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Testing the Effectiveness of Mobile Home Weatherization Measures in a Controlled Environment: The SERI CMFERT Project

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PREFACE

This report is an account of work conducted by the Solar Energy Research Institute in 1988 and 1989 on the weatherization of mobile homes as part of the SERI CMFERT (Collaborative Manufactured Buildings Facility for Energy Research and Training) Project. The report describes the results from testing three mobile homes within a warehouse modified to allow tight control of environmental variables. Reference is also made to two mobile homes that were tested in other, unmodified warehouses.

The report is intended for weatherization professionals and researchers. The executive summary and Appendix B, which describes the weatherization measures and installation techniques, will be of greatest interest to the weatherization practitioner. The sections describing testing and analysis methods and detailed results will be of most interest to the researcher.

EXECUTIVE SUMMARY

Mobile homes constructed before the U.S. Department of Housing and Urban Development (HUD) enacted thermal standards in 1976 use from 1.25 to 2 times the energy per square foot 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 dwellings. A study conducted by the Meridian Corporation (1988) for the U.S. Department of Energy indicated that average energy savings in mobile homes nationally were about 5% after a weatherization expenditure of $1,012, resulting in a simple payback of about 21 years. For site-builts, energy savings were about 14% with an expenditure of $1,463, yielding a payback of about 11 years. Although mobile homes are less than 5% of the total residential building stock, they represent about 25% of the buildings that qualify for low-income weatherization. This poses both a problem and an opportunity.

A major impediment to weatherizing mobile homes more effectively has been the lack of hard data on the thermal effectiveness of various weatherization techniques. In response to this problem, the Buildings Research Branch at the Solar Energy Research Institute (SERI) developed a short-term testing method that allows mobile homes to be monitored inside an environmentally controlled warehouse.

The method consists of three tests. The first is a coheating test to measure the building loss coefficient. A constant temperature difference between the warehouse and test building is created by maintaining constant temperatures in the warehouse and the building until quasi-steady-state is attained. Generally, the warehouse and building are kept at about 40° 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 test building to maintain the desired temperatures. The building's own heating system is turned off. The electric heater power in the test building is measured under the quasi-steady-state condition to extract the building loss coefficient.

The building loss coefficient has both a conduction component and an infiltration component. To separate these components, a tracer gas test is conducted using the same temperature difference as in the coheating test. In the tracer gas test an inert, nontoxic gas, sulfur hexafluoride, is introduced into the test building until it is well mixed with the air in the unit. A gas chromatograph or an infrared specific vapor analyzer measures the decay in gas concentration over time to extract the air exchange rate, which is used to derive the conduction and infiltration components.

Some weatherization (thermal) improvements affect delivered heat efficiency as well as the building heat loss. Therefore, a third test is conducted in which the building's own heating system is used to maintain the conditions of the coheating test. We define the ratio of the electric heater power to the furnace fuel and fan energy as the delivered heat efficiency for a given temperature difference.

With these three tests, the changes in conduction, infiltration, and delivered heat efficiency caused by any single thermal improvement, or by a given combination of thermal improvements, can be determined rapidly as follows.

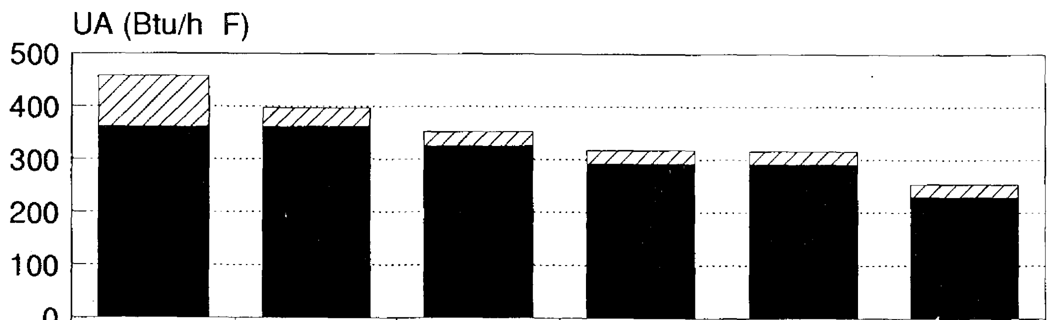
A mobile home is moved into the warehouse and tested in its initial condition to determine the heat losses from infiltration and conduction, and to determine the delivered heat efficiency of the furnace and duct system. A single weatherization measure is then installed, and the testing is repeated to determine the changes in conduction and infiltration losses and delivered heat efficiency caused by that measure. This process is repeated until the individual effects of an entire set of weatherization measures have been determined. The warehouse allows each measure to be tested under equivalent conditions. Each test usually takes only one or two nights, so it has been possible to combine testing with weatherization training workshops. The trainees install a measure one day and find out how effective their work has been 12 to 36 hours later.

To date SERI has tested five mobile homes using the warehouse technique. Figure 1 shows the building heat loss coefficient associated with a series of weatherization measures installed on unit #1, a 12 ft × 60 ft 1971 Champion, which is typical of mobile homes treated in the federal low-income weatherization program. The bottom and top portions of each bar represent the conduction and infiltration portions of the heat loss, respectively. The installation of this weatherization package resulted in a total reduction of 44% in the heat loss coefficient; the measures in the package were blower-door-directed air sealing, duct repair, furnace tune-up, interior storm panels, belly blow, and roof blow. The belly wrap was removed before proceeding with the belly blow.

Figure 2 shows the overall reduction in heat loss coefficient for each weatherization measure in the three mobile homes that were tested in the environmentally controlled warehouse.

Figure 3 shows the change in delivered heat efficiency caused by each weatherization measure installed on mobile home #1. Sealing holes in the ducts, belly wrap, belly blow, and furnace tune-up all increase the efficiency. The roof blow shows a decrease in efficiency. We hypothesize that this decrease is because as the mobile home becomes better insulated the furnace becomes relatively oversized for the load, and thus furnace cycling losses increase. The floor insulation measures more than compensate for this effect by also insulating the heat distribution duct.

Figure 4 shows the overall increase in delivered heat efficiency for three of the mobile homes. Units #2 and #3 showed larger efficiency increases than unit #1, primarily because they had larger leaks in their duct systems.

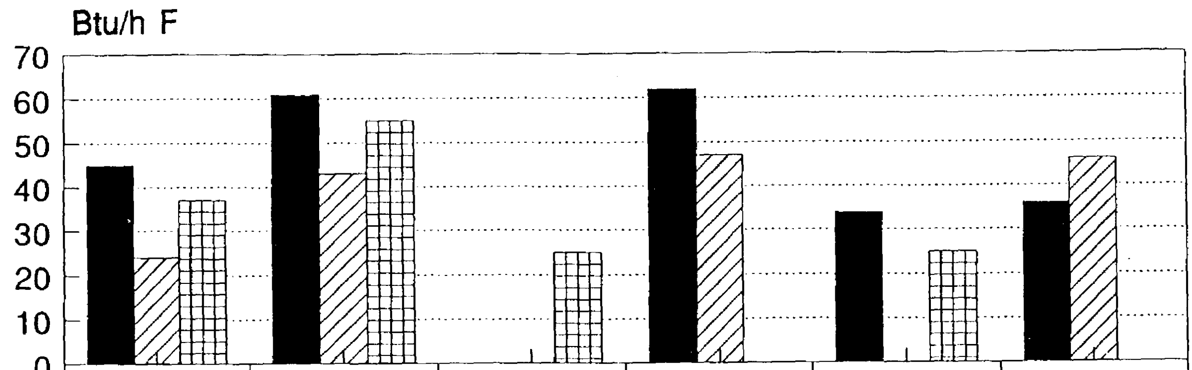


	Base	Heat Waste	Storms	Belly Wrap	Belly Blow	Roof Blow
Infiltration	96	35	26	26	25	24
Conduction	362	362	326	292	291	230
Total	458	397	352	318	316	254

■ Conduction ▨ Infiltration

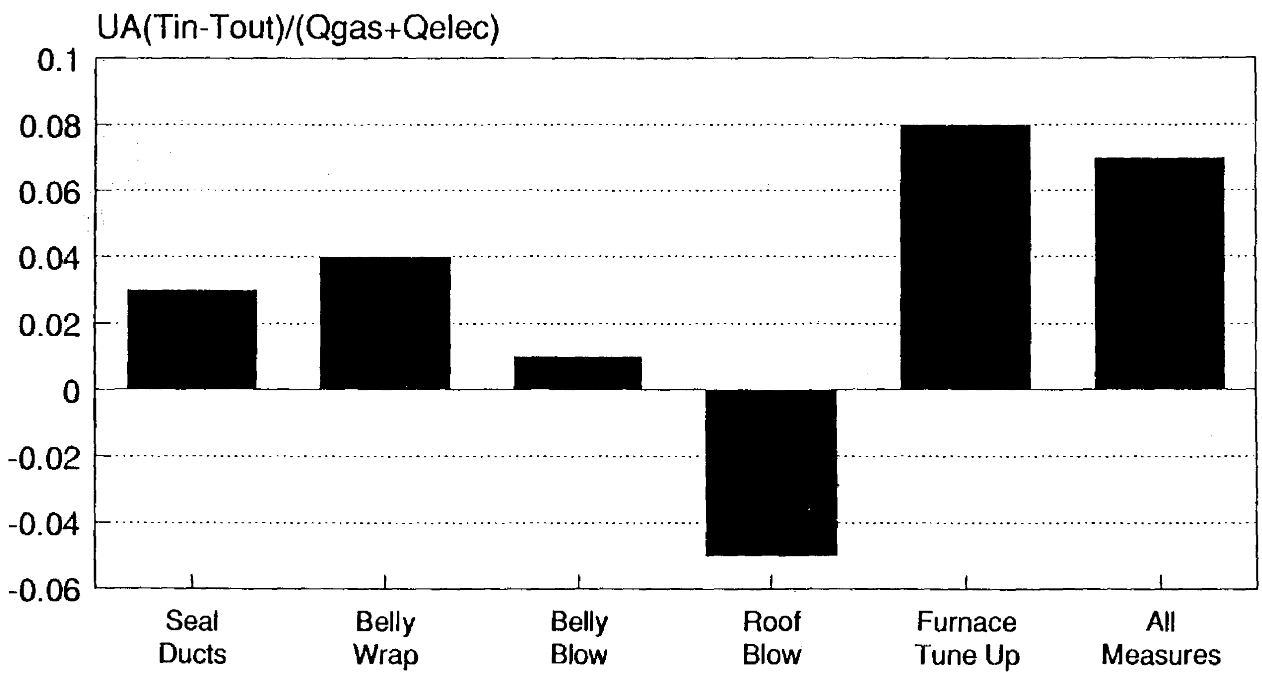
Total Reduction = 44.5% (204 Btu/h F)
Belly wrap removed before belly blow

Figure 1. Mobile Home #1: Measured UA Overall, Conduction and Infiltration



	Storm	Heat Waste	Roof Cap	Roof Blow	Belly Wrap	Belly Blow
Unit 1	45	61		62	34	36
Unit 2	24	43		47		46
Unit 3	37	55	25		25	

Figure 2. Mobile Homes #1, #2, and #3: Measured UA Savings, Conduction and Infiltration



0.03	0.04	0.01	-0.05	0.08	0.07

Figure 3. Mobile Home #1: Change in Furnace Efficiency due to Weatherization Measures

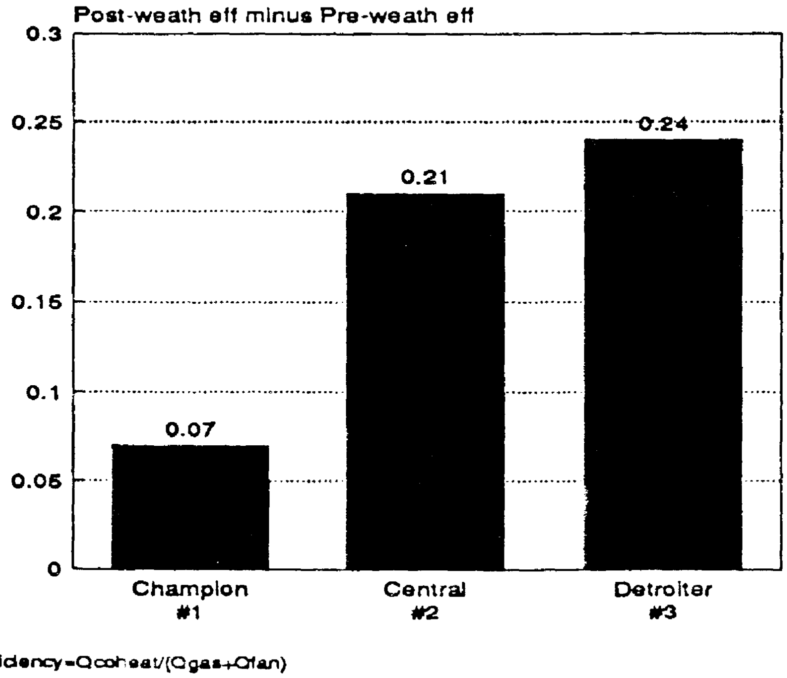


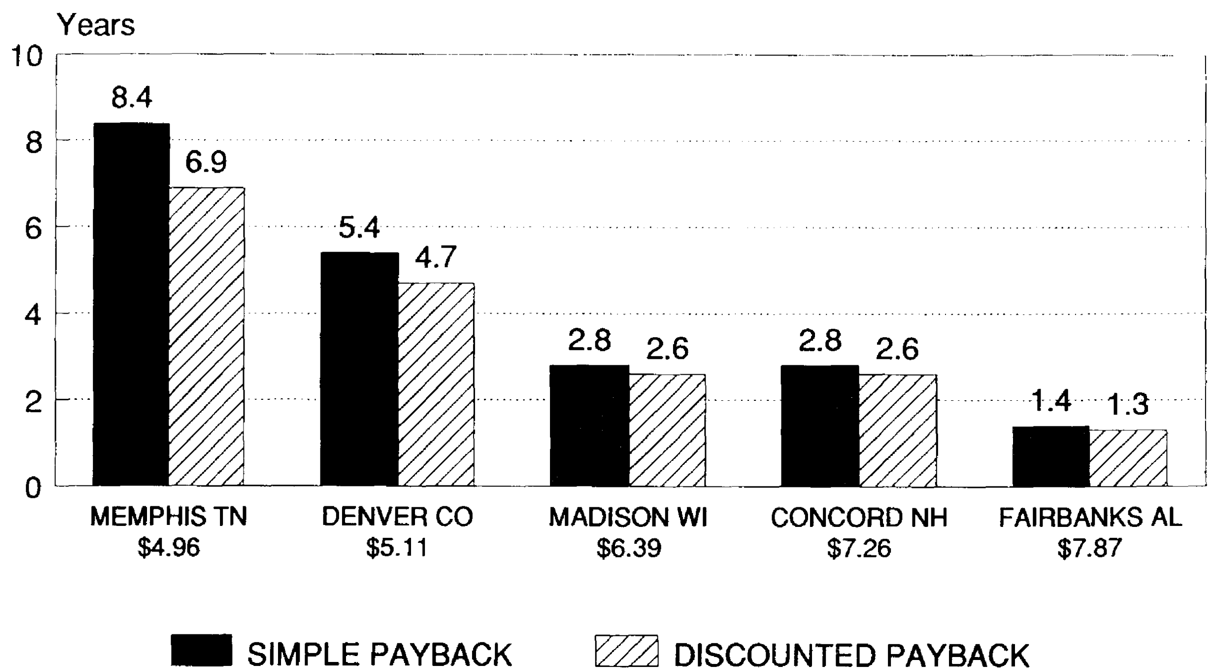
Figure 4. Mobile Homes #1, #2, and #3: Increase in Measured Combined Furnace and Duct Efficiency

The information shown in Figures 1 through 4 is based on data directly measured in the controlled warehouse environment. To project savings in the outside environment, we used SUNCODE, the microcomputer version of SERIRES, an hourly building energy analysis simulation program developed at SERI (Palmiter et al. 1983). The program uses statistical weather data known as typical meteorological years to model the thermal response of the building to weather and occupant behavior hour by hour throughout the year. The weather inputs include temperature, wind speed, solar radiation, and moisture. Occupant behavior inputs include thermostat control, window and door openings, use of curtains, and use of appliances and lights. The data collected in the warehouse help us model the mobile home and its associated weatherization measures more accurately by allowing us to calibrate the model to the data.

Figure 5 is based on the results of the simulation model. It shows the simple and discounted payback that might be expected for mobile home #1 in several locations, assuming local fuel costs. The analysis is based on blower-door-directed air sealing and duct repair, furnace tune-up, interior storm panels, and belly blow (the roof blow was included for the Denver location only). These four measures were estimated to cost $1,162 in the Denver area (roof blow = $420). Costs will differ somewhat by locale. To generalize these results to locations for which simulations had not been run, we investigated the relationship between degree-days$_{(\text{base } 65)}$ (DD_{65}) and energy savings from the four weatherization measures installed on mobile home #1. Figure 6 demonstrates that the relationship is quite linear; it can be represented by

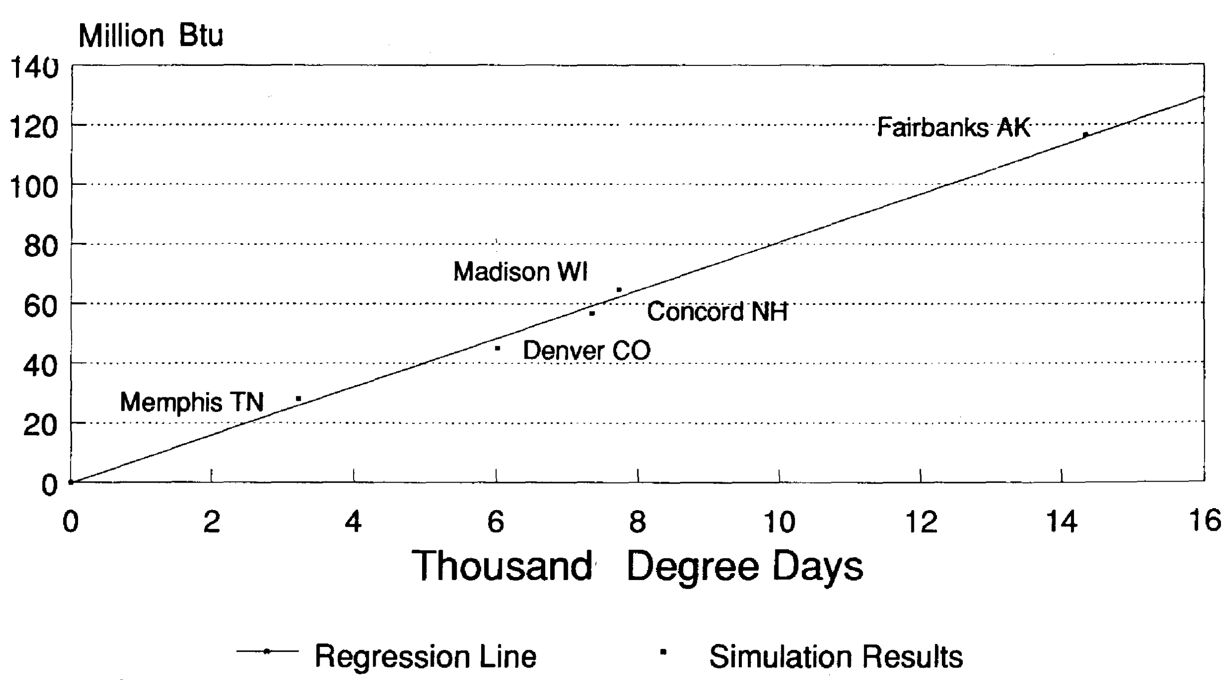
$$\text{SAVINGS}_{(\text{million Btu})} = (DD_{65} \times 0.0081) - 0.2467 \ .$$

The points on Figure 6 represent some typical climates, from warmest to coldest: Memphis, Tenn.; Denver, Colo.; Concord, N.H.; Madison, Wis.; and Fairbanks, Alaska.



Roof blow only in Denver
Fuel cost in $/million Btu

Figure 5. Mobile Home #1: Payback of Measures Package in Several Cities



Linear Regression
RSQ=.996 St.Dev=2.71
Slope=.0081 Yint=-.2467

Figure 6. Energy Savings versus Degree Days (Base 65)

The simple payback (PB_{yrs}) for any location can then be determined, given the degree-days, fuel cost per million Btu ($FC), and retrofit cost ($RC), by

$$PB_{yrs} = \$RC/(0.0081 \times DD_{65} \times \$FC) \ .$$

If we assume that the cost of the package of four retrofit options is $1,162, then we can generate Figure 7, which allows graphic determination of the payback any place in the United States where degree-day and fuel cost data are available.

Over the past two winters we tested these 10 weatherization measures:

- blower-door-directed air sealing and duct repair
- furnace tune-up
- interior storm panels
- window repairs and replacements
- belly blow (fiberglass and cellulose)
- belly wrap
- skirting
- roof blow (fiberglass and cellulose)
- roof cap
- wall insulation

In general, we find the most cost-effective measures for colder climates to be blower-door-directed air sealing and duct repair, furnace tune-up, interior storm panels, belly blow, and roof blow. The roof blow may result in moisture damage if used in humid climates, and it should probably be studied further before being applied widely.

The blower door has shown itself to be an essential tool in weatherizing mobile homes. Not only does it help crews tighten the units more effectively, it also prevents overtightening, which can be especially dangerous in low-volume buildings.

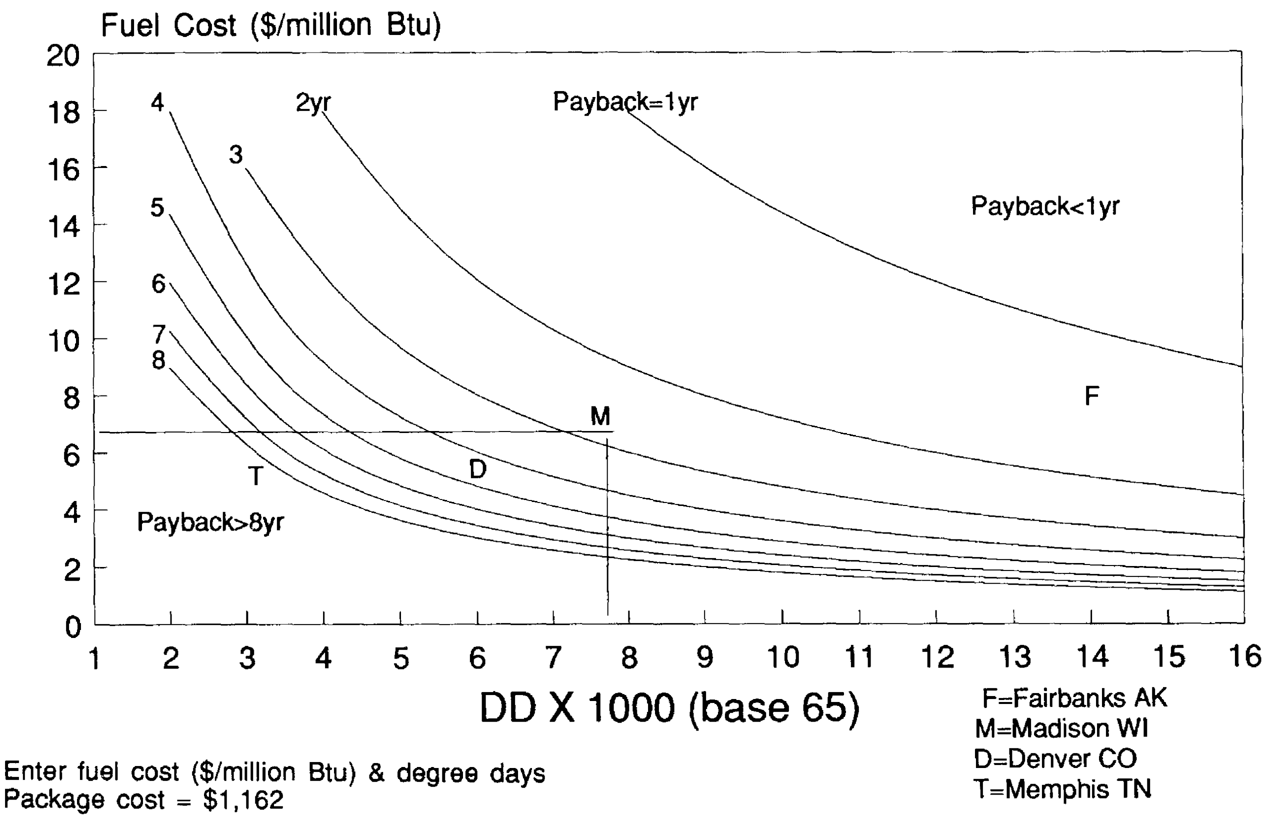


Figure 7. Simple Payback USA, Mobile Home Weatherization Package

Our tests to date have shown skirting, insulated skirting, and roof caps to be less cost-effective. However, more research is needed on those measures. Our research also indicates that window and door replacements should be used only when repair would be more expensive than replacement. Even for jalousie and awning windows, money is better spent on interior storm panels than on window replacement.

Finally, the research indicates that cost-effective energy savings are possible if we apply weatherization measures adapted to the unique construction details in mobile homes.

The study by Meridian Corporation established that application of traditional weatherization techniques in mobile homes had resulted in average energy savings of only 5% per home at a cost of more than $1,000. A growing number of states are beginning to improve on this by applying the techniques suggested here for cold climate weatherization. Through proper training and testing, an agency can easily increase the average heating energy savings to about 20% to 50% at the same cost per home. Agencies wanting to quantify the effectiveness of their current mobile home weatherization practices should consider using these testing techniques to improve their programs.

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Meridian Corporation. (August 1988). *Weatherization Evaluation Findings: A Comparative Analysis* (Draft). Alexandria, VA: Meridian Corporation.

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1.0 INTRODUCTION

Between 3 million and 5 million mobile homes built before the U.S. Department of Housing and Urban Development (HUD) enacted thermal standards in 1976 (U.S. Department of Commerce 1983; *Quick Facts* 1980, 1985) are in use in the United States today. These homes consume from 1.25 to 2 times the energy per square foot of comparable conventional single-family detached houses. Currently, weatherization services spend about $1,000 to $1,500 retrofitting each of these units. However, very little information exists on the effectiveness of retrofit measures in mobile homes. Most weatherization services and programs freely admit a need for additional knowledge about retrofitting mobile homes. Many weatherization services simply apply those measures considered cost-effective in site-built housing. This is usually ineffective because the construction details in manufactured buildings are quite different from those in site-builts. With a potential national cost of approximately $5 billion to weatherize qualifying units, the U.S. Department of Energy (DOE) is supporting a research effort to evaluate and further improve the effectiveness of weatherizing mobile homes.

1.1 Background

In 1979, the Solar Energy Research Institute (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 before 1976, when the HUD thermal standards went into effect. This was under the auspices of the DOE Building Energy Retrofit Research Program. The findings from that effort were used by DOE for multiyear planning (Dekeiffer and Edwards 1985). The multiyear plan identified three areas of research that related specifically to mobile homes built before 1976:

- Option-specific monitoring to ascertain the contribution of retrofit measures being used or considered for use in weatherization delivery programs
- Evaluation of new materials and retrofit techniques
- Evaluation of innovative energy equipment options.

The work described in this report concentrated on the first area, which had been deemed of highest priority by state and local weatherization field organizations.

SERI began the project, which came to be known as the CMFERT (Collaborative Manufactured Buildings Facility for Energy Research and Training) 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 were emphasizing retrofit measures intended to reduce infiltration (called "general heat waste" by many weatherization services). The air-sealing strategies were essentially identical to those used for conventional, site-built houses, 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 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 the results of 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 nonprofit 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, paid Sunpower to retrofit 20 mobile home units in accordance with Colorado Division of Housing guidelines. SERI collected data on the 20 units, which 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.

Sunpower completed its work in April 1987, and SERI then analyzed the data. The results from that study were documented in *Mobile Home Weatherization Measures: A Study of Their Effectiveness* (Judkoff et al. 1988). Major conclusions from that project were the following.

- The primary infiltration sites are different in mobile homes than in site-built residences.

- Primary leakage sites were
  - heating ducts
  - furnace closets
  - envelope penetrations for ducts, flues, plumbing, wiring, and vents
  - water heater closets
  - broken windows and operator mechanisms
  - swamp cooler chases (for units having these evaporative coolers).

- Air-sealing weatherization measures typically used for site-built houses are ineffective in mobile homes.

- A blower door is an excellent tool for locating infiltration sites, and an essential tool to prevent overtightening of these low-volume buildings.

- The average reduction in infiltration rate was about 40%, resulting in about 15% heating energy savings in the Denver climate.

In late 1987, SERI began working on measuring the effect of conduction-reducing weatherization options. A short-term monitoring technique was developed that involved moving a mobile home into a warehouse and maintaining quasi-steady-state conditions for the test (Judkoff et al. 1988). Heater power in the mobile home was measured, as was the temperature difference between the mobile home and the warehouse, to extract the effective overall conductance of the unit. Theory indicated that this could be done on consecutive single nights of testing, with the different weatherization measures installed during the daytime. Two series of tests were conducted to try the method. The first was done in Jackson, Wyo., in conjunction with a Wyoming State Weatherization Workshop. The second set of tests was done in Glenwood Springs, Colo., 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

- tighter control of warehouse environment
- greater warehouse-to-mobile-home temperature difference
- longer testing period (12-36 h) instead of 8-12 h.

In the summer of 1988, a warehouse near SERI was instrumented and modified to incorporate these improvements. Three mobile homes were tested during the winter of 1988-1989. Two of the three were tested in conjunction with a weatherization training workshop held in April 1989.

1.2 Objective

The primary objective of this research was to directly monitor the effect of individual weatherization measures on infiltration losses, conduction losses, and furnace and duct-delivered heat efficiency. The purpose was to provide weatherization services with thermal data on the measures so that cost-effectiveness could also be determined. A secondary objective was to combine testing and training to provide feedback to trainers on the effectiveness of various measures and installation techniques.

1.3 General Technical Approach

Our general approach involves a combination of direct measurement and calculational models. The direct measurements taken in the warehouse under controlled, repeatable conditions allow us to calibrate our models of the mobile homes and the weatherization measures. We can then use these models to simulate the energy use of the mobile homes and the savings associated with each weatherization option in any climate for which hourly typical meteorological year (TMY) weather data exist.

An alternative method for determining the energy impact of the retrofits would have been to use the Princeton Scorekeeping Method (PRISM) to analyze utility bill data from occupied homes (Fels, Reynolds, and Stram 1986). This kind of testing seems to be attractive because the conditions are completely realistic. However, this approach would have required a much larger sample size (preferably about 100 per retrofit) and several years to establish the baseline performance of the units, install the weatherization measures, and track post-weatherization energy performance. The large sample size would have been necessary because new tenants, lifestyle, or operational changes can strongly affect the energy performance of the units, thereby masking the effects of the retrofits. In the PRISM type of testing, the measured results apply only to the climate or climates where the testing was done. If we wished to extrapolate the results to other climates we would have had, again, to rely on calculational models.

Our warehouse format allows application of classic, controlled experimental techniques where all conditions are held constant while only one parameter is changed at a time, a technique very different from statistically based approaches such as PRISM. We judged that a short-term, highly controlled testing approach had several advantages. First, testing could be accomplished in days rather than years. Second, the warehouse allowed close inspection of the appropriateness of a given weatherization measure for the special construction details in mobile homes. This enabled us to better understand the energy flows in the homes, and thus to better adapt the weatherization measures to the construction type. Third, we could use the warehouse to train weatherization personnel.

The approach used here, a combination of short-term direct measurements and modeling, was designed to be accurate in measuring energy differences. Because our primary interest is the energy savings from various retrofit options, we believe that the approach is the most cost-effective for evaluating individual measures and improving mobile home weatherization techniques. However, this approach cannot account for the effect of individual human behavior patterns. In this sense, our results are analogous to an Environmental Protection Agency gas mileage test. They indicate the savings owing to weatherization measures under a set of assumed standard operating conditions. As such they are more indicative of the overall efficiency of the "fleet" than of a given home with given occupants.

More details on the monitoring technique are provided in Section 2.0 of this report.

2.0 METHODOLOGY

2.1 Test Facility

Because a mobile home can be easily moved, it is a particularly good candidate for testing in an environmentally controlled chamber. For our purposes, an insulated warehouse with an adequate heating system is a sufficient environmental chamber. Figure 2.1 is a photograph of the warehouse used in these experiments. The warehouse has approximately 5000 ft^2 of floor area and a ceiling height of 24 ft. It has no windows and is reasonably well insulated, with approximately R-10 walls and R-5 roof. One overhead door, 18 ft wide × 14 ft high, is large enough to accommodate almost any mobile home. The warehouse is heated with two gas-fired unit heaters suspended from the ceiling. No cooling equipment is available, so some restrictions on temperature control in the facility are unavoidable and tests can be conducted only during the winter months. The testing season lasts for about 5 months in the Denver climate. Additional features of the site include adequate outdoor space for storing or testing one or two mobile homes and an adjacent building with classroom facilities.

2.2 Mobile Home Description

In accordance with this study's goals, the mobile homes selected for analysis were built before the 1976 HUD thermal standards. Three mobile homes were tested: (1) a 1971 Champion, 12 ft × 60 ft; (2) a 1972 Central, 14 ft × 53 ft; and (3) a 1974 Detroiter, 14 ft × 65 ft.

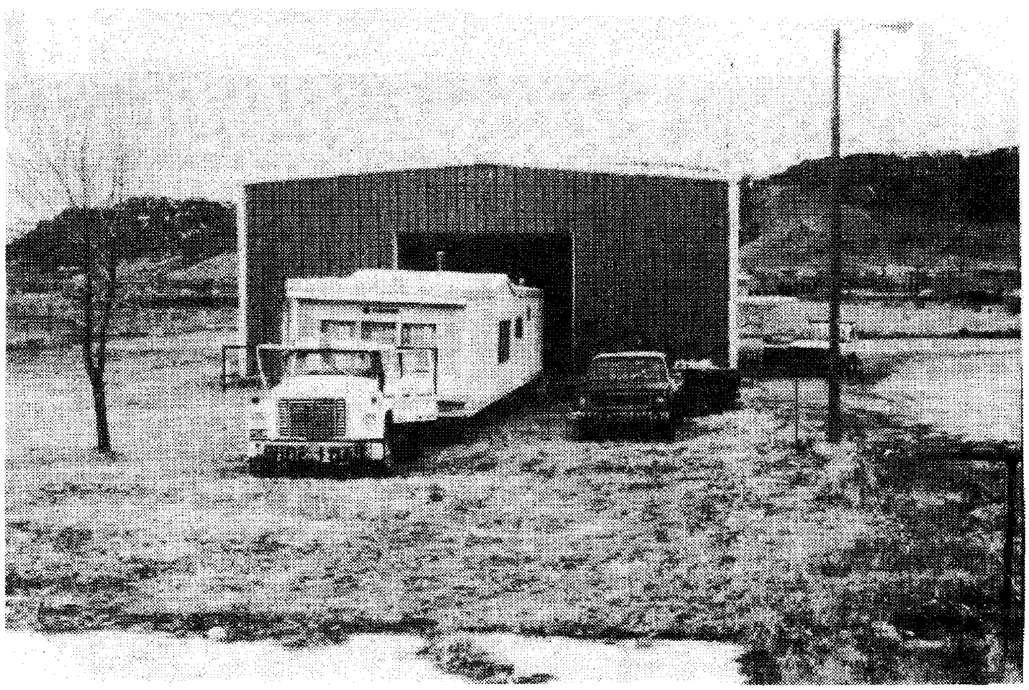


Figure 2.1. Environmentally Controlled Warehouse used in Weatherization Experiments

The most extensive tests were conducted on mobile home #1. It was tested and retested in each weatherization condition, providing many data sets for evaluation. Mobile homes #2 and #3 were weatherized during a weatherization workshop held in April 1989. Thus, although mobile homes #2 and #3 were tested repeatedly in their initial and final conditions, they were tested only once or twice per retrofit during the 5-day workshop. Also, the delivered heat efficiency could be tested only before and after the workshop because of insufficient time between installation of measures during the workshop.

These homes were selected for testing because their construction characteristics represented typical pre-1976 units. For more information concerning the definition of a typical unit, refer to *Mobile Home Weatherization Measures: A Study of Their Effectiveness* (Judkoff et al. 1988).

A brief description of the mobile homes is given in Table 2.1. The conduction and infiltration values are for the homes in their initial preweatherization condition. The dimensions listed are interior measurements. More detailed construction characteristics are given in Appendix A.

Table 2.1 Mobile Home Description

	#1	#2	#3
Cond UA (Btu/h °F)	362	327	358
ELA-Canadian (in.^{2})	330	418	688
Inside length (ft)	56.6	49	61
Inside width (ft)	11.2	13.5	13
Wall insulation (R-value)	8.0	4.8	4.8
Roof insulation (R-value)	4.8	4.8	6.4
Floor insulation (R-value)	4.8	4.8	6.4
Furnace type	downdraft	downdraft	downdraft
Cold air return	closet	closet	belly

2.3 Description of Weatherization Measures

The three mobile homes were tested in their initial condition and after the implementation of retrofits. Quantifying the thermal condition of the home before and after installation of a weatherization measure permits thermal evaluation of the retrofit by a simple subtractive approach. A brief description of each weatherization measure investigated in this study is given below. For detailed descriptions of the retrofits, see Appendix B.

General Heat Waste is the implementation of general infiltration-reducing measures. These measures generally differ from the infiltration-reducing measures performed on site-built houses. For this reason it is strongly recommended that a blower door be used during infiltration reduction work on mobile homes. The blower door permits quick identification of leakage sites and helps avoid overtightening. Air tightening for mobile homes includes sealing holes in ducts, sealing around plumbing and electrical penetrations, installing ludwig clips on loose awning and jalousie primary windows, tightening the wall between the water heater closet and the unit, filling gaps around combustion air intakes and flues, repairing kitchen and vent fan dampers, sealing swamp cooler chases, and tightening doors.

Furnace Tune-Up includes cleaning the blower, replacing the filter, adjusting or replacing fan switches, adjusting the thermostat anticipator, clearing duct blockages, and performing basic health and safety checks.

Storms is installing storm windows on the inside of existing windows. An interior installation is recommended because it cuts an infiltration path passing through the wall cavity and window frame. An exterior storm panel will not interrupt this infiltration path.

Belly Wrap involves wrapping the underside of the mobile home with 6-in. batts of vinyl-backed fiberglass insulation. A wire grid system attached to the rim joists of the mobile home provides support for the batts. Field conditions may prohibit this retrofit because it requires full access to the underside of the mobile home. This retrofit should not be performed on mobile homes that will be moved. Long-term durability of this retrofit is currently unknown, but it is considered doubtful.

Belly Insulation is blowing insulation into the area between the underside of the floor and the rodent barrier. This area is often called the belly cavity. The effectiveness of this retrofit depends on the depth of the cavity.

Roof Insulation involves blowing insulation into the bow-string truss area of the mobile home. This can be done from inside or outside the home. The effectiveness of this retrofit depends on the depth of the cavity. This retrofit is currently recommended only in mobile homes located in dry climates. In humid climates this retrofit may exacerbate moisture buildup in the ceiling because of condensation from the underside of the metal roof. Further research is needed to determine under what conditions this will actually occur.

Roof Cap is installing rigid-board roofing insulation on top of the existing roof. The rigid-board insulation is then covered with a continuous and seamless elastomeric membrane such as Hypalon or EPDM. This retrofit requires that the existing plumbing, heating, and exhaust vents be extended above the new roof level. This method of roof insulation will not cause moisture problems; however, it is expensive.

Table 2.2 shows which retrofits were performed on which mobile homes.

Table 2.2 Weatherization Measures Implemented

	Mobile Home		
Retrofit	#1	#2	#3
General heat waste	X	X	X
Furnace tune-up	X	X	X
Storms	X	X	X
Belly wrap	X		X
Belly blow	X	X	
Roof blow	X	X	X
Roof cap			X

2.4 Test Method

The objective of our tests on mobile homes is to determine the effectiveness of certain weatherization measures. To do this, total thermal losses from a mobile home are carefully measured both before and after a particular weatherization measure is applied. Because the tests are done under carefully controlled environmental conditions, changes in the total loss coefficient as little as about 5% can be adequately measured. Figure 2.2, a plot of measured building load coefficient (UA) versus time, indicates excellent repeatability. Although field test methods are available (Fels, Reynolds, and Stram

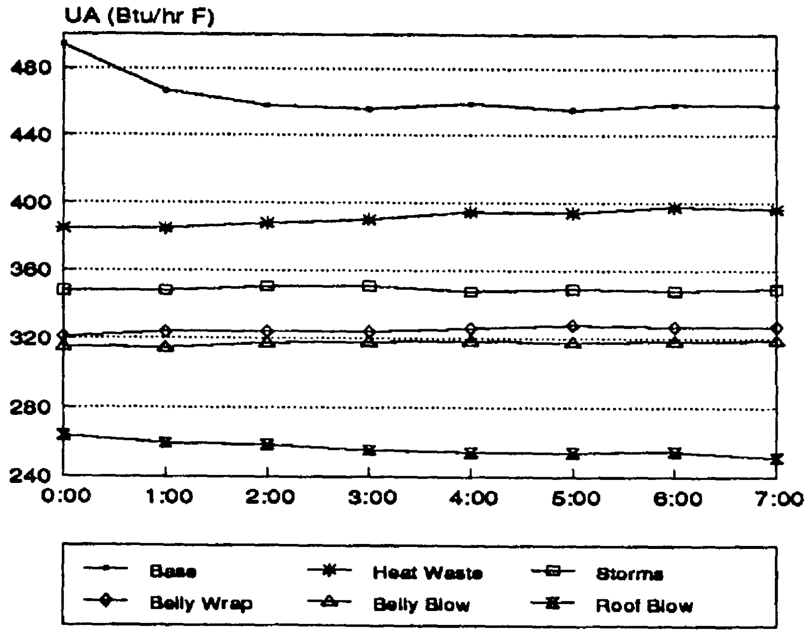


Figure 2.2. Mobile Home #1: Measured UA Values, Quasi Steady Steady State (0:00-7:00)

1986; Lee and Hadley 1988; Subbarao 1988), a test of this type is thought to be essential for evaluating individual weatherization measures that produce changes of 10% or less. In addition, the test results are expected to provide enough information to estimate weatherization performance for a wide range of real environmental conditions. To accomplish this, four experimental procedures are required: steady-state electric heating to determine total heat loss, tracer gas infiltration measurement to separate infiltration heat flow from conduction heat flow, blower door measurement of equivalent leakage area for use in extrapolation models, and calorimetric measurement of heating system efficiency.

The building thermal load coefficient (BLC) is the essential parameter that is measured during the steady-state test. The BLC is defined by

$$BLC = Q/(T_{in}-T_{out}) ,$$

where

Q = energy required to maintain inside temperature

T_{in} = mobile home average air temperature

T_{out} = warehouse average air temperature.

For the purposes of the present work, thermal losses from a building are considered to be caused by two different mechanisms that should be measured separately. These are conduction losses through the shell of the building and infiltration losses caused by air exchange between the mobile home and the warehouse. The thermal conduction occurs because of the difference in temperature between the inside and outside environments. Air flow through cracks in a building is caused by pressure differences between the inside and outside that, in turn, can be caused by both wind and temperature differences.

The heat flow caused by infiltration occurs because the inside air and outside air are at different temperatures. However, it is not entirely straightforward to determine heat flow for a given air flow because some of the heat can be "recovered" as air flows through cracks, depending on the characteristics of the cracks (Claridge and Bhattacharyya 1989). The main reason for separately measuring conduction and infiltration is that they must be treated differently when using a simulation or other simplified model to predict the effects of the weatherizaton measures under a wide range of climatic conditions.

2.4.1 Instrumentation, Data Acquisition, and Control

The steady-state heat loss tests performed on the mobile homes are fundamentally simple in concept, and the measurements required are not particularly complex. However, care must be taken in making these measurements because accuracy is also required.

The principal data acquisition and control hardware includes a Keithley Series 500 motherboard with a 16-bit analog-to-digital converter, 48 channels of analog inputs with thermocouple compensation available, and 32 channels of digital input/output. The Keithley system is connected to and controlled by an IBM-compatible personal computer with an 80286 processor and a 20-megabyte hard disk. A relatively simple program written in BASIC samples the sensors, processes the data to convert to engineering units, stores data, and controls the heaters that maintain temperatures in the mobile home and the warehouse. Data from the analog inputs are processed and stored every 30 s. The instrument reading for each channel is sampled 20 times and averaged to minimize the effects of electromagnetic noise. Hourly average values of important quantities are printed on paper as well as stored electronically.

Temperature and electric power are the principal quantities measured in these experiments. To measure the BLC, air temperatures inside and outside the mobile home are measured, and the energy required to maintain the inside temperature is measured. All temperatures are measured using type T thermocouples. Multiple-point measurements are made inside and outside to sample the vertical and horizontal distribution and to obtain an average bulk temperature. Each temperature sensor is placed in a concentric cylinder of relatively low emissivity material to shield the sensor from radiative exchange with the surfaces of the mobile homes and the warehouse. Temperatures of the inside surfaces of the warehouse are also measured so that radiative exchange with the mobile home can be calculated, and the BLC results can be corrected if necessary.

Electric power is measured with a Hall-effect watt transducer mounted at the breaker panel of each mobile home. The accuracy of this instrument is approximately 0.5%.

2.4.2 Measurement of Air Leakage

Two different measurements are made of the infiltration characteristics of each building. A blower door (Sherman and Grimsrud 1980) is used to measure the equivalent leakage area (ELA) of cracks in the mobile home, and a tracer gas test measures the air infiltration rate during a steady-state test. The ELA is used in a mathematical model (Sherman and Modera 1986) to predict air leakage under various weather conditions. The results of the tracer gas test are used to partition the total heat loss into conduction and infiltration components.

The blower door used in all our mobile home tests is manufactured by the Minneapolis Blower Door Company, and the computer programs used to process the data were written at SERI (Judkoff 1988). At least two blower door tests were done for each retrofit measure of the mobile home, and the results of each two tests were compared. If the results did not agree to within less than 5%, more tests were done until this criterion was met. The conditions inside the warehouse are particularly favorable for blower door testing because there is no wind.

Tracer gas tests used sulfur hexafluoride (SF6) as the tracer, and tracer concentrations were measured with either a Sentex Scentograph gas chromatograph, with a 60/80 molecular sieve column and an electron capture detector, or a Foxboro Miran 101 infrared specific vapor analyzer. SF6 was injected into the air inside the mobile home and allowed to mix for about 15 min. The decay in SF6 concentration was measured over a period of about 1 h, and the air flow rate was calculated as follows:

$$V(dc/dt) = F_t - Q_tC_t$$

$$C_t = C_i e^{-(Q/V)t}$$

$$Ln(C_i/C_t)/t = Q/V$$

$$Q/V = I$$

$$Ln(C_i/C_t)/t = I$$

where

C_i = initial concentration for each interval
C_t = concentration at time (t)
Q = volumetric flow rate (ft^3/h)
V = volume of mobile home (ft^3)
t = time (h)
F_t = tracer gas injection rate at time (t); this term is 0 for decay method
dc/dt = time rate of change of concentration (h^{-1})

The sample period is relatively short because mobile home air is being exchanged with warehouse air (not outside air as in a normal tracer test) so even though the warehouse volume is about 20 times greater than the volume of a mobile home, warehouse air might eventually become significantly contaminated. The contamination problem can be minimized by alternately sampling the mobile home and the warehouse tracer concentration. However, a computer-controlled alternate sampling device would have to be built and tested. Tracer gas tests are only begun after thermal steady-state conditions have been reached; therefore, a short sample period does not appear to be a limitation because infiltration should be a constant under these conditions.

2.4.3 Electric Heating Tests

Portable electric convective heaters are placed inside the mobile home and controlled by the data acquisition computer to maintain a constant average temperature. The readings of the nine interior thermocouples are averaged and compared to a programmed set-point temperature. Typically, only one of the three or four heaters is controlled, and the others are on constantly. An attempt is made to distribute the heaters so that all parts of the home are heated to a uniform temperature in the horizontal direction. A vertical temperature stratification of approximately 5°F is typically observed during electric heating. Excellent control of the interior temperature can normally be achieved with hourly variances of less than 0.02°F observed.

2.4.4 Heating System Efficiency Tests

Combustion efficiency of furnaces can be measured relatively simply in the field as a diagnostic test; however, this test alone does not provide adequate information for estimating actual energy requirements of mobile homes. The efficiency of the entire heating system, including heat losses from distribution ducts, must be measured to obtain useful estimates of annual energy savings. This measurement can be made with relative ease for steady-state conditions inside the warehouse. The mobile home furnace, controlled by its normal thermostat, is operated to maintain a constant temperature, and the warehouse temperature is also controlled to be constant. This test is best performed at temperatures close to those used for measuring the BLC so that the radiative environment and infiltration conditions will be the same. Gas consumption of the furnace is measured by recording the length of time the gas valve is open. Heating system efficiency can then be calculated as follows:

$$\text{efficiency} = BLC \times (T_{in} - T_{out})/(Q_{gas} + Q_{fan}) ,$$

where

Q_{gas} = energy content of natural gas consumed
Q_{fan} = electrical energy consumed by distribution fan.

The test provides a measure of the net change in system efficiency because of installation of a particular weatherization retrofit, but it does not determine the cause of the change within the heating system.

The heating system efficiency is typically measured after each weatherization measure has been installed. Some measures such as repair of leaky ducts are intended to directly reduce duct losses. Other measures such as insulation of the belly are primarily intended to reduce conduction through the shell but also will usually reduce conduction losses from the ducts to the outside and may reduce air leakage in the ducts. Sometimes changes in heating system efficiency are observed when weatherization measures such as roof insulation are installed that appear to be completely unrelated to the furnace or ducts. The explanation for this appears to be that because the total heating requirement is reduced, the existing furnace becomes relatively more oversized and thus less efficient because of cycling losses. Although this effect seems obscure, it is important to recognize that the furnace, ducts, and thermostat interact with the rest of the building in complex ways, and that a whole system test is the most reliable way to determine the effect.

2.5 Data Analysis

To determine whether steady-state BLC values have been achieved, average heating energy required, mobile home air temperature, and warehouse air temperature are calculated for each hour. Each quantity must be constant within strict limits for several hours before data are accepted as steady state. In a typical test, the air temperatures reach their set points rather quickly, but the heat flow required to maintain the internal temperature requires several more hours to reach steady state as the massive elements of the structure reach their final temperatures. Because outside ambient temperatures are most constant between midnight and 6 a.m., the steady-state period usually occurs then. Daytime tests are not usually possible, especially on sunny days, because the balance-point temperature of the warehouse rises above the ambient temperature. Thus, the warehouse temperature becomes too warm for testing and also uncontrollable because there is no cooling system. The test hours selected exhibit a maximum difference of less than ±1% for at least 4 to 6 h. Data for all other test hours are discarded. A tracer gas infiltration measurement must also be made during the steady-state period.

The total BLC is calculated for the above steady-state data as

$$BLC_{total} = Q_{total}/(T_{in} - T_{out}) .$$

The tracer gas measurement is used to calculate the heat flow caused by infiltration:

$$Q_{inf} = mC_p(T_{in} - T_{out}) ,$$

where

Q_{inf} = infiltration heat flow
m = mass flow rate of air leakage
C_p = heat capacity of air.

Then the so-called conduction portion of the total BLC can be calculated by subtracting infiltration from the total:

$$BLC_{cond} = (Q_{total} - Q_{inf})/(T_{in} - T_{out}) .$$

The most accurate comparisons between different weatherization measures are achieved if the temperatures in both tests are exactly the same. It is also important that the difference between the mobile home and warehouse air temperatures is the same to provide the best comparability for infiltration. Several options are available for checking the consistency of repeated tests. For each mobile home, repeated tests were done under essentially identical conditions. These tests demonstrated that essentially identical results could be achieved for the repeated tests. For some retrofit measures, such as general heat waste, only the infiltration part of the total BLC was changed, and the calculated conduction value is expected to remain constant. Essentially this is a thermal measurement of the change in infiltration heat flow, which can be compared to the tracer gas measurement. There is also the potential for measuring the infiltration heat recovery effect using this method; however, this was not pursued because of time constraints.

Another consistency check is possible because storm windows can be easily removed and reinstalled in combination with each of the other weatherization measures. Results indicate that applying storm windows to what amounts to different base cases produces results that can differ by 20%, or about 6 Btu/h. The results are inconclusive as to whether the difference is caused by interactions with different base cases or is an indication of the expected uncertainty in the measurement. However, in a second test where storm windows were applied to the mobile home in its initial condition and then in its final condition, the difference was only 3 Btu/h. This implies that the differences are due to measurement uncertainty rather than order dependence. Discussion of the complete results follows in Section 3.0.

Additional information on the monitoring methods is available in Judkoff et al. (1988).

3.0 TEST RESULTS

Three mobile homes were tested in a controlled environment to determine the effectiveness of implemented retrofits. The tests performed, described in detail in Section 2.0, led to the collection of data needed to quantify retrofit effectiveness. The test results for mobile home #1 are presented in detail, and a summary of the results for the three mobile homes is given.

3.1 Infiltration Test Results

Blower door and tracer gas tests were performed to quantify the air infiltration rate. The tracer gas tests were performed to directly measure the air changes per hour (ACH) occurring during the electric coheating tests. The electric coheating test measures the combined losses caused by infiltration and shell conduction. Performing the tracer gas test permitted these two separate heat transfer paths to be quantified.

The tracer gas test measures ACH over the test period. The testing data do not supply information about what infiltration rate would occur if the mobile home is placed in a different environment. To obtain this type of data, a blower door test is conducted. A blower door test measures the ELA in the building for a particular pressure difference. Models have been developed that use this measured ELA value to determine the ACH that would occur under different climatic conditions (Sherman and Modera 1986).

Table 3.1 summarizes the measured infiltration data for mobile home #1. Tracer gas and blower door tests were performed on the mobile home for six different weatherization measures. From the blower door tests, the average measured ELA Canadian at 10 pa for each measure is listed. The tracer gas tests measured ACH occurring during the electric coheating tests. The ACH measurement needs to be taken with the same temperature difference that was maintained under the coheat test so that accurate UA conduction values can be determined.

As shown in the table, the infiltration UA for the base case varies slightly from the value calculated from the tracer gas test. The infiltration UA for the base case was determined by using the conduction UA value established for the heat waste retrofit. This conduction UA value was subtracted from the measured overall UA for the base case to find the infiltration UA for the base case. The conduction UA of the heat waste case is the same as the base case because the heat waste retrofit changes only infiltration. Although the UA conduction determined from the base case could have been used for the two cases, it was believed that the UA conduction determined from the heat waste case was more accurate. This is assumed because the heat waste condition has a smaller infiltration component resulting in less error in the tracer gas measurement and higher confidence in the determination of the conduction UA.

Table 3.1 Infiltration Summary for Mobile Home #1

Weatherization Measure	ELA Canadian	Tracer Gas Test Delta T (°F)	ACH	UA (Btu/h °F)	Infiltration UA (Btu/h °F)
Base	330	32.0	1.24	91	96
Heat waste	178	38.0	0.51	35	35
Storms	145	37.6	0.38	26	26
Belly wrap	145	38.6	0.35	24	26
Belly blow	142	37.7	0.34	23	24
Roof blow	133	38.5	0.35	24	24

3.2 Electric Heating Test Results

The electric heating tests were performed to determine an overall BLC for the mobile home in each weatherization condition. The BLC includes the effects of conduction and infiltration. Subtracting the infiltration UA component from the BLC gives the conduction component.

Table 3.2 summarizes the measured coheating test data for mobile home #1. Figures 3.1 and 3.2 present the coheating test results in graphic form. The second and third columns in Table 3.2 are the mobile home-warehouse temperature difference and the measured BLC from the electric heating tests. Values are given for the mobile home with the six different weatherization measures.

In the second set of columns, the BLC values are separated into their infiltration and conduction components. The conduction component is found by subtracting the infiltration UA from the BLC. The last column in Table 3.2 lists the actual conduction UA used in the evaluation of the retrofit.

The measured UA conduction for storms differs slightly from the assumed UA conduction value for storms. This adjustment was made to reflect the measured results of other tests involving storm installation on mobile home #1. These tests are not based on the mobile home in the general heat waste condition with and without storms but rather on the mobile home in the belly wrap condition with storms and without storms. The effect storms had on the mobile home in the belly wrap conditon resulted in a change in UA conduction of 33 Btu/h °F compared to a change of 39 Btu/h °F for the general heat waste condition. Based on these two different tests, an average reduction in conduction UA of 36 Btu/h °F was assumed.

Although the difference between the two measurements is relatively small, the possibility of an implementation order dependence on retrofit effectiveness exists. To investigate the matter, storm window effectiveness was evaluated for mobile home #3 in two different weatherization stages. With mobile home #3 in its initial condition, storms were found to decrease the BLC by 37 Btu/h °F. With mobile home #3 in its final weatherization condition, the decrease was measured to be 40 Btu/h °F. These test results show that the decrease in storm effectiveness measured in mobile home #1 was not repeatable in mobile home #3. Therefore, the two tests do not support order dependence, because the differences were from larger to smaller for home #1, and smaller to larger for home #3.

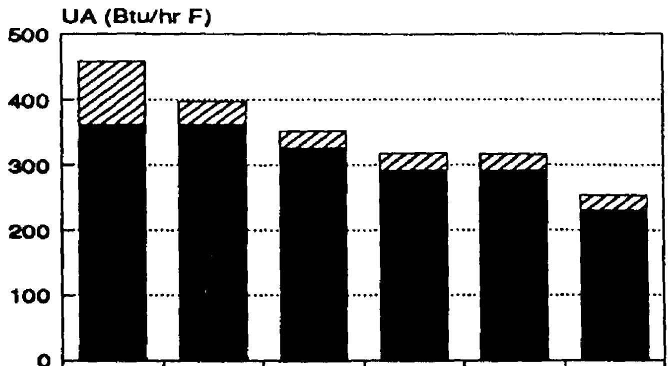
Based on the implementation of four retrofits—heat waste, storms, belly blow, and roof blow—the BLC for mobile home #1 was reduced from 458 Btu/h °F to 254 Btu/h °F, a reduction of 44.5%. For a breakdown of the reduction in the BLC for each retrofit, see Figure 3.2.

Table 3.2 Electric Coheating Summary for Mobile Home #1

Weatherization	Electric Heating Test		Test		Actual
Measure	Delta T (°F)	BLC (Btu/h °F)	UA Infil	UA Cond	Conduction UA
Base	38.4	458	96	362	362
Heat waste	38.1	397	35	362	362
Storms	37.7	349	26	323	327
Belly wrap	37.3	318	26	292	292
Belly blow	39.2	316	25	291	291
Roof blow	38.0	254	24	230	230

3.3 Delivered Heat Efficiency Test Results

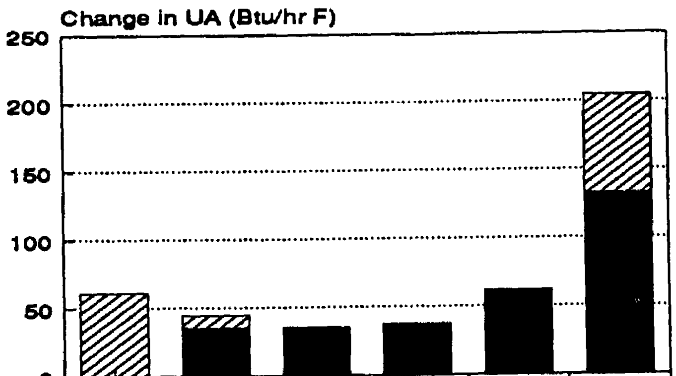
Besides reducing air infiltration rate and shell conduction, retrofits may also affect the delivered heat efficiency. Changing the delivered heat efficiency affects the energy that must be purchased to meet the building load.



	Base	Heat Waste	Storms	Belly Wrap	Belly Blow	Roof Blow
Infiltration	96	35	26	26	25	24
Conduction	362	362	327	292	291	230
Total	458	397	353	318	316	254

Total Reduction = 44.5% (204 btu/h F)
Belly-wrap removed before belly blown

Figure 3.1. Mobile Home #1: Measured UA Overall, Conduction and Infiltration



	Heat Waste	Storms	Belly Wrap	Belly Blow	Roof Blow	All Measures
Total	61	44	35	37	62	204
Infiltration	61	9	0	1	1	72
Conduction	0	35	35	36	61	132

Figure 3.2. Mobile Home #1: Reduction in Measured UA due to Weatherization Measures

Figure 3.3 shows the change in efficiency resulting from the retrofits. The delivered heat efficiency appears to decrease when the roof blow retrofit is implemented. Yet, realistically, the roof blow retrofit has no effect on the heating ducts or the furnace settings. A possible explanation for the decrease in efficiency is the heat load decrease. As the heat load gets smaller, the furnace becomes more oversized, and cycling efficiency decreases. Therefore, although it appears that the roof blow is causing a decrease in delivered heat efficiency, it is really a result of all the retrofits causing a decrease in the heating load. The six retrofits implemented on mobile home #1 and the furnace tune-up produced a net increase of 7% in delivered heat efficiency. Had there been no loss in cycling efficiency, then the gross increase would have been at least 12%. This suggests that developing a procedure for downsizing the furnace may be worthwhile.

3.4 Special Studies

Besides testing the effectiveness of the six retrofits, the study also investigated variations on retrofit implementation. Mobile home #1 was tested to evaluate the effect of tightening primary windows with and without storms installed. Leaky primary windows were simulated by placing a 16-penny nail between the window glass and the metal window frame. Electric coheating tests were conducted, and the effective BLC evaluated for the following conditions: (1) leaky primary windows, (2) tight primary windows, (3) tight primary windows with storms, and (4) loose primary windows with storms. The results of the study are presented in Figure 3.4. In the figure, the change in the measured BLC is presented for three cases. The tight primes case is the change in the BLC resulting from tightening the primary windows (removing the nails and installing ludwig clips). The tight primes with storms case is the change in the BLC resulting from storms being added to the tight primary windows. The loose primes with storms case is the change in the BLC resulting from the primary windows' becoming leaky (ludwig clips removed and nails in place) with the storm still in place. With stack-driven infiltration it appears that the tightness of the primary windows has little effect on the load coefficient when

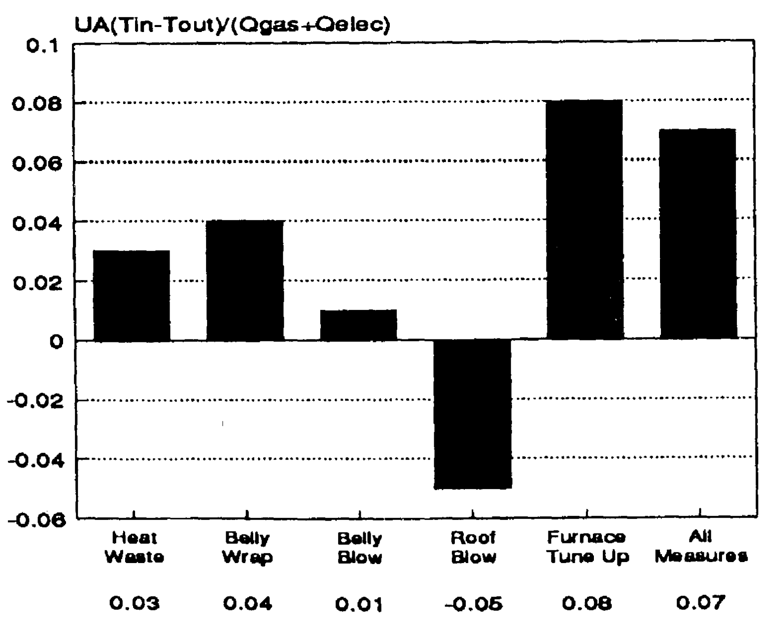


Figure 3.3. Mobile Home #1: Change in Delivered Heat Efficiency due to Weatherization Measures

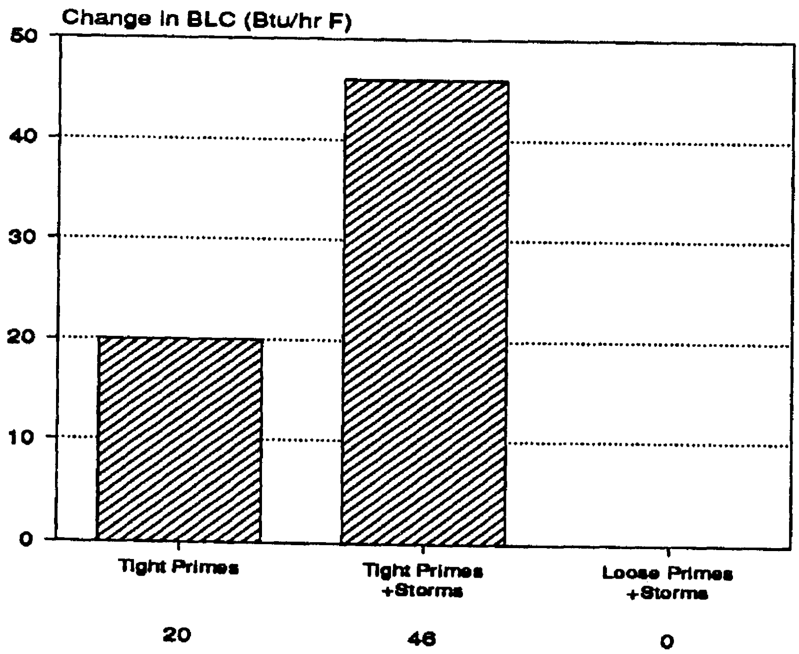


Figure 3.4. Mobile Home #1: Variations on Window Savings

storms are in place. Therefore, it is not recommended that expensive repairs to tighten primary windows be made if storm windows are installed. Further work under typical wind conditions is necessary to fully support this recommendation.

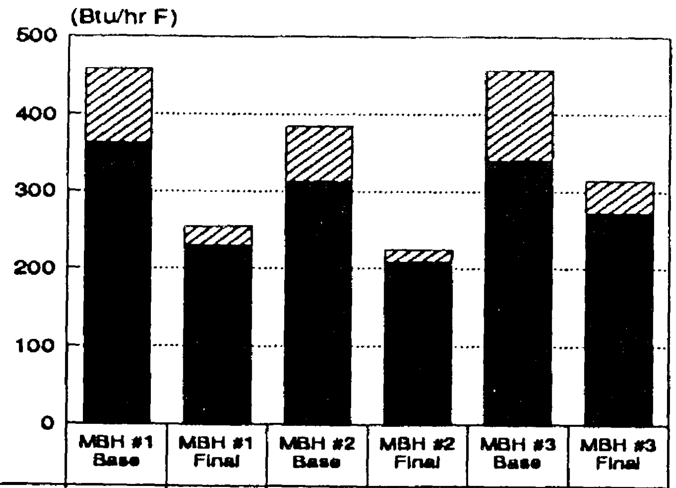
3.5 Test Results Summary - Mobile Homes #1, #2, #3

The same tests conducted on mobile home #1 were also completed for mobile homes #2 and #3 except that in homes #2 and #3, delivered heat efficiency tests were performed only under the initial and final conditions. Figure 3.5 presents the measured UA overall for the three mobile homes in their initial and final conditions.

The testing for mobile homes #2 and #3 was conducted during a 2-week period in April, and the testing for mobile home #1 was conducted from December through March. Because of the warmer temperatures in April, the testing of mobile homes #2 and #3 was conducted with a 28°F temperature difference, in comparison to the 38°F temperature difference maintained during the testing of mobile home #1. The test temperature difference affects the infiltration UA. Therefore, a direct comparison between each home's infiltration UA and overall UA should not be made.

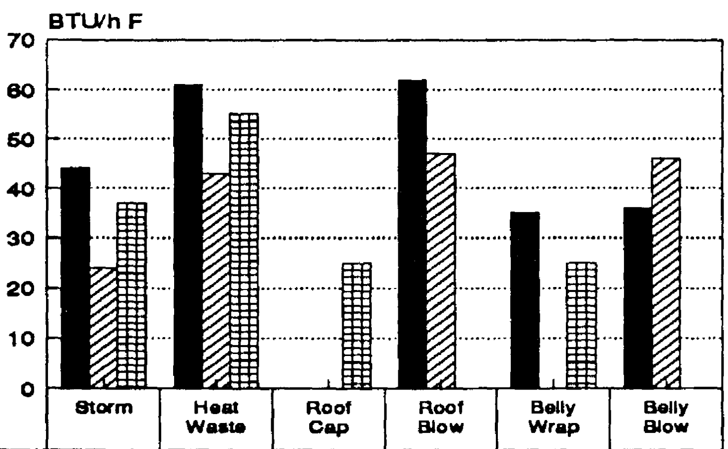
Figure 3.6 shows the measured change in the overall UA that resulted from implementing a retrofit. Variations within the retrofit measured savings can be attributed to many factors. Much of the difference is a result of the heat transfer areas associated with the retrofit being different from home to home. Also, for the retrofits involving insulation blown into a cavity, the blown insulation density, consistency, and cavity depth also have an effect on the measured savings. Figure 3.7 shows the measured savings in UA resulting from the retrofits as a percentage of the initial overall UA.

The measured change in delivered heat efficiency varied significantly in mobile homes #2 and #3 from that measured in mobile home #1. Figure 3.8 presents the measured change in efficiency experienced in each mobile home. As shown in the figure, mobile homes #2 and #3 both experienced large improvements in furnace efficiency. Both of these mobile homes had very large holes in their duct systems initially. Mobile home #3 also had a below-floor return air system. Repair of these items resulted in the vast improvements in delivered heat efficiency.



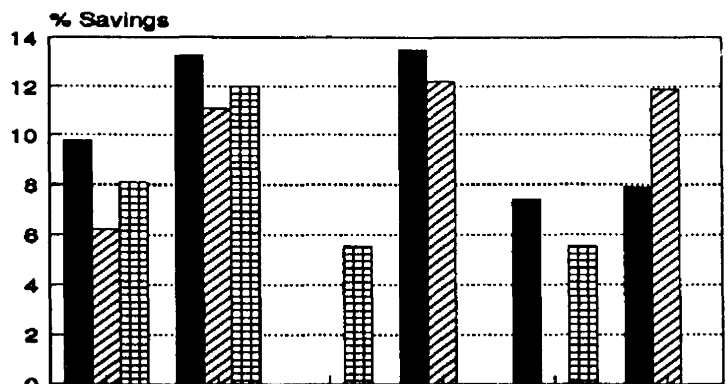
	MBH #1 Base	MBH #1 Final	MBH #2 Base	MBH #2 Final	MBH #3 Base	MBH #3 Final
Infiltration	96	24	72	16	117	42
Conduction	362	230	313	209	340	273
Total	458	254	385	225	457	315

Figure 3.5. Mobile Homes #1, #2, and #3: Initial and Final UA Overall



	Storm	Heat Waste	Roof Cap	Roof Blow	Belly Wrap	Belly Blow
Unit 1	44	61		62	35	36
Unit 2	24	43		47		46
Unit 3	37	55	25		25	

Figure 3.6. Mobile Homes #1, #2, and #3: Measured UA Savings, Conduction and Infiltration



	Storm	Heat Waste	Roof Cap	Roof Blow	Belly Wrap	Belly Blow
Unit 1	9.8	13.3		13.5	7.4	7.9
Unit 2	6.2	11.1		12.2		11.9
Unit 3	8.1	12	5.5		5.5	

Figure 3.7. Mobile Homes #1, #2, and #3: Measured UA Savings Percentage, Conduction and Infiltration

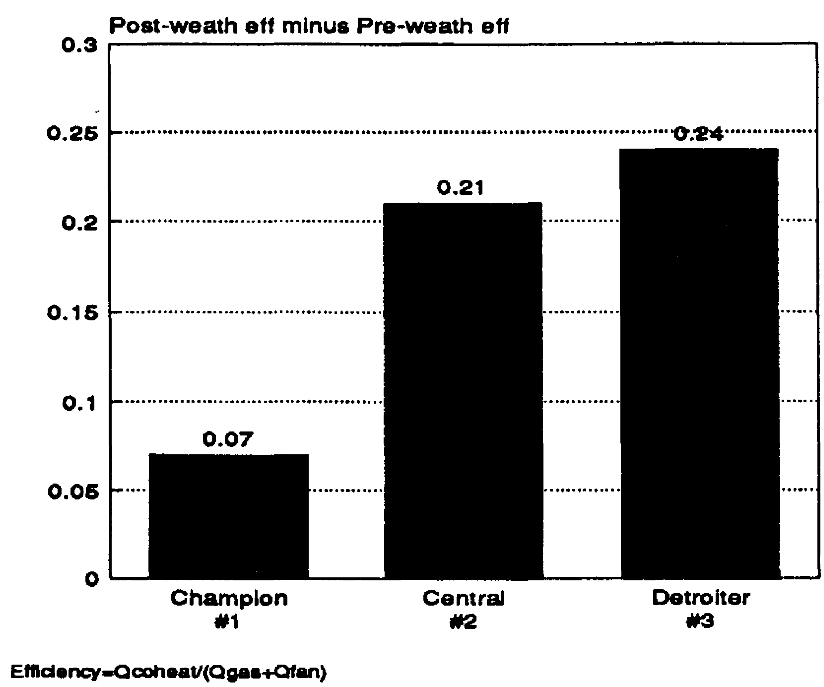


Figure 3.8. Mobile Homes #1, #2, and #3: Increase in Measured Delivered Heat Efficiency

4.0 GENERALIZATION OF MEASURED RESULTS FOR OTHER CLIMATES

From the mobile home tests, the effect of the retrofits on the BLC and air infiltration rate was measured. To determine the cost-effectiveness of the retrofits, these data must be translated into expected energy savings in various climates. This analysis was completed using the test data collected for mobile home #1, because these were thought to be the most reliable data of the three mobile homes tested. An explanation of the analysis process for determining energy use from infiltration rate and building conductance is given below.

The infiltration rates measured with tracer gas during the electric coheating tests were not the same rates that would be experienced with the mobile home placed in the real environment. Unfortunately, there is no direct way to extrapolate tracer gas results to different environmental conditions. Therefore, we used the Lawrence Berkeley Laboratory (LBL) infiltration model (Sherman and Modera 1986), which, given leakage area as measured with a blower door, and crack distribution, can predict infiltration rates for any location for which long-term temperature and wind data are available. Once infiltration rate is determined, the energy associated with air infiltration is simply the heat needed to warm the incoming air from the outdoor temperature to the indoor temperature.

The building conductance is the heat transfer coefficient of the mobile home envelope. The energy associated with the conduction losses can be estimated by multiplying the building conduction load coefficient by the indoor-outdoor temperature difference. This simplified calculation does not account for internal gains generated within the home, solar gains, and thermal capacitance of the building. To accurately calculate the change in the heating load associated with implementing a retrofit, a more detailed analysis was done. To achieve this, a computer simulation program was used to model the dynamic thermal response of a mobile home. The program uses hourly weather data depicting a typical meteorological year for a specified location. Heat flows within the building are calculated for each hour in the year, and the heating and cooling loads for the building are determined.

4.1 Calculated Building Conductance

The thermal model of the mobile home in the computer program is based on the collected audit data for mobile home #1 and the thermal characteristics of the construction materials. To ensure that the model accurately represents the measured building conduction UA, the building conduction UA was calculated and compared to the measured UA conduction determined from the infiltration and electric coheating tests. In calculating the building conductance, standard methods outlined in the *1985 ASHRAE Handbook of Fundamentals* (ASHRAE 1985) were used.

In performing the audit calculations, some uncertainty exists as to the exact values to use for material properties and for some dimensions of materials such as insulation thickness. To obtain the best comparison of measured and predicted heat flows for all conditions of the mobile home, an iterative process of adjusting the audit parameters was used. The best judgment of the auditor led to an initial audit description that was within about 5% of the measured heat loss coefficient for the base case condition. However, as measured changes were compared to calculated changes for the various retrofits, it was apparent that the initial audit probably contained offsetting errors. Changes were made in the audit description to best reconcile the results of the entire series of tests. These changes are not arbitrary and capricious but are made to reasonably represent the expected uncertainty in material properties and dimensions. The validity of this method of extrapolating results depends to a significant extent on obtaining a good estimate of the initial condition for each component (walls, floor, etc.). Therefore it was worth making this effort to get the best possible estimate of the initial state of the mobile home.

The audit observations led the initial American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) calculation to a close match with the measured UA of mobile home #1 in its base condition. For the base condition, the calculation anticipated that the UA conduction value would be 381 Btu/h °F; the measured value was 362 Btu/h °F. By changing the wall insulation R-value from 6.4 to 7.8, the discrepancy was eliminated. This adjustment was well within the uncertainty in measuring the wall insulation thickness and the uncertainty in R-value per inch reported by ASHRAE. Comparing the measured changes in the UA conduction with the anticipated changes based on the calculation resulted in a few other adjustments to the heat transfer calculation. These adjustments are discussed below.

An additional heat transfer path was added to the floor and to the roof. The heat flows through the perimeter of the floor cavity and the roof cavity were added to the ASHRAE conductance analysis. This resulted in a better correlation with the measured data. The final heat transfer model used to represent the mobile home in its six weatherization conditions agreed with the measured data. That is, the model's calculated ASHRAE conduction values were the same as the conduction values measured in the study. The material R-values used in the ASHRAE conduction calculation are listed in Table 4.1. Conduction calculations characterizing the mobile home in its initial and final conditions are given in Table 4.2 and 4.3.

Comparing the ASHRAE heat transfer calculated value with the measured coefficient resulted in some interesting observations. The belly wrap and the belly blow retrofits performed less well than expected, and the roof blow performed better than expected.

Table 4.1 Material Conductance Values

Material	Thickness (in.)	1/K (h ft^2 °F/Btu in.)	R (Btu/h ft^2 °F)
carpet thin	0.13	2.46	0.31
carpet thick	0.50	2.46	1.23
foam rubber	0.25	5.00	1.25
linoleum			0.05
mineral fiberboard	0.50	2.64	1.32
metal window			1.35
metal window w/storm			2.22
wood stud 2	1.62	1.23	1.99
wood stud 3	2.62	1.23	3.22
wood joist 5	4.62	1.23	5.68
wood panel	0.25	1.23	0.31
particleboard	0.63	1.06	0.66
fiberglass blanket 10	1.00	3.20	3.20
fiberglass blanket 15	1.50	3.20	4.80
fiberglass blanket 25	2.45	3.20	7.84
fiberglass batt 60	4.25	3.20	13.60
fiberglass blown 4.25	4.25	3.86	16.41
fiberglass blown 4.5	3.00	3.50	10.50
fiberglass blown 10	3.50	3.50	12.25
air film coefficients			
horizontal-flow down			0.92
horizontal-flow up			0.61
vertical-flow horizontal			0.68
surface coefficients			
3.5 horizontal down			1.15
3.5 horizontal up			0.91
1.5 horizontal up			0.83
0.75 horizontal down			1.02

Table 4.2 ASHRAE UA Calculation — Mobile Home #1 Base Condition

ROOF (ASHRAE heat transfer coefficient calculation)

R-Values	Path 1	Path 2	Path 3	Path 4	
air film-hor up	0.61	0.61	0.61	0.68	
fiberglass blnkt 1"			3.20		
truss/joist 16"OC	7.07	2.76			
fiberglass blown		0	0	0	
air space >4" hor up					
film coef-hor up			0.61		
film coef-hor up			0.61		
air space - hor up		0.91		0.83	
mineral fiberbrd 0.5"	1.32	1.32	1.32	1.32	
air film-hor up	0.61	0.61	0.61	0.61	
R-path	9.61	6.21	6.96	3.44	
Area	38.92	38.92	544.88	22.00	
UA-path	4.05	6.27	78.29	6.40	
UAtot					95.00

WALLS (ASHRAE heat transfer coefficient calculation)

R-Values	Path 1	Path 2	Path 3	Path 4	
air film-vert hor	0.68	0.68			
metal window			1.35		
metal window w/storm				2.22	
stud 2"×3"	3.22				
fiberglass blnkt 2.5"		7.84			
paneling 1/4"	0.31	0.31			
air film-vert hor	0.68	0.68			
R-path	4.89	9.51	1.35	2.22	
Area	109.63	767.38	125.00	0.00	
UA-path	22.42	80.71	92.59	0.00	
UAtot					195.72

Table 4.2 ASHRAE UA Calculation — Mobile Home #1 Base Condition (Concluded)

FLOOR (ASHRAE heat transfer coefficient calculation)

R-Values	Path 1	Path 2	Path 3	Path 4	Path 5
air film-hor down	0.92	0.92	0.92	0.92	0.92
carpet	0.54	0.54	0.54	0.54	0.54
particle board 5/8"	0.66	0.66	0.66	0.66	0.66
air space 0.75"	1.02		1.02		
joist 2"×5"	5.68		5.68		1.99
air space > 4"					
film coef-hor dwn		0.92	0.92	0.92	0.92
film coef-hor dwn		0.92	0.92	0.92	
fiberglass blnkt 1.5"		4.80	4.80	4.80	
fiberglass added	0	0	0	0	0
rodent barrier 1/16"					
air film - hor down	0.92	0.92	0.92	0.92	
air film - vert					0.68
R-path	9.74	9.68	16.38	9.68	5.71
Area	25.02	225.18	37.25	335.27	51.21
UA-path	2.57	23.27	2.27	34.64	8.97
UAtot					71.72

Total MBH					
UAcond					362.4

Table 4.3 ASHRAE UA Calculation — Mobile Home #1 Final Condition

ROOF (ASHRAE heat transfer coefficient calculation)

R-Values	Path 1	Path 2	Path 3	Path 4	
air film-hor up	0.61	0.61	0.61	0.68	
fiberglass blnkt 1"			3.20		
truss/joist 16"OC	7.07	2.76			
fiberglass blown		13.51	16.405	3.86	
air space >4" hor up					
film coef-hor up			0		
film coef-hor up			0		
air space - hor up		0		0	
mineral fiberbrd .5"	1.32	1.32	1.32	1.32	
air film-hor up	0.61	0.61	0.61	0.61	
R-path	9.61	18.81	22.15	6.47	
Area	38.92	38.92	544.88	22.00	
UA-path	4.05	2.07	24.61	3.40	
UAtot					34.12

WALLS (ASHRAE heat transfer coefficient calculation)

R-Values	Path 1	Path 2	Path 3	Path 4	
air film-vert hor	0.68	0.68			
metal window			1.35		
metal window w/storm				2.22	
stud 2"×3"	3.22				
fiberglass blnkt 2.5"		7.84			
paneling 1/4"	0.31	0.31			
air film-vert hor	0.68	0.68			
R-path	4.89	9.51	1.35	2.22	
Area	109.63	767.38	0.00	125.00	
UA-path	22.42	80.71	0.00	56.31	
UAtot					159.44

Table 4.3 ASHRAE UA Calculation — Mobile Home #1 Final Condition (Concluded)

FLOOR (ASHRAE heat transfer coefficient calculation)

R-Values	Path 1	Path 2	Path 3	Path 4	Path 5
air film-hor down	0.92	0.92	0.92	0.92	0.92
carpet	0.54	0.54	0.54	0.54	0.54
particle board 5/8"	0.66	0.66	0.66	0.66	0.66
air space 0.75"	1.02		1.02		
joist 2"×5"	5.68		5.68		1.99
air space > 4"					
film coef-hor dwn		0	0	0	0
film coef-hor dwn		0	0	0	
fiberglass blnkt 1.5"		4.80	4.80	4.80	
fiberglass added	0	10.5	12.25	12.25	7.875
rodent barrier 1/16"					
air film - hor down	0.92	0.92	0.92	0.92	
air film - vert					0.68
R-path	9.74	18.34	26.79	20.09	12.67
Area	25.02	225.18	37.25	335.27	51.21
UA-path	2.57	12.28	1.39	16.69	4.04
UAtot					36.97
Total MBH					
UAcond					230.5

The belly wrap retrofit consists of suspending 6-in. fiberglass batts against the underside of the mobile home. The added R-value for this retrofit is 19.2, but the measured effect the insulation had on the mobile home was equivalent to adding an R-value of 13.6. It was observed that the batts were not properly in place against the belly. When the belly wrap, wire grid, and insulation were dropped from mobile home #1, it was seen that in some places the batts overlapped, and in other places there were gaps where no insulation was present. The irregularity of the batt covering is a result of the difficulty in installing this retrofit.

The belly blow and roof blow retrofits involve blowing insulation into the belly and roof cavities. It is difficult to accurately calculate savings for any retrofit using blown insulation because it is difficult to determine the density and uniformity of blown insulation. The blown insulation density affects the insulation's R-value per inch, which, of course, affects the retrofit's effectiveness. Also in blown insulation installations, it is difficult to determine if the cavity has been completely filled. For this study, the lower than expected performance of the belly blow retrofit was attributed to the pan cavity's not being completely filled. It was anticipated that mobile home #1's pan cavity would be filled with 8.5 in. of insulation, and the wing cavity filled with 3 in. of insulation. Yet, assuming the insulation was blown at the manufacturer's recommended density with an R-value of 3.5/in., there was effectively 3.5 in. of insulation in the pan and 3 in. of insulation in the wings. Thus, the performance of the belly blow retrofit would have been better if the pan cavity had been completely filled with insulation.

For the roof blow retrofit, observations led to the opposite conclusion as for the belly blow retrofit. During the roof blow installation, the force from the blowing insulation actually pushed the roof up to increase the depth of the roof cavity. This retrofit was expected to add an R-14.9 to the roof, assuming the blown insulation R-value/in. is 3.5 and the average roof cavity is 4.25 in. The measured results reveal that an R-16.4 was added to the roof. This is equivalent to adding 4.75 in. of insulation to the roof cavity.

4.2 Computer Simulation of Performance: Mobile Home #1

The computer simulation used to determine the thermal performance of the retrofits was SUNCODE (Palmiter, Wheeling, and DeLaHunt 1981). SUNCODE, the PC version of SERIRES, is a detailed dynamic thermal analysis program using time steps of less than 1 h (Palmiter et al. 1983). The mathematical representation of the building is a thermal network with nonlinear temperature-dependent controls. The mathematical solution techniques used in the program include forward finite differencing, Jacobian iteration, and constrained optimization.

All building energy simulation programs require certain input data for characterizing the thermal behavior of the building. For mobile home #1, the heat flow paths and the materials' R-values defined in the ASHRAE UA calculation and based on the measured results were modeled in the SUNCODE program. Each of the six weatherization conditions of mobile home #1 were evaluated: base, heat waste, storms, belly wrap, belly blow, and roof blow. The input data reflect the results of the mobile home testing.

Other program inputs reflect assumptions about the behavior of the mobile home occupants (i.e., operating thermostats, and opening and closing windows). For these types of inputs, commonly accepted references were used to define average behavior (Fels, Rachlin, and Socolow 1986; Krieder 1982). The assumptions used in creating the SUNCODE input file are presented below. A copy of the input files is available on request.

4.2.1 Infiltration

The equivalent and effective leakage areas (ELA-Canadian and ELA-LBL) were determined before and after each implemented retrofit. The ELA values are calculated from data collected from the blower door tests. 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 the ELA-LBL assumes that the equivalent open area has a rounded edge, and ELA-Canadian assumes a sharp edge. Also, the reference pressure difference for ELA-LBL is 4 pa, and for ELA-Canadian it is 10 pa.

An infiltration model developed by Sherman and Grimsrud (1986) was used to determine the climate-dependent air infiltration rates from the measured ELA-LBL values. Average air infiltration rates were determined for each month for each weatherization condition of the mobile home. To use the model, the values of the ELA-LBL, the monthly average wind speed, the monthly average indoor-outdoor temperature difference, and the relative location of the measured leakage areas must be known. The climate variables are easily obtained from TMY weather data, but there is no direct practical method for determining crack distribution. We used the method described by Judkoff et al. (1988) to define the crack distribution for each case. This analysis was completed for each climatic location in which SUNCODE was run. The monthly infiltration values calculated using the model were used as input to the SUNCODE program.

4.2.2 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 (1985).

Many occupants will open windows under overheated conditions. However, no consistent pattern has been determined to characterize this behavior. To assume that windows were never opened would show unjustifiably large savings for some retrofits. Therefore, assumptions were made concerning this effect.

To simulate the occupants' opening and closing the windows, the ventilation set point was scheduled seasonally. In September and October, and March through May, it was assumed that the occupants would open the windows when the indoor temperature equaled or exceeded 75°F. In November through February, it was assumed that occupants would open windows if the indoor temperature equaled or exceeded 79°F. In June through August, it was assumed that occupants would open the windows if the indoor temperature equaled or exceeded 71°F. These assumptions are conservative in the sense that failure to adhere to this strategy would result in greater heating savings.

4.2.3 Calculating the Natural Ventilation Capacity

The capacity for natural ventilation is limited by the available open window area, indoor-outdoor temperature difference, and wind speed and direction. Several different techniques for calculating this effect exist. One of the more detailed methods was developed by Aynsley, Vickery, and Melbourne (1977), and one of the more simplified approaches was developed by Olgyay (1963). In previous work Judkoff (1981) demonstrated close agreement between these two methods for simple building geometries. Thus, the simplified method of calculation was used to determine monthly average natural ventilation from window openings in the different analysis locations. The equation used is

$$ACH = 60 \times E \times A \times V ,$$

where

E = factor-dependent inlet area to outlet area ratio
A = inlet window area (ft^2)
V = onsite wind velocity normal to the open face (mph)
ACH = ventilation capacity per hour.

For the calculation it was assumed that half the window area was available for ventilation. Half this area carried air flowing in and half carried air flowing out. The yearly average ventilation rate was used in the SUNCODE input file.

4.2.4 Internal Gains

Internal gains are heat contributions to a space from such activities as cooking, hot water use, appliances, and lighting. Internal gains occurring in the winter contribute to heating the unit. The amount of internal gains used in the mobile home model are 2400 Btu/h. This gain is based on the average daily nonheating energy consumption for homes in the Denver area (Fels, Rachlin, and Scolow 1986) and is considered realistic for mobile homes in other areas.

4.2.5 Orientation and Windows

In the SUNCODE program, the orientation of the mobile home was specified such that one short wall faced 45° from south. Thus, one long wall was also 45° from south. The window areas were set equal on each long wall and each short wall. The total window area still equaled the window area measured in mobile home #1. These specifications were made to eliminate the bias in retrofit savings that could result from variation in solar orientation. (If there is a choice of orientation, however, it is recommended that the maximum window area be toward the south in heating-dominated climates.)

4.3 Simulation Results

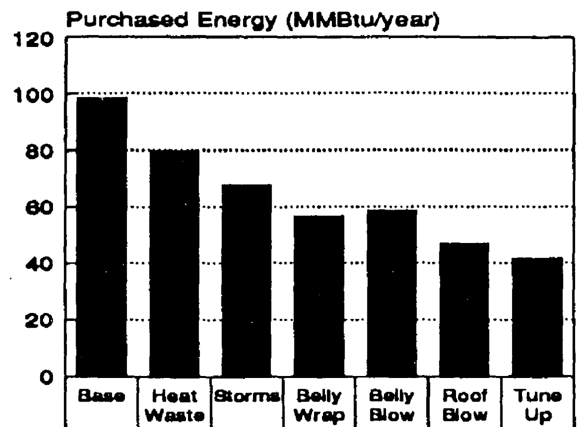
The SUNCODE simulations were run for the mobile home in five different climates. The selected climates were Denver, Colo.; Madison, Wis.; Memphis, Tenn,; Fairbanks, Alaska; and Concord, N.H. The simulation outputs state the yearly heating load for the mobile home in the different weatherization conditions. The roof blow condition was analyzed only for Denver because more research is needed to determine if this retrofit will cause ceiling moisture problems in more humid climates.

The amount of fuel needed to heat the home can be found by dividing the heating load by the measured delivered heat efficiency. Figures 4.1 and 4.2 present load data for the mobile home in Denver and Madison. The tables in the figures report the determined loads, furnace efficiencies, and calculated purchased energy requirements.

Figure 4.3 presents the purchased energy savings caused by the implementation of retrofits in Denver and Madison. In comparing the results, it is helpful to know that Denver has 6545 degree days and total horizontal solar radiation equaling 581,000 Btu/ft^2, and Madison has 7572 degree days and total horizontal solar radiation equaling 434,000 Btu/ft^2. The total purchased energy savings for Denver excluding the belly wrap retrofit is 57 million Btu/yr, representing a 58% reduction in energy use. The total purchased energy savings for Madison excluding the belly wrap and the roof blow retrofits is 65 million Btu/yr, representing a 47% reduction in energy use.

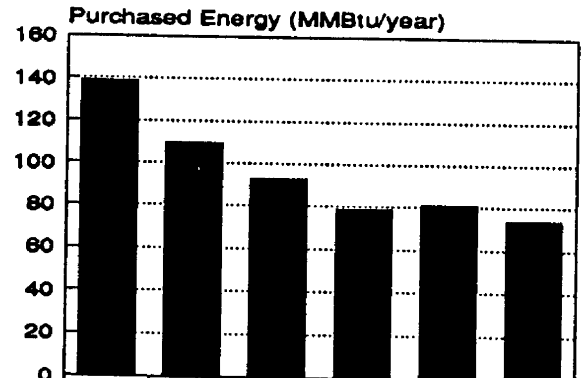
4.4 Retrofit Economics

The simple and discounted payback periods were calculated for the retrofits in the five different locations. The belly wrap retrofit was not considered in this economic analysis. The durability of the belly wrap retrofit needs to be investigated further before its implementation is recommended.



	Base	Heat Waste	Storms	Belly Wrap	Belly Blow	Roof Blow	Tune Up
Purchased Energy	98.5	79.7	67.7	56.6	58.4	46.7	41.7
Heating Efficiency	0.68	0.71	0.71	0.75	0.72	0.67	0.75
Heat Load	67	56.6	48.1	42.5	42.1	31.3	31.3

Figure 4.1. Mobile Home #1: Heating Energy Use in Denver



	Base	Heat Waste	Storms	Belly Wrap	Belly Blow	Tune Up
Purchased Energy	138.8	109.4	92.8	78.9	81.2	74
Heating Efficiency	0.68	0.71	0.71	0.75	0.72	0.79
Heat Load	94.4	77.7	65.9	59.2	58.5	58.5

■ Purchased Energy

Figure 4.2. Mobile Home #1: Heating Energy Use in Madison

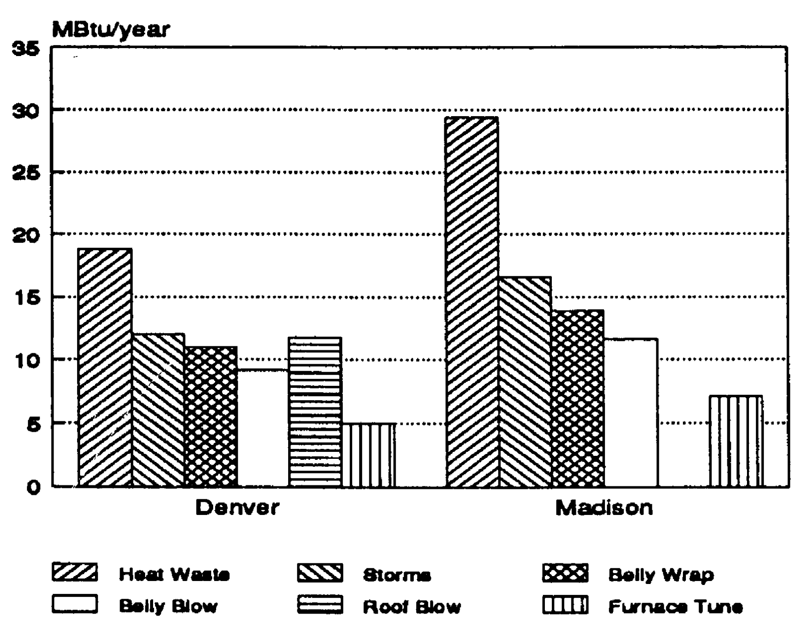


Figure 4.3. Mobile Home #1: Purchased Energy Savings, Denver and Madison

The simple payback is calculated by dividing the retrofit cost by its energy cost savings. The discounted payback is a more complicated calculation, taking into consideration the time value of money. Three economic factors are used in this calculation: the discount rate (i), the general inflation rate (j), and the fuel inflation rate (je). The discount rate is the interest rate or the expected rate of return on a potential investment. Its upper limit is the cost of borrowing money, and its lower limit is the foregone return on the homeowner's next best alternative investment. The general inflation rate is used to calculate the real discount rate i′, where

$$i' = (i - j)/(1 + j) .$$

This formula modifies the discount rate with the inflation rate. The fuel inflation rate includes the general inflation rate plus the anticipated energy rate increase beyondinflation. This rate is used to calculate the inflation-adjusted discount rate for energy, i″, where

$$i'' = (i - je)/(1 + je) .$$

The discounted payback is the time required for the initial investment to equal the future energy savings. This relationship is represented by

$$\text{Initial Cost} = N * \text{Yearly Energy Savings} * \frac{[CRF,i',N]}{[CRF,i'',N]} ,$$

where N = years, CRF = the capital recovery factor, and $CRF(i,N) = i/[1 - (1 + i)^{-N}]$.

The retrofit costs assumed in the economic evaluation are listed below. They are based on figures provided by the State of Colorado Weatherization Office.

Heat waste	$200
Storms	$450
Belly blow	$400
Roof blow	$420
Furnace tune-up	$112

The discounted and simple paybacks for the retrofits are presented for each of the five locations in Figures 4.4 through 4.8.

The particular values for i, j, and je are those recommended by Kreider (1982). The calculated time for payback is somewhat sensitive to the values chosen, and there is no consensus as to what values are correct. However, the particular values of i, j, and je do not have any influence on the relative paybacks among the various weatherization measures.

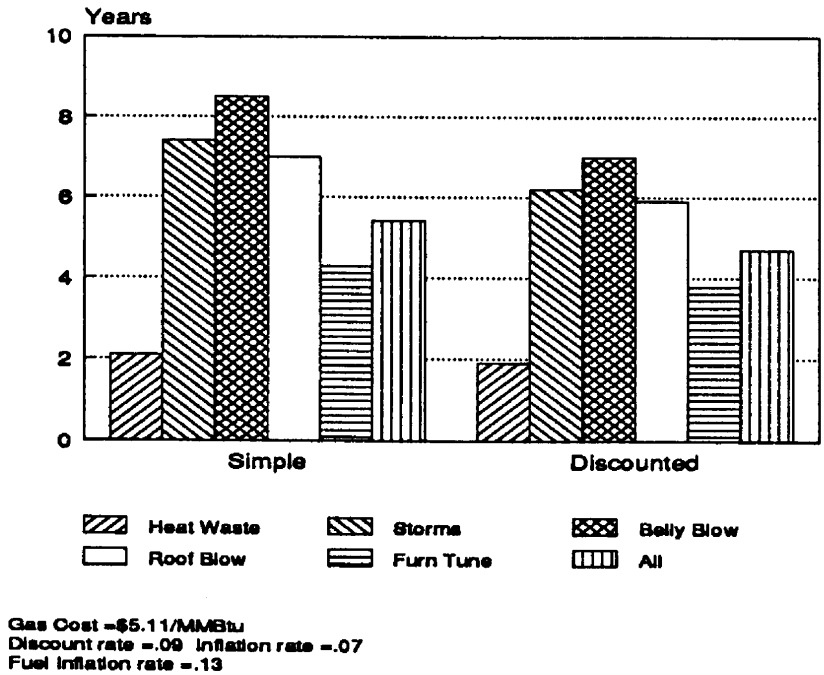


Figure 4.4. Mobile Home #1: Retrofit Payback, Denver

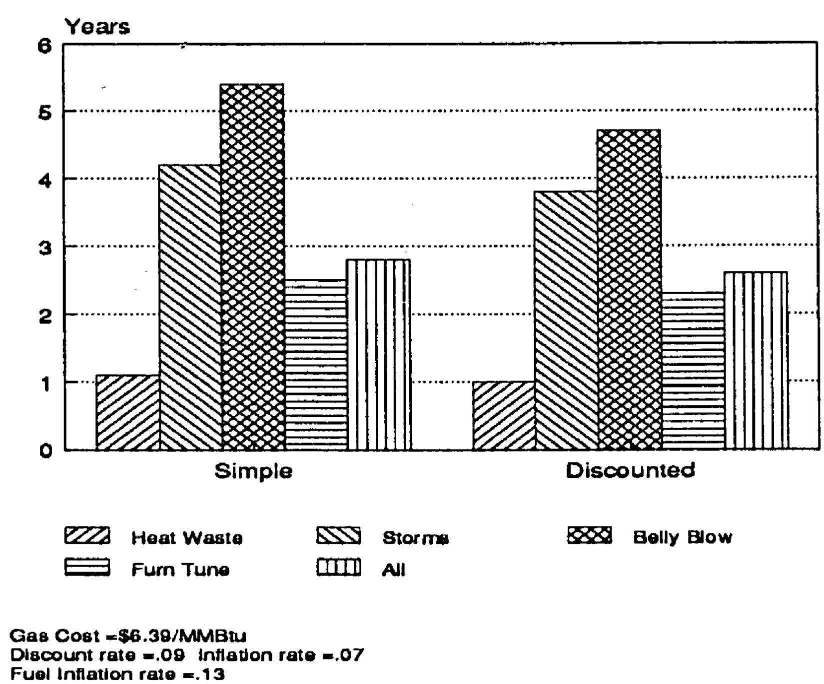


Figure 4.5. Mobile Home #1: Retrofit Payback, Madison

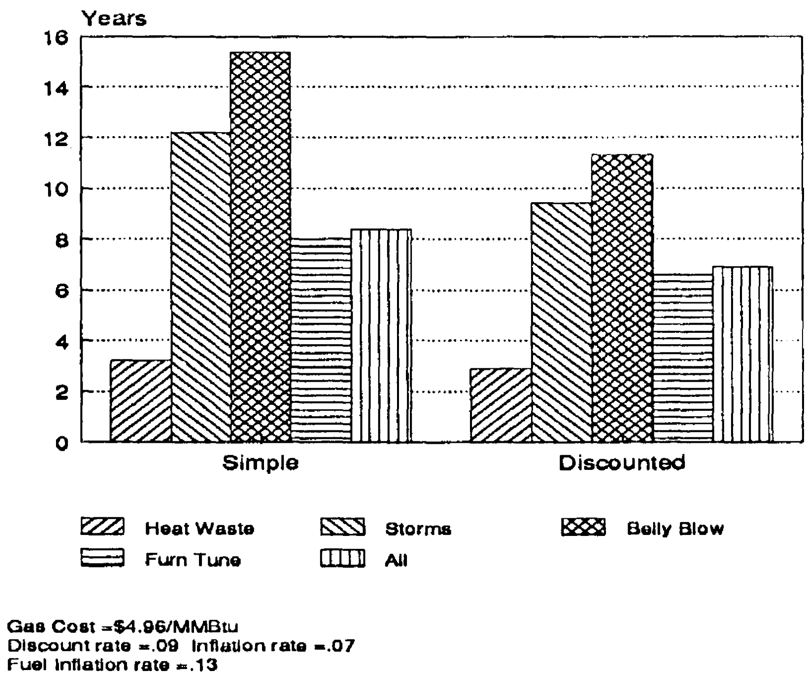


Figure 4.6. Mobile Home #1: Retrofit Payback, Memphis

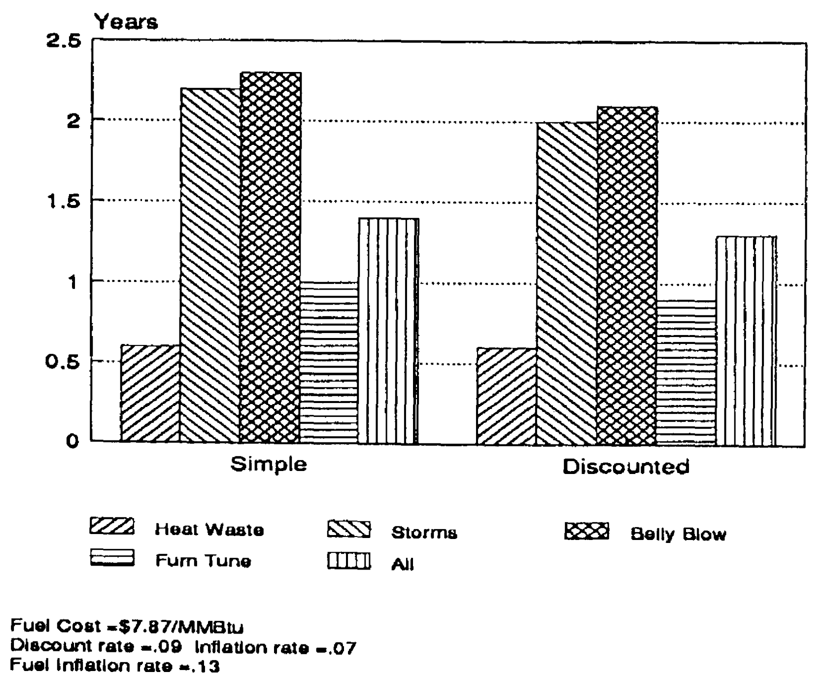


Figure 4.7. Mobile Home #1: Retrofit Payback, Fairbanks

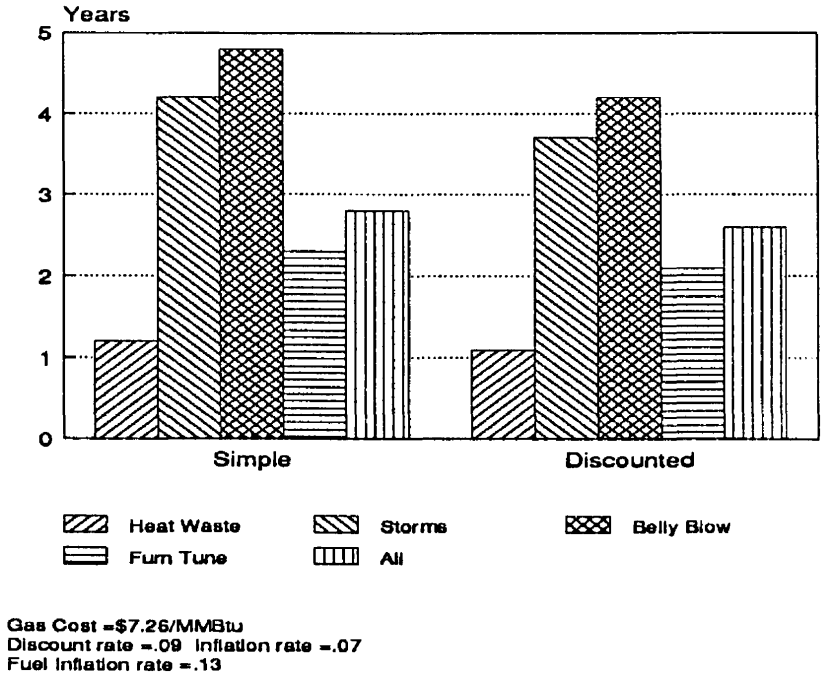


Figure 4.8. Mobile Home #1: Retrofit Payback, Concord

5.0 MOBILE HOME RETROFIT ANALYSIS TOOL

5.1 Description

The retrofit energy savings predicted by the SUNCODE analysis are valid for mobile homes that have initial conditions identical to those of mobile home #1. To provide an analysis technique for mobile homes with different initial conditions, the Mobile Home Retrofit Analysis Tool was developed.

The tool helps the user to determine the mobile home load coefficient from audit data. The computer tool is designed to be used by state weatherization personnel or individual auditors. The analysis is based on a particular mobile home's dimensions, construction materials, and location. The program output is retrofit energy savings and payback periods.

The aim of the Mobile Home Retrofit Analysis Tool is to couple the calculation power of a personal computer with the knowledge of experienced mobile home auditors. The program combines conventional programming techniques with innovative expert system programming methods. Expert system programming is quite different from conventional programming. Conventional programs involve the processing of data by algorithms. Expert system programs are based on processing logical statements. Experts' rules of thumb are encoded into the program. These rules are accessed during the program execution and are used to help an inexperienced person solve a complicated problem.

In the case of the Mobile Home Retrofit Analysis Tool, the lessons learned from the mobile home study and some rules of experienced auditors are contained in the program. This built-in guidance helps the user to input accurate audit data. The program also provides helpful hints for the successful implementation of recommended retrofits. Currently, the program serves to demonstrate the capabilities of a knowledge-based mobile home audit tool. Further development needs to be completed before the program can have widespread use.

The program comprises four major components, each addressing different aspects of mobile home retrofit analysis. These four sections are (1) a presentation of the mobile home weatherization research conducted at SERI, (2) a mobile home audit analysis, (3) an evaluation of the energy savings of six mobile home retrofits, and (4) an economic evaluation of the six retrofits. A brief description of each program component is given below.

The weatherization research conducted at SERI is presented in the program to provide background information to the user. The research results are the basis for the analysis used in the program to predict expected retrofit energy savings. Described in the program are SERI's mobile home weatherization test procedures, the results of the tests, and a discussion of the mobile home retrofit workshop held at the testing facility.

The mobile home audit analysis guides the user in the thermal characterization of the mobile home. The goal of the audit is to deterimine the BLC for the mobile home in its present condition. The program requires the user to enter structural and material data into the computer. The data may be typed in or selected from a menu of possible responses. Based on the data and accepted methods of calculating heat transfer coefficients, the conduction component of the BLC is determined. The infiltration component of the load coefficient is determined from a one-point blower door measurement. An average natural infiltration rate is calculated from air changes per hour measured at 50 pa and a location-dependent factor (Meier 1986).

To evaluate the retrofit energy savings, the heating load is calculated for the mobile home in a specified location. Although the calculation could be performed using SUNCODE or other simulation programs, the program uses a simplified load model. A simulation program was not used to perform the calculation because it would take too long to run. The simple model adapted from Mitchell (1983) provides results instantaneously to the audit tool. The results from the simple model are comparable to those predicted by SUNCODE. Comparison results are provided in Section 5.2.

The program evaluates the six mobile home retrofits: general heat waste, storm windows, insulation wrapped around the belly, insulation blown into the belly cavity, insulation blown into the roof cavity, and furnace tune-up. The evaluation is performed by determining the heating energy use of the mobile home before and after retrofit implementation.

The economic evaluation section of the program translates the energy savings anticipated by the retrofit analysis into dollar savings. Based on default or user-specified cost data and economic factors, the simple payback and discounted payback are presented for each retrofit.

Currently, the program can determine retrofit savings for mobile homes in four different locations. In order for the tool to analyze other locations, more weather data files must be made. Because the temperature data used in the simple model are monthly averaged values, it is feasible to have many locations available for analysis.

5.2 The Mobile Home Tool's Analysis Method

5.2.1 Mobile Home Load Coefficient

The mobile home tool uses accepted analysis methods to determine the BLC. The methods outlined by ASHRAE and described in Section 4.0 were used to determine the conduction component of the BLC. To determine the infiltration component, the results of a one-time blower door pressurization test are used. The method is a refinement of Persily's 1982 infiltration research in which natural air changes per hour were found by dividing the air changes at 50 pa by 20. Refinements to Persily's method were made by Sherman to customize the formula to include factors correcting for different climate conditions, stack effects, wind shielding, and crack characteristics (Meier 1986). The factor values are derived from the most commonly accepted infiltration model used for estimating infiltration rates (Sherman and Modera 1986).

5.2.2 Mobile Home Heating Energy Load

The simple load model used to determine the mobile home's heating energy load is a steady-state heat loss analysis based on variable degree days. This method is described by Mitchell (1983). In the method the building's energy loss is determined from the BLC and monthly heating degree days at a particular base temperature. A sample calculation using the simple load model is given in Table 5.1. The values listed are based on mobile home #1 in its initial condition located in Denver.

As shown in the table, the simple model predicts a yearly load of 62.4 million Btu for the mobile home. The SUNCODE detailed simulation determined the load to be 67.0 million Btu. As can be seen, the absolute load values from the two methods are quite close. The more important comparison is the measured effect that retrofits have on the load. The simple model predicts a load decrease of 35.7 million Btu if all weatherization measures are implemented. SUNCODE sets this value at 34.6 million Btu.

The simple model results were compared to SUNCODE results for other locations. Table 5.2 lists the locations and their respective loads. For Madison and Memphis the final weatherization condition is after the general heat waste, storms, and belly blow retrofits have been implemented. For Denver, the final weatherization condition is after the general heat waste, storms, belly blow, and roof blow retrofits have been implemented.

Although the simple model does appear to underestimate the heating load for sunny climates, overall it comes very close to matching the SUNCODE load. The simple model does succeed in accurately determining energy savings from retrofit implementation. Therefore, the simple load model appears to be an acceptable, abbreviated calculation method for determining retrofit energy savings in mobile homes for the climates studied to date.

Table 5.1 Simple Model Calculation

Parameter	Units	Name	Value											
Temperature Data														
Room temperature	°F	Ted	69											
Shell UA Data														
Conduction UA	Btu/h °F	UAshell	399.0											
Infiltration UA	Btu/h °F	UAinf	141.0											
Total UA	Btu/h °F	UAtotal	540.0											
Annual Heat Loss Calculation			**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
days in month		days	31	28	31	30	31	30	31	31	30	31	30	31
monthly avg temp	°F	Tm	29.0	30.9	38.4	48.8	57.3	64.7	72.8	70.1	62.3	49.1	38.3	30.7
UA shell Inf	Btu/h °F	UAt	540	540	540	540	540	540	540	540	540	540	540	540
daylength	h	hda	9	11	12	13	14	15	15	14	12	11	10	9
Windows	**area**						**Insolation through Window (Btu/ft² day)**							
SW	45		884	851	919	835	813	799	791	835	950	979	809	840
SE	22		848	844	1035	946	914	868	916	926	998	1000	835	800
NW	22		161	247	412	535	659	719	662	566	443	291	186	139
NE	45		157	241	429	578	720	762	741	599	452	289	184	136
total window gain	Btu/day	Gwd	69023	73155	92442	96171	103610	105175	103629	97346	94784	85437	67141	74579
	Btu/h	Gwh	7343	6574	5899	5269	4861	4664	4728	5075	5612	6332	7116	7502
internal gain	Btu/h	GI	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400
net day gain	Btu/h	Gtd	9743	8974	8299	7669	7261	7064	7128	7475	8012	8732	9516	9902
net night gain	Btu/h	Gtn	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400
b. temp day	°F	Tbd	51	52	54	55	56	56	56	55	54	53	51	51
b. temp night	°F	Tbn	65	65	65	65	65	65	65	65	65	65	65	65
Degree day calculations														
		std dev	21.2	19.8	19.5	17.2	15.9	14.3	13.0	13.5	14.7	17.5	19.2	20.9
		Hd	1.034	1.083	0.782	0.348	-0.110	-0.614	-1.307	-1.106	-0.552	0.214	0.682	0.955
		Hn	1.675	1.697	1.344	0.915	0.456	-0.010	-0.634	-0.410	0.153	0.885	1.370	1.619
		Fd	0.003	0.002	0.008	0.056	0.249	0.632	1.307	1.107	0.575	0.096	0.013	0.004
		Fn	0.000	0.000	0.001	0.005	0.036	0.196	0.650	0.454	0.120	0.005	0.001	0.000
		DDbd	682	603	477	209	69	8	0	1	10	168	400	621
		DDbn	1102	942	811	475	243	80	7	18	121	482	788	1050
Monthly Heat Loss														
day		Qd	3.46	3.42	3.01	1.48	0.53	0.06	0.00	0.01	0.07	0.99	2.09	3.09
night		Qn	8.69	6.87	5.39	2.80	1.28	0.40	0.03	0.10	0.76	3.41	6.08	8.39
total		Qtot	12.15	10.29	8.40	4.27	1.81	0.46	0.04	0.11	0.83	4.40	8.18	11.48
		Qtotyear	62.4											

Table 5.2 Simple Model versus SUNCODE Analysis

Load (million Btu)	Denver	Madison	Memphis
Initial			
Simple	62.4	93.7	37.5
SUNCODE	67.0	94.4	38.6
Final			
Simple	27.8	57.6	21.4
SUNCODE	31.3	58.5	22.7
Delta			
Simple	34.6	36.1	16.1
SUNCODE	35.7	35.9	17.2

6.0 CONCLUSIONS

Over the past two winters we tested a number of weatherization measures, including the following:

- blower-door-directed air sealing and duct repair
- furnace tune-ups
- interior storm panels
- window repairs and replacements
- belly blow (fiberglass and cellulose)
- belly wrap
- skirting
- roof blow (fiberglass and cellulose)
- roof cap
- wall insulation.

In general for colder climates we find the most cost-effective measures to be blower-door-directed air sealing and duct repair, furnace tune-up, interior storm panels, belly blow, and roof blow. The roof blow may result in moisture damage if used in humid climates, and it should probably be studied further before it is widely applied.

The blower door has shown itself to be an essential tool in the weatherization of mobile homes. Not only does it help crews tighten the units more effectively, but it also prevents overtightening, which can be especially dangerous in low-volume buildings.

Our tests to date have shown skirting, insulated skirting, and roof caps to be less cost-effective. However, more research needs to be done on those measures. Our research also indicates that window and door replacements should only be used when repair would be more expensive than replacement. Even for jalousie and awning windows, money is better spent on interior storm panels than on window replacement.

Finally, the research indicates that cost-effective energy savings are possible if we apply weatherization measures adapted to the unique construction details in mobile homes.

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APPENDIX A

AUDIT SUMMARY — MOBILE HOMES #1, #2, #3

	Champion #1	Central #2	Detroiter #3
Dimensions - Interior			
length (ft)	56.6	49	61
width (ft)	11.2	13.5	13
height (ft)	7.5	7	7.5
floor area (ft^2)	624	662	793
volume (ft^3)	4753	4590	5948
window area (ft^2)	129	64	70
opaque wall area (ft^2)	877	811	1060
floor wing area (ft^2)	250	282	293
floor pan area (ft^2)	374	385	500
Wall Section			
interior material	1/4" paneling	1/4" paneling	1/4" paneling
studs	2×3 16"OC	2×2 16"OC	2×2 16"OC
cavity	2.5"	1.5"	1.5"
insulation	2.5" batt	1.5" batt	1.5" batt
lath	1×2 24"OC	1×2 24"OC	1×2 24"OC
exterior material	metal siding	metal siding	metal siding
Floor Section			
interior floor 1	1/2" carpet 1/2" foam rubber	3/4" carpet 1/2" foam rubber	1/4" carpet 1/2" foam rubber
interior floor 2	1/4" carpet linoleum	1/2" carpet linoleum	1/4" carpet linoleum
subfloor	5/8" particleboard	1/2" particleboard	1/2" particleboard
joists	2×5 20"OC	2×5 16"OC	2×6 20"OC
pan cavity	10"	13"	10"
wing cavity	4.5"	4.5"	5.5"
insulation	1.5" batt	1.5" batt	2" batt
exterior material	1/16" rodent barrier	1/16" rodent barrier	1/16" rodent barrier
Roof Section			
interior material	1/2" mineral board 6 mil polyethylene	1/2" mineral board 6 mil polyethylene	1/2" mineral board 6 mil polyethylene
truss	bowstring 16"OC	solid 16"OC	bowstring 20"OC
cavity depth	3.5" avg	5.5" avg	7" avg
insulation	1" batt	1.5" batt	1.5" batt
exterior material	galvanized metal	galvanized metal	galvanized metal

APPENDIX B

THE WEATHERIZATION MEASURES

The weatherization techniques described here are those we observed being used by Region VIII weatherization personnel and subcontractors, and those that were taught at the National Training Workshop conducted by SERI and the Colorado Division of Housing in April 1989. 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 SERI 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 different methods. The primary purpose of this section is to describe what was done to weatherize the mobile homes tested during the project and what was taught at the weatherization training workshop.

Blower-Door-Directed General Heat Waste

Plumbing and Electrical Penetrations

These penetrations 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.-O.D. or smaller pipe. Much larger openings were sometimes found where sloppy plumbing or electrical repairs had been made. Weatherization consisted of plugging these openings with expanding foam, silicone with backerod, 6-mil polyethylene sheet and construction adhesive, or insulating aluminized foil and silicone.

Furnace Closet and Heating System

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, or silicone. The combustion air duct penetration was sealed with silicone, open-cell foam, sheet metal, 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. Also, with these repairs care should be taken to respect furnace and flue clearances, to use sealing materials with proper fire retardancy ratings, and to inspect for appliance backdrafting and spillage.

Most mobile home furnaces use a register in the furnace closet door as the cold air return. In some mobile homes a separate return air system was found between the floor and the rodent barrier. Such systems are extremely leaky and unnecessary because of the small volume of single-wide units. Weatherization consisted of sealing the return air floor registers and the return air chase at the base of the furnace. A large register was then installed in the furnace closet door to accommodate the cold air return. Finally, a clearance of about 1 to 1½ in. was assured between the top of the floor or carpet and the bottom of interior doors by trimming the door bottom if necessary.

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. They are also usually poorly fitted to the opening in the subfloor, allowing leakage between the belly and the living space. 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 aluminum tape, silicone, or expanding foam. Access to these leaks is sometimes difficult. However, a blower door can help to isolate duct leak locations by successively sealing off sections of duct with temporary air blocks inserted through the floor registers. semi-rigid tape measure inserted in the end registers can identify holes at the duct ends.

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 underfloor 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 underfloor space and then to the outside environment. Thus the overall efficiency of the heating distribution system is decreased.

Gas Water Heater Closet

In most of the mobile homes in our study the gas water heater was 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 or under-tub areas. Where possible, these points were best sealed with 1/8-in. hardboard and silicone. For less accessible areas, 6-mil polyethylene sheet or insulating aluminized foil and construction adhesive sometimes worked. For smaller penetrations, expanding foam or silicone and backerod were effective. Others have tried stuffing large openings with batt insulation, then sealing them off with an insulating foil membrane. Generally, the approach should be to air seal between the closet and the living space, and to insulate wherever possible including the common wall, the outside wall, and the door of the closet. Make sure adequate combustion air is available from outside.

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 carbon monoxide, backdrafting, and spillage.

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.

Evaporative Cooler

Many mobile homes have rooftop evaporative coolers, sometimes called swamp coolers. The cooler chase is a major source of air leakage. Cooler covers made of reinforced vinyl and fastened with screw clips are commercially available. However, an easier, less expensive, and more effective method is to use a commercially available interior plastic cover on the chase itself. These are easily accessible on the ceiling, allowing the occupant the option of removing the cover in summer without having to climb on the roof.

Windows, Repairs, Replacements and Interior Storm Panels

Most older mobile homes have some air leakage from the windows. The mobile homes in our study frequently had awning or jalousie 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 malfunctioning of the operator mechanism, rendering tight closure impossible. The second most common problem was degradation of the seals between panes. Additionally, cracked, broken, and missing panes were frequently found. Occasionally, cable TV lines, antennae wire, and antifreeze tapes were routed through the windows, preventing tight closure of the assembly.

There are several ways to weatherize windows. The general approach should be to minimize expenditures on the primary windows in order to preserve budget for installation of interior storm panels. Replacement windows should only be used when the cost of repair would exceed the cost of replacement. This is because primary windows do not reduce the air leakage path through ventilated walls into the window frames. Inexpensive repairs to primary windows included ludwig clips, operating mechanisms, and pane replacement. Damaged seals at awning and jalousie pane edges were repaired or replaced with weatherstripping. TV lines and antennae wires were rerouted through the floor or wall. Cracks between the window trim and interior wall were sealed with siliconized acrylic caulk.

Storm windows reduce energy consumption by reducing infiltration and by reducing conduction losses. Several vinyl interior storm panel systems are available commercially, which can reduce the installed cost to about $1.50/ft^2. The durability of these systems should be further investigated, but reports from the field indicate that some vinyl systems have not significantly degraded after as long as five years. Conventional glass interior panels at $3.00-$4.50/ft^2 are still cost-effective in many cold climates.

Doors

Doors were not usually major sources of air leakage in these mobile homes. For those doors that 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 weatherstripping on a flange that 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 for mobile home doors were:

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

Kitchen Vent Fans

When in proper working condition, the vent dampers provide 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 can be corrected by replacing the seals.

Rodent Barrier

Rodent barriers are commonly constructed of relatively fragile fiberboard-type materials. Holes and loose seams in the rodent barrier allow additional infiltration through the floor and unwanted cold air circulation around the heating distribution ducts. This air flow also short circuits whatever insulation may be in the underfloor area. Openings in the rodent barrier were sealed with insulating aluminized foil, silicone adhesive, and stitch staples.

Exterior Walls

Exterior walls of a mobile home tend to be vented because of the vertical ridges in the aluminum 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 leak source was found with the blower door, these sites were not sealed. These cracks should not be sealed from the exterior because of the potential for moisture buildup in the walls. A certain amount of diffuse air leakage is beneficial to meet ASHRAE minimum fresh air standards. The blower door is essential to prevent overtightening.

Belly Insulation

Most methods involve blowing loose fill insulation in the cavity between the rodent barrier and the floor. An alternative method called a belly wrap was also tested in this project. A contractor, Sunpower, installed 6 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. O.C. Wires were secured to the nails and pulled tight across the width of the unit. The grid hangs 6 to 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 to 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 some minor thermal advantages over blown-in insulation. However, problems with the durability of such installations have been observed in the field, especially when the units are moved.

Roof Blow

On average, blowing the bow-string truss area full of insulation will save about 12% of the heating bill. However, more research is needed to determine if this retrofit may eventually cause moisture damage to the ceiling from condensation in humid climates. This measure has been successfully applied with no long-term problems in arid areas like Colorado.

Insulation can be blown into the bow-string truss area from either inside or outside the home. For the interior application, holes must be drilled neatly to accommodate plastic filler plugs. Holes are drilled in each truss cavity either down the center or at the "third" points, depending on the characteristics of the blowing equipment and the fill material. The goal is to get a complete fill out to the perimeter. A fill tube can help achieve a uniform fill to the perimeter. An occasional hole drilled at the perimeter in a closet or cabinet can be used to check that insulation is reaching the perimeter. Insulation should be directed away from furnace flues and other potential fire hazards. This can be done by drilling extra holes close to the flue and blowing in the direction away from the flue on each side of it. When carefully done, the finished job is hardly noticeable from the inside. Both chopped fiberglass and cellulose are commonly used for roof blow applications. Cellulose is generally easier to blow than fiberglass. However, cellulose is heavier than fiberglass and will absorb more water than fiberglass if exposed to moisture.

For an exterior roof blow, holes are cut in the roof over the roof trusses at the peak so that only a minimum number of holes are needed, and drainage is away from the holes. The roof is then filled in the usual manner, and special care is taken around the furnace and hot water flues to allow adequate clearance. A jointed fill tube will minimize the number of holes that must be cut in the roof for a uniform fill. Batt material can be used to "dam" a clearance area around flues before blowing starts. Careful watertight repair of the holes is crucial. First, a square of galvanized sheet metal is beaded with roofing caulk and secured to the roof with a tight pattern of self-tapping screws. Then the patch is covered with high-quality roofing compound. Reinforcing mesh is placed over the patch and covered with a second coat of roofing compound. When properly applied, the patches will be leakproof for the life of the roof.

Furnace Efficiency Improvements

The furnace efficiency procedures suggested here are fairly simple. However, they should not be attempted by untrained personnel because of the potential health hazards associated with an improperly operating furnace. Mobile home furnaces are commonly fueled by gas, propane, oil, or electricity, and should always be of the sealed combustion type for safety. The procedures emphasize increasing efficiency on the air delivery side of the furnace, and simple safety checks with respect to furnace combustion and exhaust. A 5-min heat rise test is conducted by measuring temperatures at the return air intake and the closest heating register. The temperature difference, fan-on temperature, and fan-off temperature help diagnose potential problems. For example, excessive heat rise usually indicates insufficient air flow because of a dirty or faulty blower, a clogged filter, duct blockage, or an oversized fuel jet. Low heat rise usually indicates a clogged fuel line, faulty gas valve, duct leaks, or undersized fuel orifice. Service procedures consist of cleaning out duct blockages, repairing duct leaks, cleaning the blower, replacing the filter, replacing or adjusting fan on and off switches, and adjusting the thermostat anticipator. All furnace work should include basic safety checks for carbon monoxide, spillage, backdrafting, flame color, and cracked heat exchangers.

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15. Supplementary Notes

16. Abstract (Limit: 200 words) For several years the Solar Energy Research Institute has been testing the effectiveness of mobile home weatherization measures, with the support of the U.S. DOE Office of State and Local Assistance Programs Weatherization Assistance Program, the DOE Office of Buildings and Community Systems, the seven states within the federal Weatherization Region VII, the Colorado Division of Housing, and the DOE Denver Support Office. During the winter of 1988-89, several weatherization measures were thermally tested on three mobile homes under controlled conditions inside a large environmental enclosure. The effects of each weatherization measure on conduction losses, infiltration losses, and combined furnace and duct-delivered heat efficiency were monitored. The retrofit options included air sealing, duct repair, furnace tune-up, interior storm panels, floor insulation, and roof insulation. The study demonstrated that cost-effective heating energy savings of about 20% to 50% are possible if weatherization techniques adapted to the special construction details in mobile homes are applied.

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