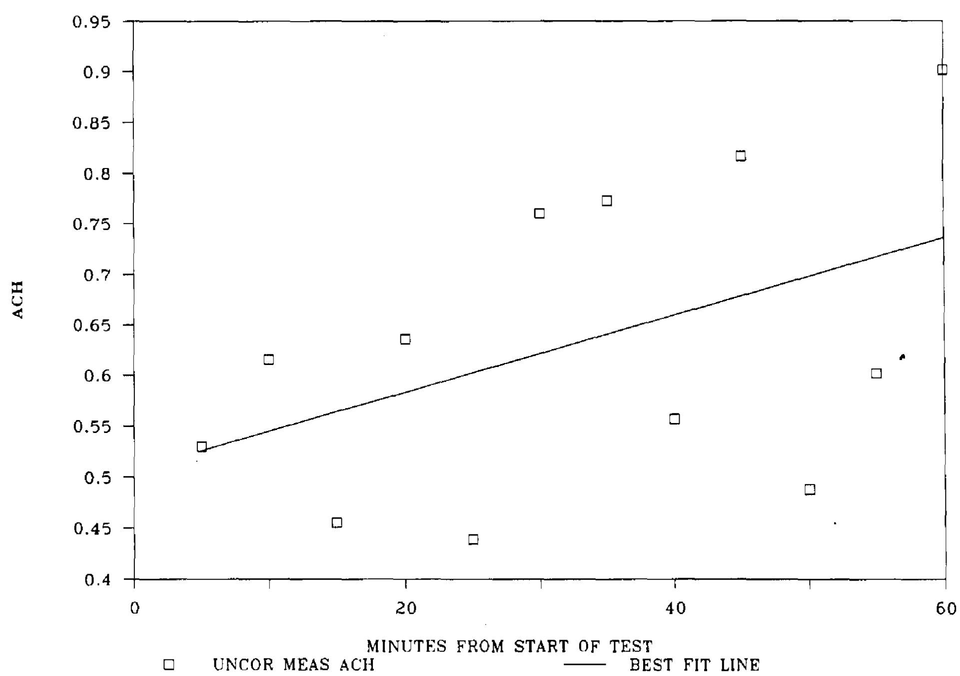

Figure 9. CMC Belly SF6 Test (Uncorrected ACH and Linear Regular Line)

To compare the results from the two studies we had to convert the measured reductions in UA to annual energy savings in the Denver climate. This process involved several steps as outlined below:

1) Use the Sherman/Grimsrud model to calculate annual average pre- and post-retrofit infiltration rates based on measured leakage areas and average heating-season temperatures and windspeeds
2) Calculate the heat loss associated with the pre- and post-retrofit infiltration rates
3) Add the infiltration heat loss to the measured solid-conduction heat loss
4) Calculate the annual combined conduction and infiltration savings using Denver typical weather data
5) Calculate simple paybacks using the same assumptions about furnace efficiency, fuel costs, and retrofit costs as were used in the infiltration study.

Table 16 shows simple paybacks in Denver, assuming seasonal heating-system efficiencies of .61 and .4, and retrofit costs reported by Sunpower and other weatherization organizations.

These paybacks agree quite closely with those calculated in the infiltration study (Tables 8 and 9). This is not a definitive result. However, it is encouraging that the paybacks, based on purely theoretical calculations, agree reasonably well with those based on measured results from the CMC study.

6.6 Warehouse Tests: Improvements and Limitations

Many of the above mentioned problems could be eliminated by creating a dedicated, mobile-home testing facility in a carefully selected warehouse. Such a facility would allow for considerable improvement in the testing methods. Nevertheless, there are some inherent limitations to the approach which are also noted here.

Belly insulation, to the extent that it may improve heating system efficiency, is not well handled by the test in its current form. However, heating-system efficiency curves could easily be determined in the context of a dedicated warehouse testing facility where environmental conditions could be set and

TABLE 16 DENVER PAYBACKS
BASED ON CMC WAREHOUSE TESTS

(YEARS)

	E=.61		*E=.40*	
	SUNPOWER	OTHER	SUNPOWER	OTHER
STORMS	1.75	3.7	1.0	2.4
BELLY	6.6	4.4	4.3	2.9

repeated. The method would involve doing a standard co-heating test, using electric resistance heaters in the living space of the unit as the heat source. That test would be followed by an identical test, except that the existing furnace and duct system would supply the heat to the unit. The combined furnace and heat distribution efficiency would then be:

(electric heater energy use ÷ furnace energy use) × 100 = efficiency (%)

This would also allow such retrofits as furnace tune-ups and replacements to be properly evaluated.

Questions concerning the degradation of retrofit measures cannot be answered directly with the short-term test. However, a combination of short- and long-term tests could be very effective for studying degradation issues. For example, units could be warehouse tested during, or immediately after, installation of a single retrofit (or a group of retrofits). They could then be moved to the field, occupied for several years, and retested using the warehouse procedure.

Certain kinds of retrofits are not fairly treated by the warehouse tests. For example, skirting and skirt insulation will effect the long-term ground temperature underneath the mobile home as well as shelter the mobile home floor from wind. These effects cannot be properly determined with a short-term test conducted inside a warehouse. For these retrofits, the approach should probably be long-term testing of several carefully selected unoccupied units.

Questions concerning the costs of measures are best answered by recording data on installations done by weatherization services in the field. Installations done in a sheltered environment will not be particularly useful in this regard.

6.7 Conclusions from Conduction Study

The results of initial attempts at short-term warehouse testing of mobile home weatherization measures were very encouraging. They indicate that very reliable tests can be done by imposing more control on the procedure than was possible in the Jackson or CMC cases. We believe that this can be accomplished best by carefully selecting and outfitting a warehouse facility near SERI.

The savings attributable to each weatherization measure are shown in Table 17. We are told that these savings are lower than some weatherization experts expect from such retrofits. Additional testing, under sufficiently controlled conditions, will be necessary to answer these concerns more definitively.

7.0 COMPARISONS WITH OTHER STUDIES

This report documents two related studies by SERI, one primarily concerned with infiltration reduction and the other emphasizing conduction heat loss. These two studies, when considered together, present a fairly consistent message on how the special problems of weatherizing mobile homes may be approached. Additionally, several other studies are in various stages of completion around the country. These studies represent a variety of methods and assumptions which make direct comparisons of their results somewhat difficult.

TABLE 17 %SAVINGS FROM BASE CASE CMC MOBILE HOME

MEASURE	%SAVINGS
STORMS	10%
SKIRT	3%
BELLY	10%
WALL	11%
ROOF	7% *

* low because vents were left unplugged

Nevertheless, consideration of these supplementary data sources can be informative and can help form a more complete picture of the opportunities for energy savings from weatherization of mobile homes.

The data reviewed in this section were taken from several sources including the New York State Energy Research and Development Administration (NYSERDA), the National Center for Appropriate Technology and Pennsylvania Electric project (NCAT/PENELEC), the Iowa State Weatherization Assistance Program Evalauation, and the Illinois Weatherization Program. The results from the NYSERDA and the NCAT/PENELEC studies are preliminary.

7.1 Infiltration Data Comparisons

NYSERDA blower door tested 50 pre-HUD-Standard mobile homes distributed throughout nine New York state counties. For the New York sample set, the average air changes per hour at 50-pascals pressure difference (ACH @ 50 pa) was about 25.6, with a standard deviation (STD) of about 10.1. The median was 24.2 (19). For the 17 mobile homes from the SERI sample set the average ACH @ 50 pa was 30.87, with a STD of 13.63. The median was 26.19. The two medians and means agree within about 8% and 17%, respectively, indicating some consistency in base-line air tightness, independent of geographical distribution.

In the SERI Denver study, the Sunpower crews used the blower door as a diagnostic tool while they tightened the units. On average, leakage was reduced by about 40%, from a leakage ratio of 11 to 6. In the New York study, the crews did not use a blower door and applied measures developed for site-built housing. Preliminary data from the New York study showed little or no measurable reduction in leakage (20). In a follow-up study, New York modified the procedure so that a blower door was used to identify air leakage sites. In that study, as in the Denver study, significant leakage reduction was achieved (21).

7.2 Measured Energy Usage Comparisons

SERI and NCAT/PENELEC each performed warehouse tests on two pre-HUD-Standard mobile home units. NYSERDA recorded degree-day normalized furnace usage before and after installation of weatherization measures. The results from these three studies are summarized in Table 18.

TABLE 18 ENERGY SAVINGS COMPARISON

MEASURE	SERI	NCAT/PEN	NYSERDA
BLC BEFORE (BTU/H° F) WEATHERIZATION	367	373	
(SAVINGS %)			
BELLY BLOW	10.4	13.5	14.9
ROOF CAP		13.5	21.1
WALL	10		19.2
STORMS/WINDOWS	10.4	9.1	15.2
SKIRT	3.3		5.8

The preweatherization BLC's (including infiltration) measured by SERI and NCAT were remarkably similar (22). The values for the two SERI units were 380 and 354 Btu/h°F. Those for NCAT were 385.6 and 360 Btu/h°F. These values all agree within 9%, even though the four mobile home units came from Colorado, Wyoming, and Pennsylvania. While not definitive, there does seem to be some similarity in pre-HUD-Standard mobile homes with respect to major thermal characteristics.

The percent savings for various weatherization measures determined from the three studies were also fairly consistent. This suggests that significant improvements in the energy performance of older mobile homes are possible if specially adapted weatherization techniques are used.

The results from the Iowa/Meridian study appear not to support this conclusion (23). In this study, before and after utility bills were analyzed for 16 mobile homes using the Princeton Scorekeeping Method (PRISM). An average expenditure of $560/unit resulted in only 3.6% energy savings or 2.4 million Btu out of 64.9 million Btu. Illinois experienced similar difficulty in weatherizing mobile homes (24). However, in both these cases no specially adapted weatherization techniques were used. The same measures that were developed for site-built houses were used to weatherize the mobile homes.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Pre-HUD-Standard mobile homes use from 1.25 to 2 times the energy per unit area of comparable site-built houses. Their unique construction detailing makes them difficult for weatherization agencies to treat effectively using the measures and techniques developed for site-constructed buildings. This poses both a problem and an opportunity.

In general, the evidence from this study indicates that significant energy savings can be realized with weatherization measures specifically adapted for mobile homes. Furthermore, the costs for these measures need not go beyond current weatherization guidelines. Unfortunately, the vast majority of weatherization providers still treat mobile homes like site-builts. The results presented here suggest that this is extremely ineffective.

Mobile homes have higher infiltration rates than comparable site-built houses. The air leakage locations are often difficult to find, difficult to reach, and are very different from those in site-builts. For these reasons we strongly recommend the use of a blower door as the most important infiltration-reduction tool for weatherization personnel. With the use of the blower door it is feasible, safe, and cost effective to greatly reduce infiltration heat losses and heating duct leaks. The blower door also helps ensure that air exchange levels are not reduced below those commensurate with health and safety standards. The evidence indicates that the use of the blower door results in cost-effective energy savings. Failure to use the blower door results in weatherization expenditures, but little or no energy savings in mobile homes.

Mobile home weatherization measures are extremely climate dependent. Measures which are cost effective in climates like Denver or Madison, will be ineffective in climates like Phoenix or Miami. Most of the weatherization measures investigated in this work are intended for climates in which heating loads are more important than cooling loads. Further studies are needed for hot and humid climates.

In general, there is a lack of hard data on the effectiveness of weatherization measures in mobile homes. However, our preliminary results indicate that envelope and duct tightening using the blower door, floor insulation, and strategic application of storm windows should be high priority measures for mobile homes in cold climates. Further data is needed on such items as:

- furnace tune-ups
- skirt insulation
- wall insulation
- roof caps and ceiling insulation
- belly wraps
- the interactive effects of furnace tune-ups, heat duct tightening, and various floor and skirt strategies on combined furnace and heat delivery efficiency
- appropriate measures for hot and humid climates.

We hope to investigate these issues in future work.

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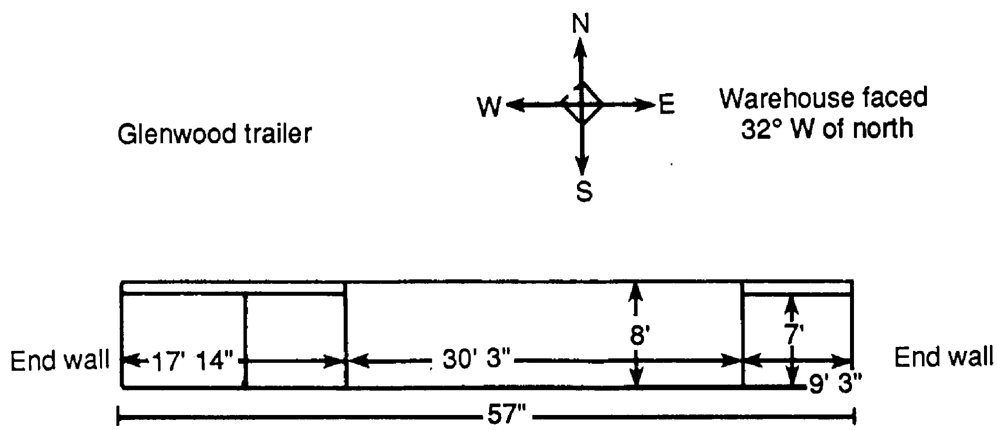
Appendix I

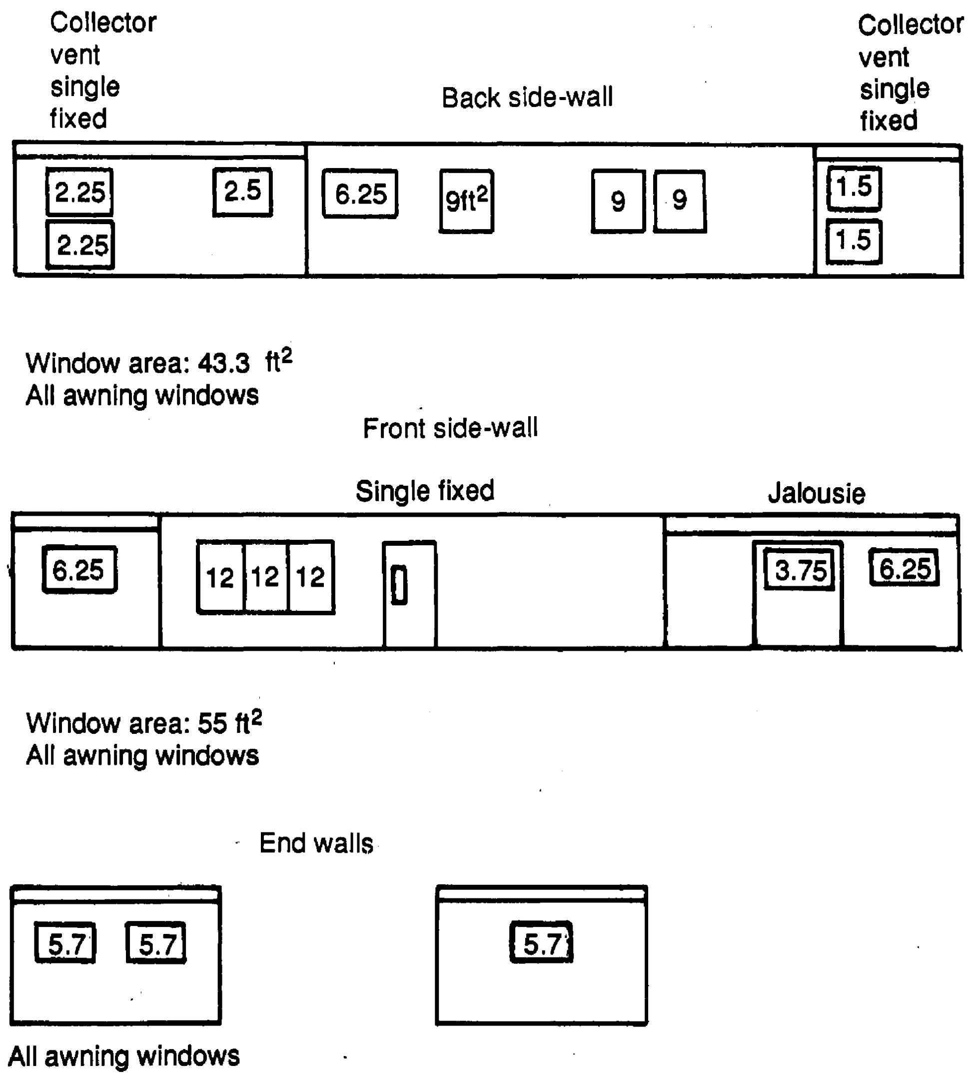


Avg. height:	7.5 ft.
Length:	57 in.
Width:	11.25 ft.
Floor area:	641 ft^2
Volume:	4809 ft^3
Window area:	115 ft^2
Opaque wall area:	977 ft^2
Carpet area:	250 ft^2

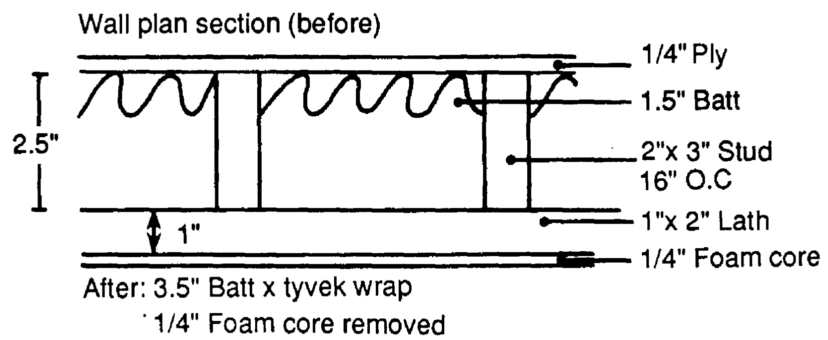
<u>Retrofits</u>

Storms:	Single glass storms added
Skirt:	1in. polystyrene insulation added
Belly:	4in. shredded fibreglass blown-in
Wall:	2in. Glass batt added, 1/4 in. foam core removed, tyuek wrapped
Roof:	3in. R-5/inch rigid board insulation added + hypalon roof membrane

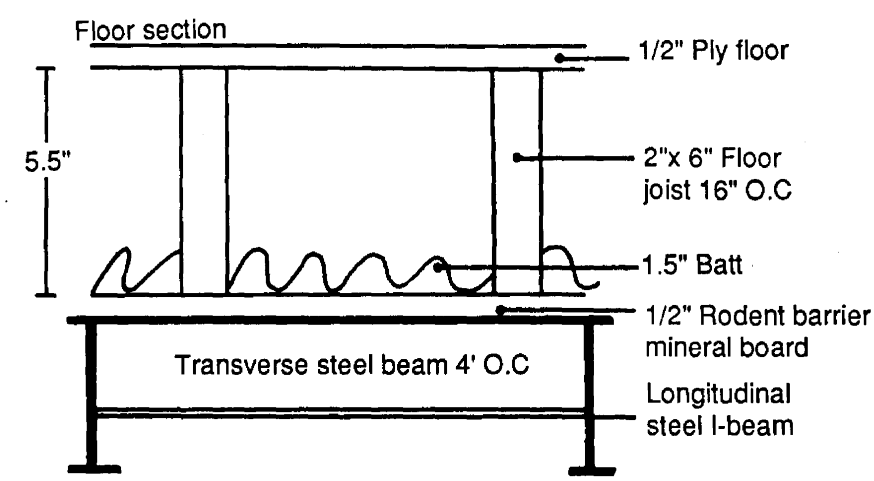
CMC Mobile Home - Longitudinal Section



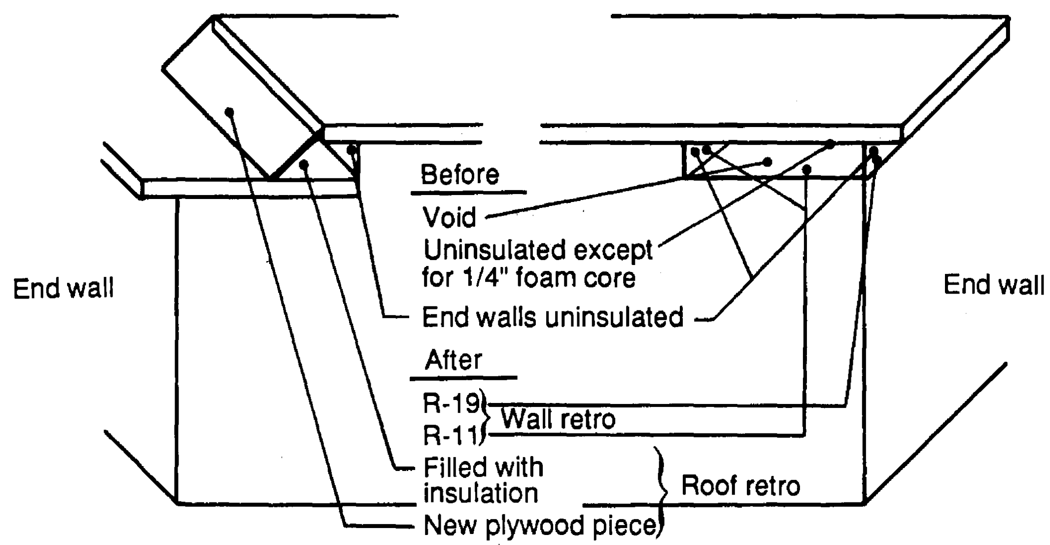
CMC Mobile Home - Inside Elevation



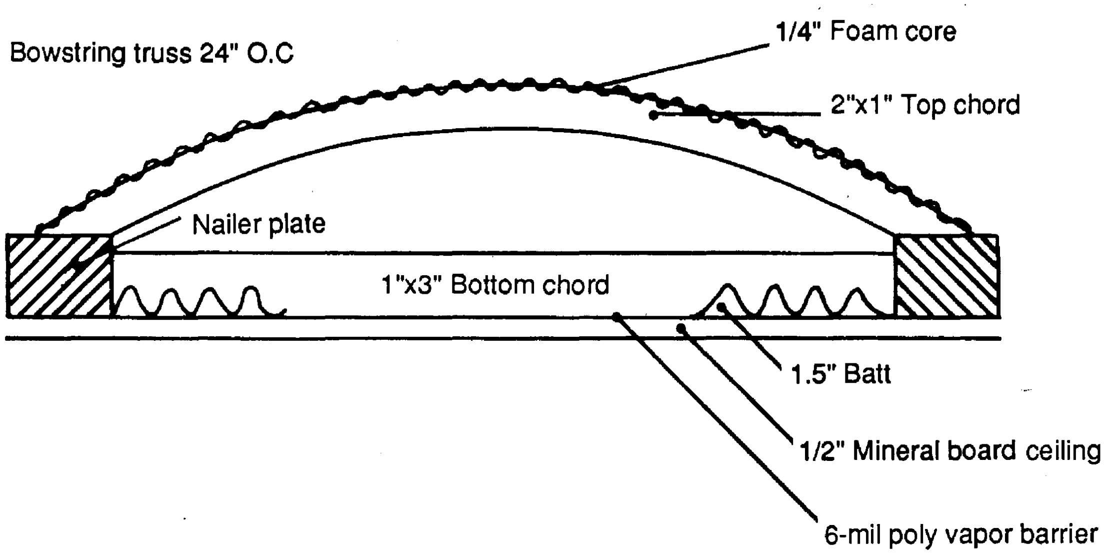
CMC Mobile Home - Wall-Plan Section (before weatherization)



CMC Mobile Home - Floor Section (before weatherization)



CMC Mobile Home - Roof Detail



CMC Mobile Home - Roof Cross Section

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The Solar Energy Research Institute (SERI) was funded by the Department of Energy's Office of Buildings and Community Systems (DOE OBCS) in FY 1987 and 1988 to investigate cost effective ways to weatherize mobile homes constructed prior to the enactment of HUD Thermal Standards in 1976. In FY 1987 SERI studied the effectiveness of a variety of infiltration-reducing retrofits by monitoring 20 units in the field before, during, and after application of air tightening measures. In FY 1988 we began studying measures intended to reduce envelope conduction losses. These measures included storm windows, insulated skirting, and wall, roof, and floor insulation. This part of the project resulted in the development of a short-term testing method for measuring the thermal impact of individual conduction-reducing retrofits.

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