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The National Fuel End-Use Efficiency Field Test: Energy Savings and Performance of an Improved Energy Conservation Measure Selection Technique

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LIST OF ACRONYMS

Alliance	Alliance to Save Energy
BCR	Benefit-to-cost ratio
ECM	Energy conservation measure
ID	Identification
LIHEAP	Low-Income Heating Energy Assistance Program
NF	National Fuel Gas Distribution Corporation
NPV	Net present value
NYSDPS	New York State Department of Public Service
ORNL	Oak Ridge National Laboratory
SAS	Statistical Analysis Software
TMY	Typical Meteorological Year
WECC	Wisconsin Energy Conservation Corporation

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ABSTRACT

The performance of an advanced residential energy conservation measure (ECM) selection technique was tested in Buffalo, New York, to verify the energy savings and program improvements achieved from use of the technique in conservation programs and provide input into determining whether utility investments in residential gas end-use conservation are cost effective. The technique analyzes a house to identify all ECMs that are cost effective in the building envelope, space-heating system, and water-heating system. The benefit-to-cost ratio (BCR) for each ECM is determined and cost-effective ECMs (BCR > 1.0) are selected once interactions between ECMs are taken into account.

Eighty-nine houses with the following characteristics were monitored for the duration of the field test: occupants were low-income, houses were single-family detached houses but not mobile homes, and primary space- and water-heating systems were gas-fired. Forty-five houses received a mix of ECMs as selected by the measure selection technique (audit houses) and 44 served as a control group. Pre-weatherization data were collected from January to April 1988 and post-weatherization data were collected from December 1988 to April 1989. Space- and water-heating gas consumption and indoor temperature were monitored weekly during tbe two winters. A house energy consumption model and regression analysis were employed to normalize the space-heating energy savings to average outdoor temperature conditions and a 68°F indoor temperature. Space and water-heating energy savings for the audit houses were adjusted by the savings for the control houses.

The average savings of 257 therms/year for the audit houses was 17% of the average pre-weatherization house gas consumption and 78% of that predicted. Average space-heating energy savings was 252 therms/year (25% of pre-weatherization space-heating energy consumption and 85% of the predicted value) and average water-heating savings was 5 therms/year (2% of pre-weatherization water-heating energy consumption and 17% of predicted). The overall BCR for the ECMs was 1.24 using the same assumptions followed in the selection technique: no administration cost, residential fuel costs, real discount rate of 0.05, and no fuel escalation. A weatherization program would be cost effective at an administration cost less than $335/house. On average, the indoor temperature increased in the audit houses by 0.5 °F following weatherization and decreased in the control houses by 0.1 °F.

The following conclusions regarding the measure selection technique were drawn from the study: (1) a significant cost-effective level of energy savings resulted, (2) space-heating energy savings and total installation costs were predicted with reasonable accuracy, indicating that the technique's recommendations are justified, (3) effectiveness improved from earlier versions and can continue to be improved, and (4) a wider variety of ECMs were installed compared to most weatherization programs. An additional conclusion of the study was that a significant indoor temperature take-back effect had not occurred.

EXECUTIVE SUMMARY

The performance of an advanced residential energy conservation measure (ECM) selection technique was tested in Buffalo, New York, to verify the energy savings and program improvements achieved from use of the technique in conservation programs. The technique was also tested Co provide input into determining whether utility investments in residential gas end-use conservation are cost effective.

The technique is a commercially available, proprietary audit program and runs on a personal computer. The technique focuses on reducing space- and water-heating energy consumption. Under the technique, each house is analyzed individually to identify all ECMs that are cost effective in the building envelope, space-heating system, and water-heating system. Information on each house is collected through house surveys, discussions with the occupants, examinations of previous billing data, and diagnostic testing (measuring house air-leakage rates using a blower door and space-heating system efficiencies through a flue gas analysis). The benefit-to-cost ratio (BCR) for each ECM is determined using this information and other economic data, allowing the cost-effective ECMs (BCR > 1.0) to be selected once interactions between ECMs are taken into account. Because cost-effective ECMs are selected uniquely for each house, inefficient houses that can benefit most from weatherization receive more ECMs and greater amounts of money are spent on them.

Eighty-nine houses were monitored for the duration of the field test: 45 houses received a mix of ECMs as selected by the measure selection technique (audit houses) and 44 served as a control group. Pre-weatherization data were collected for all houses during one winter season (January to April 1988). ECMs were installed in the audit houses between August and November 1988. Post-weatherization data were collected for all houses during the following winter season (December 1988 to April 1989).

Houses included in the field test were limited to those meeting selected characteristics to meet the basic objectives of the field test. Important characteristics were that:

1. occupants were low-income, defined as being eligible for the Low-Income Home Energy Assistance Program administered by the state;

2. houses were single-family detached houses but not mobile homes;

3. primary heating systems were either gas-fired furnaces or hot water boilers;

4. secondary fuels (such as wood or kerosene) were not used to substantially heat a house (use of supplemental fuel in each house up to a half day per week or in the bathroom was acceptable); and

5. domestic water was heated by natural gas.

The following time-dependent data were manually collected weekly for all houses during the two winter test periods: house gas consumption, house electricity consumption, space-heating gas consumption, and domestic water-heating gas consumption. Hourly indoor temperatures were monitored in each house and hourly outdoor temperatures were monitored at three sites near the houses. Time-independent information collected or measured during the field test included: house and occupant descriptive information, house air-leakage rates, steady-state space heating-system efficiencies, and ECMs actually installed in the houses and their costs.

Houses used in the field test ranged between 15 and 90 years old, with their average age being 47 years. Almost all houses had a concrete block basement and most had two floors built above. The non-basement floor area of the houses (which, in most, was the main living area) averaged 1305 ft^2, with 70% of the houses being between 1000 and 1600 ft^2. Total floor area (which includes the basement) ranged from 866 to 3424 ft^2 and averaged 2082 ft^2. Eighty-seven percent of the houses had furnaces and the remaining had boilers. The average age of the furnaces was 19 years while the boilers were slightly older. The initial thermal condition for many houses was poor for the Buffalo area. Ninety percent of the houses had no foundation insulation, 62% had no exterior wall cavity insulation, and 18% had no attic insulation.

Eleven different ECMs were installed in at least one of the audit houses. Three water-heating system measures (pipe insulation, insulating blanket, and temperature reduction), infiltration reduction, and attic, wall, and sill box insulation were frequently performed. Space-heating system tune-ups were routinely performed to ensure that the systems were operating safely and to avoid any liability issues, although energy savings were still expected. Floor insulation, foundation insulation, and space-heating system replacement were measures infrequently performed. Eight measures considered by the audit were never installed: storm windows, intermittent ignition device, heating system thermal vent damper, heating system electric vent damper, gas power burner, outdoor temperature reset control, continuous circulation pump, and water heater thermal vent damper. Had a clock thermostat with a 5°F setback been an option, it would have been selected in only one house.

Infiltration reduction was performed before the installation of other ECMs following a blower-door-guided infiltration reduction procedure. This procedure was designed to increase energy savings at reduced costs by using a blower door to locate major house leaks and to determine when infiltration work was no longer cost effective. The infiltration procedure was applied to all audit houses, but sealing work was not performed in 14% of the houses because the air-leakage rate was already below minimum guidelines (1500-1800 cfm50) . By requiring infiltration reduction work to be performed at a BCR of 2.0, expenditures were limited to an average of $73/house (excluding a $70/house set up cost). Greater expenditures and reductions would result if the BCR for the work was lowered.

ECMs could not always be installed in houses as recommended. This did not have a serious impact on installation costs or other ECMs selected because the ECMs not installed were usually inexpensive and small energy savers. Auditing errors and the manner in which infiltration reduction is included in the selection technique contributed to this problem.

The amount of money spent on each house averaged $1453 ($1387 for 32 houses used to determine the BCR of the measures and weatherization program) but varied over a large range: less than $500 per house was spent in five houses and more than $2000 per house was spent in 11 houses. Expenditures were predominately for wall and attic insulation: an average of $750 and $400, respectively, was spent in each house for these measures, while less than $75 was spent (on average) on each of the remaining measures. The average cost for performing the ECMs in the houses was estimated quite reliably by the selection technique (within 2%), but individual house estimates varied more widely.

The measured space-heating energy savings in this study were normalized to average annual outdoor temperature conditions and a standard house indoor temperature (68°F for all houses before and after weatherization). Normalized energy savings were found by subtracting post-weatherization consumption from the pre-weatherization consumption. The following house energy consumption model and regression analysis were employed to estimate normalized annual space-heating energy consumptions from the pre- and post-weatherization data:

$$EC = A + (B * DT) ,$$

where

EC — energy consumption of the space-heating system,
DT - indoor minus outdoor temperature difference,
A - intercept coefficient (determined by regression), and
B - slope coefficient (determined by regression).

The normalized energy savings for the audit houses were adjusted by the normalized energy savings for the control houses to account for factors affecting the space-heating energy consumptions that could not be considered directly.

Water-heating efficiency measures provide energy savings year-round. To determine the annual energy consumption of the water-heating system before and after weatherization, an average weekly energy consumption was determined using water-heating energy consumption data collected from January through April for each period and multiplied by 52. Energy savings were found by subtracting post-weatherization consumption from pre-weatherization consumption. As with the space-heating energy savings, the water-heating savings of the control houses were used to adjust the savings of the audit houses. The analysis of water-heating energy savings was limited because neither seasonality nor hot water consumption were taken into account.

The average space-heating energy consumption of the control houses increased 61 therms/year, about 7% of pre-weatherization space-heating energy consumption (902 therms/year). Average water-heating energy consumption decreased 12 therms/year to 278 therms/year. A reason for the increase in space-heating system energy consumption is not known, especially considering that the energy consumptions were normalized to constant indoor temperature.

Adjusted and predicted savings for the audit houses are summarized in Table ES.1. The average adjusted savings was 257 therms/year: 252 therms/year from space-heating energy savings and 5 therms/year from water-heating energy savings. Adjusted space-heating energy savings was 25% of the average pre-weatherization space-heating energy consumption (1022 therms/year), adjusted water-heating energy savings was 2% of the average pre-weatherization water-heating energy consumption (272 therms/year), and the total adjusted savings was 17% of the average pre-weatherization house gas consumption.

Table ES.1. Summary of adjusted savings for the audit houses

	Annual pre-weatherization energy use (therms/year)	Annual energy savings (therms/year)		Percent savings	Percent of predicted
		Adjusted	Predicted		
Space-heating	1022	252	298	25%	85%
Water-heating	272	5	30	2%	17%
Other gas use	182				
Total	1476	257	328	17%	78%

The space- and water-heating savings of the individual houses was quite variable. On average, the space-heating energy savings was largest in houses with higher pre-weatherization space-heating energy consumption and that received greater expenditures for ECMs. Adjusted space-heating energy savings ranged from -136 to 1120 therms/year (25% of the houses had positive energy savings less than 100 therms/year and only two houses had negative savings) and adjusted water-heating energy savings ranged from -98 to 172 therms/year. The variability of the individual house energy savings and the relation between savings and expenditures can be largely attributed to the selection technique, which was designed to concentrate ECMs in houses that would most benefit from them.

The total adjusted savings of the audit houses was 78% of that predicted. The adjusted space-heating energy savings was only 46 therms/year below the predicted 298 therms/year, or about 85% of the predicted value. The adjusted water-heating energy savings was 17% of predicted.

The difference between predicted and adjusted space-heating energy savings in individual houses is significant at the 95% confidence level in all but six houses. However, a graphical comparison shows that houses were generally grouped around a line representing equality between adjusted and predicted savings. Agreement between predicted and adjusted savings was especially good for houses in which few ECMs were installed (low predicted savings). If the base temperature of 60°F used in the selection technique to estimate savings of envelope ECMs was lowered to

57°F, the average predicted and adjusted savings would be nearly the same. Inaccuracies in predicting attic insulation savings may also be a source of the observed differences, but a definitive conclusion is hard to reach.

The overall BCR for the ECMs was 1.24 assuming just costs to install the ECMs (no administration costs), residential fuel costs ($0.579/therm), a real discount rate of 0.05, and no fuel escalation (same assumptions as made in the measure selection technique). A weatherization program would be cost effective at an administration cost less than $335/house.

Under this field test, 18.5 therms/year were saved for every $100 spent on ECMs as compared to 15.9 therms/year measured in a previous study in Wisconsin. Although this improvement could certainly be due to differences between the experiments in housing characteristics and climate, improvements made to the technique are also likely contributors (especially limiting recommended ECMs to those with predicted BCRs greater than 1.0).

If envelope and water-heating system ECMs only were to be installed in homes similar to those tested, a simpler selection technique could be devised based on the field test results that could produce near equivalent results. This occurs because the consistency of the housing stock allows patterns to develop regarding correct installations. If space-heating system ECMs are also considered, a simpler technique may not be able to be developed; proper decisions regarding the replacement of the space-heating system can be made only after the energy savings of the ECM are interacted with the savings of other ECMs.

The measure selection technique could be improved to increase accuracy and ease of use by making changes in its design. Implementation of the procedure could also be improved by handling selected ECMs with parallel procedures: low-cost ECMs should be selected using simple criteria, other ECMs should be included in an occupant education program, and infiltration reduction work should be performed independently following the procedure used in the field test.

Average pre- and post-weatherization indoor temperatures were calculated for each house by averaging data collected in the months of January through April. Average pre-weatherization indoor temperatures ranged from about 60°F to 78°F. The average for the control houses was 68.9°F and the average for the audit houses was 68.1°F, a difference that is not statistically significant at a 95% confidence level. In the post-weatherization winter, the indoor temperature increased or decreased in individual audit and control houses by as much as 8°F, although changes were less than 2°F in more than 70% of the houses. On average, the indoor temperature increased in the audit houses by 0.5°F and decreased in the control houses by 0.1°F. However, neither of these changes nor the difference between changes are statistically significant at the 95% confidence level (although the change in the audit houses is significant at a 90% level).

Five main conclusions were drawn from the field test results:

1. Use of a measure selection technique to select unique ECMs for individual houses resulted in a significant cost-effective level of energy savings.

2. The measure selection technique predicted space-heating energy savings and total installation costs with reasonable accuracy, indicating that its recommendations are justified (ECMs were correctly recommended in individual houses and concentration of ECMs in selected houses was justified).

3. The effectiveness of the selection technique improved from earlier versions and can continue to be improved.

4. Use of the measure selection technique resulted in the installation of a wider variety of ECMs than typically installed under most weatherization programs and produced large variations in energy savings and expenditures among houses.

5. Average indoor temperature changes following weatherization were small, indicating that a significant take-back effect had not occurred.

THE NATIONAL FUEL END-USE EFFICIENCY FIELD TEST: ENERGY SAVINGS AND PERFORMANCE OF AN IMPROVED ENERGY CONSERVATION MEASURE SELECTION TECHNIQUE

1. INTRODUCTION

1.1 BACKGROUND

Utilities, state weatherization offices, and regulators face a common question in designing and evaluating residential energy conservation programs: How can energy conservation measures (ECMs) be best selected to reduce energy costs in households participating in the program? Expenditures made under low-income residential weatherization programs may not be as effective as possible (do not result in the greatest energy savings benefit per dollar invested) because:

1. a wide range of technologies that can improve building energy efficiency are not considered,
2. improved methods of performing current ECMs are not followed,
3. program funds are wasted by over-investing in some houses while under-investing in others,
4. ECMs that are not cost effective are installed (a cost-effective ECM is defined as one where the present value of its expected energy savings is greater than the present value of its installation and maintenance cost), and
5. ECMs that provide the greatest energy savings benefit per dollar expenditure are not selected.

New approaches to performing low-income residential conservation programs are needed to overcome the limitations described above and to improve the effectiveness of program expenditures. These new approaches should incorporate the following principles:

1. building-envelope, mechanical-system, and water-heating system ECMs should be given equal consideration;
2. improved methods of performing ECMs, especially regarding infiltration reduction, should be utilized;

3. houses should be analyzed individually to identify the cost-effective ECMs for each particular house; and

4. a systematic decision process for selecting the investment level for each house and the package of cost-effective ECMs to be installed should be followed.

The Oak Ridge National Laboratory (ORNL) developed a selection technique for ECMs (McCold 1987, McCold et al. 1986) based on the four principles outlined above. The technique was tested in the State of Wisconsin's Low-Income Weatherization Assistance Program in 1985 (McCold et al. 1988, Ternes et al. 1988). Results showed that the technique more than doubled the annual energy savings per dollar expenditure of the program as compared with the priority system formerly used in 1982.

1.2 PURPOSE

The National Fuel End-Use Efficiency Field Test was performed in Buffalo, New York, to determine the performance of an ECM selection technique similar to that developed and previously tested by ORNL. Additional testing of the measure selection technique was desired to verify the savings and program improvements previously measured, especially in a different climate and a different housing stock from that found in Wisconsin. Results will further improve methods for conducting weatherization programs and will help identify ECMs that really work. The field test was also performed to put National Fuel (NF) Gas Distribution Corporation in compliance with New York State Department of Public Service (NYSDPS) Commission's Opinion #86-9, Case 29088. This order required NF to develop a Demonstration Energy Conservation Program to determine whether utility investments in gas end-use conservation are cost effective.

The field test was a cooperative effort performed by NF, ORNL, The Alliance to Save Energy (Alliance), NYSDPS, and Wisconsin Energy Conservation Corporation (WECC). Financial support was provided by NF and the U.S. Department of Energy, Office of Buildings Research, Existing Buildings Energy Efficiency Research Program.

The roles of the participating organizations are more thoroughly described in an experimental plan developed for the project (Ternes and Hu 1988). The Alliance and NYSDPS provided managerial support to the project. The Alliance developed the concept plan, disseminated information on the project, and reviewed documents. NYSDPS managed the field test at the state level and ensured that information about the field test was made available to other New York state offices. NF implemented the on-site portion of the project by selecting and auditing houses, installing instrumentation, collecting data, and contracting to install ECMs. ORNL developed the experimental plan, supplied and helped install instrumentation, maintained a data base of all collected data, analyzed the data, and prepared technical reports. WECC prepared a customized version of the measure selection technique and provided technical training.

The purpose of this report is to present information gathered during the field test and results obtained from analysis of this information. The experimental plan (Ternes and Hu 1988) identifies the detailed method of the project.

2. ENERGY CONSERVATION MEASURE SELECTION TECHNIQUE

2.1 INTRODUCTION

The ECM selection technique is based on the principles identified by McCold (1987) and McCold et al. (1986), and is similar to the procedure tested in Wisconsin (McCold et al. 1988, Ternes et al. 1988). The technique focuses on reducing space- and water-heating energy consumption and, thus, is applicable to climates in which houses require significant winter space-heating and little summer space-cooling.

The chief distinction of this technique, as contrasted with a set list of priorities, is that each house is analyzed individually to identify building-envelope, space-heating system, and water-heating system ECMs that are cost effective. Information on each house is collected through house surveys, discussions with the occupants, examinations of previous billing data, and diagnostic testing (measuring house air-leakage rate using a blower door and gas- or oil-fired space-heating system steady-state efficiencies through a flue gas analysis). The benefit-to-cost ratio (BCR) for each possible ECM is determined using this information and other economic data, allowing the cost-effective ECMs to be selected once interactions between ECMs are taken into account.

An additional distinction of the technique is that it includes a systematic decision process to determine investment levels for each house in order to improve the effectiveness of conservation program expenditures by maximizing program energy savings per investment dollar within other program constraints. This is accomplished by selecting for installation only ECMs with BCRs higher than a cutoff value preselected for the conservation program. Under this procedure, houses receive different ECMs and various amounts of money are spent on each house.

The procedure previously tested in Wisconsin was modified by WECC for the State of Wisconsin to improve the accuracy of the energy savings predictions, include additional ECMs (including water-heating system ECMs), include an improved method of performing infiltration reduction work, address additional types of space-heating systems other than gas furnaces, and make it generally easier to use.

2.2 DETAILED DESCRIPTION

Version 2.1 of WECC's measure selection technique (the version used in Wisconsin at the time of the field test) was used in this field test. This version combines the measure selection process with a management system that provides a framework for administration, organization, and reporting. The technique is programmed for use on a personal computer using a standard spreadsheet program. The technique is specifically designed for use in low-income weatherization programs.

Space-heating system ECMs are considered along with building-envelope and water-heating system ECMs in the selection technique. Installation of the following building-envelope ECMs were considered by the technique for this study: wall insulation, attic insulation, infiltration reduction, storm windows, floor insulation, sill box insulation, and interior foundation wall insulation. Space-heating system ECMs included tuning the existing space-heating system, replacing a standing pilot with an intermittent ignition device, installing a thermally-activated vent damper, installing an electrically-activated vent damper, replacing an atmospheric burner with a gas power burner, installing an outdoor temperature reset control, installing a continuous circulation pump, and replacing the existing system with high-efficiency equipment. Water-heating system ECMs included adding an insulation blanket to the water tank, installing a thermally-activated vent damper, insulating hot water pipes, and reducing the hot water temperature.

Options for lowering thermostat settings for the space-heating systems, installing low-flow shower heads, and installing faucet flow restrictors are included in the technique but were not used in the field test. Reasons for not including adjustment of the space-heating system thermostat setting are discussed in Sect. 5.3. The two water-heating system ECMs were not included for programmatic reasons.

The first step in implementing the technique is to collect or measure the following: occupant information, health and safety information, building-envelope data, space- and water-heating system data, the steady-state efficiency of the presently installed gas-fired or oil-fired space-heating systems, the house air-leakage rate or reduction, and previous household fuel consumption data. The space-heating system steady-state efficiency is obtained by performing a flue gas analysis. Depending on when infiltration reduction work is performed, either the current air-leakage rate of the house or the actual air-leakage rate reduction achieved by infiltration reduction work can be used in the technique (see discussion in Sect. 2.3). The current air-leakage rate, defined to be the air flow rate into the house when the house is depressurized 50 Pa below ambient, can be estimated by the auditor or measured using a calibrated blower door. The household fuel consumption records (monthly billing data) are obtained from the local utility company or homeowner; data for approximately one year are preferred. The remaining information is obtained through house surveys and discussions with the occupants.

In the second step, the collected data are input into a personal computer (usually at the office). Additionally, the household fuel consumption records are analyzed to estimate a balance point temperature and a normalized annual space-heating energy consumption for the house.

To calculate these values, the total period of time covered by the billing data and the heating degree days for each monthly billing period, based on a chosen balance point temperature, are calculated. The billing data are plotted versus the calculated degree days and, on the same plot, a line is drawn. The intercept of the line is the monthly baseload, estimated from billing data for one or two summer months. The slope of the line is equal to the space-heating energy consumption for the total period of time (total fuel consumption for the period minus the estimated baseload consumption for the period) divided by the heating degree days for the period based on the chosen balance point temperature. After repeating the procedure using a different balance point temperature, the auditor compares the plots to determine the plot in which the data and line are most consistent and, hence, which of the two balance point temperatures best describes the house. This process is repeated until a final balance point temperature is selected. The slope of the line corresponding to the selected balance point temperature is multiplied by the average annual heating degree days for the area (based on the selected balance point temperature) to obtain the normalized annual space-heating energy consumption for the house.

In the third step, the following are calculated by the measure selection technique for each of the previously identified ECMs: installation cost, annual energy savings, first-year cost savings, BCR, and simple payback period. The installation costs are calculated using local labor and material costs for each ECM. Energy savings are determined using calculation methods that examine each ECM individually as opposed to an approach in which the entire building is modeled. The savings of building-envelope ECMs (except infiltration reduction) are estimated by a variable-base degree-day method using the change in UA-value for the building components affected by the ECM, space-heating system efficiency (steady-state efficiency reduced several percent to account for seasonal factors), and regional average degree day data corresponding to the estimated house balance point temperature. The savings of space-heating system ECMs are estimated by calculating efficiency changes and using the estimated normalized annual space-heating energy consumption. The BCRs are then calculated using the estimated installation costs and first-year cost savings, estimated lifetimes of the ECMs, appropriate financial assumptions, and a discounted BCR analysis technique. A BCR greater than 1.0 indicates that the ECM saves more money through energy savings over the life of the ECM than it costs to install; an ECM with a BCR less than 1.0 will not save as much money as it costs. The calculations for the infiltration reduction ECM are performed differently. The BCR for this ECM is selected and the amount of work that can be performed is then determined. This is discussed in more detail in Sect. 2.3.

In the fourth step, ECMs with BCRs higher than a predetermined cutoff value (at least 1.0) are selected for installation once the interactions between ECMs are considered. As discussed in Sect. 5.2, a BCR cutoff value of 1.0 was chosen for this field test. Interactions between ECMs become important when both space-heating system and building-envelope ECMs are used. For instance, attic insulation saves energy by reducing the amount of heat needed to keep a house warm, while improving the efficiency of a furnace reduces the amount of fuel needed to deliver the required amount of heat. The interaction between these two ECMs causes their combined energy savings to be less than the sum of the savings each would achieve alone. Interactions between ECMs are also important when the same piece of equipment can be modified by different ECMs. For example, installing an intermittent ignition device or installing a new high-efficiency furnace may both be cost-effective ECMs. However, because a new furnace is already equipped with an ignition device, these two ECMs cannot be performed on the same piece of existing equipment at the same time.

In the measure selection technique, ECMs are generally selected in descending order of their BCR until the cutoff value is reached. Interactions between space-heating system and building-envelope ECMs are handled by selecting the ECM with the highest BCR and then recalculating the BCRs for the ECMs that interact. ECMs that interacted are selected if the recalculated BCR is greater than the cutoff value. Interactions between space-heating system ECMs only are handled somewhat differently. From among the space-heating system ECMs that meet the BCR criteria and interact, the ECM with the "most energy savings features" is selected. In practice, this means that the space-heating system ECMs are selected in the following order: high-efficiency space-heating system (if its BCR is also greater than a preselected "interaction" value and its simple payback period is less than a preselected period), gas power burner, electrically-activated vent damper, intermittent ignition device, thermally-activated vent damper, outdoor temperature reset control, continuous circulation pump, and tuning the existing space-heating system. The "interaction" value must be equal to or greater than the cutoff value. The "interaction" value and the value for the simple payback period are chosen by the user based on judgement and experience. For this field test, the "interaction" value was 1.25 and the simple payback period was 8 years.

In the fifth and final step, the selected ECMs are listed in a work order that can be used by the weatherization installer. The work order lists the work to be performed, the amount of material and labor required for each ECM, and a cost estimate for the job.

Emergency repair work and system replacements are considered in the technique and include new space-heating system, new water-heating system, roof repairs, attic access, wall repairs, repair existing attic and floor insulation, plastic ground cover in the crawlspace, crawlspace ventilation, moisture problems, vent piping extensions, and wiring repairs. The decision on whether to perform these emergency repairs is made by the auditors based on their judgement and previous training.

2.3 INFILTRATION REDUCTION PROCEDURE

Under the measure selection technique, the installation of infiltration reduction ECMs is performed following a blower-door guided infiltration reduction procedure (Schlegel 1990, Schlegel et al. 1986, Gettings et al. 1988). The intent of the procedure is to increase the energy savings obtained from infiltration reduction work and to reduce costs. This is accomplished by using a blower door to locate major house leaks and to determine the level of work to perform.

Two guidelines are used in the procedure: a minimum ventilation guideline and a BCR guideline. Tightening of houses to air-leakage rates below the minimum guideline might cause moisture and indoor air quality problems and is not likely to be cost effective. The minimum ventilation guideline is established for each house depending on house size, number of occupants, number of smokers, and/or other appropriate criteria. The BCR guideline sets the minimum reduction in air-leakage rate that must occur per $100 expenditure in order to remain above a fixed BCR. The BCR guideline is calculated using equations presented by Schlegel (1990). Unlike the other ECMs in the selection technique where the BCR is calculated for each ECM, the BCR for the infiltration work is set first (based on program goals). The BCR guideline is established for each house based on the fixed BCR selected, measured space-heating system efficiency of the house, local climate, local fuel costs, and appropriate financial assumptions. For this field test, a BCR of 2.0 was established for the infiltration work as discussed in Sect. 5.1.

A specially trained crew begins the procedure by checking to ensure that no moisture problems currently exist. If a moisture problem exists, infiltration reduction work is suspended until the problem is corrected. The crew then determines the air-leakage rate of the house, using a calibrated blower door, at 50 Pa of depressurization. Homes whose air-leakage rate is less than the minimum ventilation guideline receive no treatment (except to seal leaks that directly affect comfort). Major leaks identified using the blower door are sealed in the houses whose air-leakage rates are greater than the minimum ventilation guideline. Periodically, the crew checks the effectiveness of their latest increment of work by determining the cost of the work and the reduction in the air-leakage rate that has occurred. The crew stops working when the air-leakage rate falls below the minimum ventilation guideline or when the effectiveness of the their latest increment of work (ratio of achieved reduction to costs) is less than the BCR guideline.

In order to incorporate the infiltration reduction procedure into the measure selection technique, the BCR for the infiltration work is set at a value greater than or equal to the predetermined cutoff value for the measure selection technique (if the BCR is set at a value lower than the cutoff value, the selection technique would not recommend any infiltration work). Depending on when infiltration reduction work is performed relative to the selection technique, the energy savings of Che infiltration work can be estimated in the selection technique based on either an estimate of the current air-leakage rate of the house, on a measured value for the current air-leakage rate, or on the actual reduction in the air-leakage rate that is achieved following the infiltration procedure. Because the infiltration reduction procedure is applied to every house (the BCR is always greater than or equal to the cutoff value), the procedure can be performed before completing the measure selection technique to select other ECMs. Under the infiltration reduction procedure, the actual reduction in the air-leakage rate is measured (equal to the air-leakage rate measured at the start of the procedure minus the air-leakage rate measured at the end). The energy savings of the infiltration work can be estimated based on this measured reduction, making this the most accurate of the three methods. However, the auditor cannot select the remaining ECMs for the house in this case until after the infiltration reduction work is completed. If the selection technique is to be completed first, energy savings must be estimated based on the current air-leakage rate only. The current air-leakage rate of the house can be estimated at the time the house is audited from the visual appearance of the building. Although this is the easiest approach, the resulting estimate of the energy savings is also the least accurate. The current air-leakage rate can be measured by the auditor using a blower door at the time the house is audited. Although this requires additional time to be spent by the auditor in the field, the estimate of the energy savings is more accurate because it is based on a measured value. An additional advantage of this latter approach is that houses that do not require infiltration work (whose current air-leakage rate is below the minimum guideline) can be identified, eliminating the need to send an infiltration reduction crew to the house.

3. FIELD TEST DESIGN AND IMPLEMENTATION

3.1 GENERAL APPROACH

The field test was performed in Buffalo, New York. The annual heating degree days (base 65°F) for Buffalo is 6910. Of 100 houses meeting the selection criteria identified in Sect. 3.2, 89 were monitored for the duration of the field test: 45 houses received a mix of ECMs as selected by the measure selection technique (audit houses) and 44 served as a control group. A stratified random assignment procedure described in Sect 3.2 was used to help achieve pre-weatherization equality between the audit and control groups.

The field test was conducted over a two-year period. Pre-weatherization data were collected for all the houses during one winter season (January to April 1988). ECMs were installed in the audit houses between August and November 1988. Post-weatherization data were collected for all the houses during the following winter season (December 1988 to April 1989).

The following time-dependent data were collected weekly for all the houses during the two winter testing periods: house gas consumption, house electricity consumption, space-heating gas consumption, and water-heating gas consumption. Hourly indoor temperatures were monitored in each house and hourly outdoor temperatures were monitored at three sites near the houses. The following time-independent information was also collected or measured during the field test:

1. house and occupant descriptive information identified in Table 3.1 in February and March 1988,

2. house air-leakage rates in the audit and control houses in July and August 1988 (before any ECMs were installed in the audit houses) and again in October and November 1988 (after all ECMs were installed in the audit houses),

Table 3.1. House and occupant descriptive Information

General
- Experimental program
- House identifier
- Interviewer
- Date of interview
- Occupant's name and phone number
- House location
- Utility distributors

House
- Type
- Number of floors
- Age
- Foundation and roof type
- Roof and external wall colors
- Number and description of rooms typically closed off
- Total and heated floor areas
- Evaluation of factors affecting air infiltration
- Plan view and sketch

Occupancy
- Ownership
- Length of time at residence
- Permanent number by age group
- Average number at home during the day

Space-heating system
- Type
- Fuel
- Distribution fluid and method
- Nameplate information (manufacturer, model, input and output capacities, and efficiency)
- Location
- Coal or oil conversion unit
- Energy efficiency devices present (vent damper and intermittent ignition device)
- Pilot light use pattern
- Auxiliary heat use

Distribution system
- Total length of ductwork or piping
- Length of ductwork or piping in unconditioned spaces
- Insulation thickness

Table 3.1 (continued)

Thermostat
Type
Number
Nameplate information (manufacturer and model)
Water-heating system
Fuel
Storage type
Heater type
Nameplate information (manufacturer, model, tank size, input capacity, and recovery)
Hot water temperature
Blanket thickness
Location
Appliances
Type
Fuel
Location
Insulation
Location and area
Construction
Type and thickness
Siding type (for walls)
Carpeted area (for sub-floor)
Windows, glass doors, and non-glass external doors
Window type
Window treatments
Area measurements per external wall facing
Number of window panes
Non-glass door type

3. space-heating system steady-state efficiencies in all houses in June and July 1988 before any ECMs were installed and again in houses receiving space-heating system ECMs between October and November 1988 after the ECMs were installed, and

4. the ECMs actually installed in the houses and their costs.

A more detailed description of the data parameters and instrumentation is provided in Appendix A. Feedback regarding the field test design and its implementation are also provided in this Appendix. Details concerning the collection and management of the field data are provided in Appendix B.

3.2 HOUSE SELECTION AND ASSIGNMENT

The population of houses studied were limited to those having the following characteristics:

1. occupants were a resident of Erie County, New York;

2. gas service was provided by NF;

3. occupants were eligible for the Low-Income Home Energy Assistance Program (LIHEAP) administered by the state at the time of being included in the field test (based on their 1987 Income Tax Statement);

4. houses were heated primarily with natural gas;

5. gas service was turned on;

6. primary gas space-heating systems were operational;

7. houses were not scheduled to receive weatherization under either the State's Weatherization Assistance Program or NF's Savings Power Loan Program and had not received weatherization by these programs in the last 5 years;

8. houses were single-family detached houses, but not mobile homes;

9. houses were occupied by the owner;

10. occupants were currently paying their own fuel bills (bills could not be paid by the county through vouchers);

11. primary space-heating systems were either gas furnaces or hot water boilers;

12. domestic water was heated with natural gas;

13. occupants were not planning an extended stay away from the house during the winter monitoring periods (a 1-2 week vacation was acceptable);

14. secondary fuels (such as wood or kerosene) were not used to substantially heat the house (use of a supplemental fuel a half day per week or in the bathroom was acceptable); and

15. monthly gas consumption over the past year was weather dependent (could be correlated to outdoor temperature).

The first seven criteria defined the population of houses needed to meet the basic objectives of the field test. The remaining criteria narrowed the population to make the experiment easier to perform, improve the accuracy of the results, and ensure that audit and control groups were not significantly different. The importance of these characteristics was described in detail in the experimental plan (Ternes and Hu 1988).

Because all the houses in the population of interest could not be studied, a sample of houses representing the population were chosen. Based primarily on cost considerations, the size of the sample was limited to 100 houses. The expected error in estimating the average house savings achieved by the measure selection technique with this sample size was determined to be acceptable. Selection of the 100 houses was performed by identifying individual houses conforming to the selection criteria, determining if the occupants were willing to participate in the field test, and accepting them if they consented until the 100 house quota was reached. This quota sampling approach was chosen because a more formal statistical sampling technique such as random sampling required time and funds that were not available.

The houses were assigned to either the audit or control group in May 1988 using a stratified random assignment procedure to help achieve pre-weatherization equality between the two groups. The strata were developed using two key variables that could significantly affect space-heating energy consumption and the space-heating energy savings that might be achieved by the measure selection technique. The type of space-heating system (furnace or boiler) installed in the house was an important criterion because the control systems and the way they deliver heat are different. Additionally, ECMs selected by the technique for a given house depend on the house's space-heating system due to hardware and cost considerations. Pre-weatherization house gas consumption was an important criterion because the average consumption of the houses in the audit and control groups should be the same.

The annual gas consumption of each house was estimated using previous billing data. The house consumptions were compared to identify the high and low energy users (houses in the upper and lower 50th percentile, respectively). The houses were classified into one of the following four strata: high energy user with a furnace space-heating system, high energy user with a boiler, low energy user with a furnace, and low energy user with a boiler. One-half of the houses from each stratum were then randomly assigned to the audit group. The remaining houses were assigned to the control group. The assignments were made after the pre-weatherization data were collected in order to minimize the effect attrition would have on creating unequal groups.

4. OCCUPANT AND HOUSE CHARACTERISTICS

Occupant and house descriptive information was collected during the first heating season for the 89 houses remaining in the field test. This information was obtained for each house through discussions with the homeowners, visual observations, and limited measurements.

4.1 OCCUPANT CHARACTERISTICS

The number of occupants in each house varied between 1 and 12 (see Fig. 4.1). Ninety-two percent of the houses had five or fewer occupants, and 39% had only one or two occupants. The average number of occupants per house was slightly more than three. The most common number of occupants per house was four.

Figure 4.2 illustrates the number of people in each age group within each household size. The majority of the people in the households with only one or two occupants were retired adults; none were preschool-aged children. Among the 17 houses reporting one occupant, 15 were retired adults and two did not report an age group. Among the 18 houses reporting two occupants, at least one retired adult lived in 15 of the houses and both occupants were retired in eight. As the household size increases beyond two, the presence of retired adults diminished (the houses were headed by non-retired adults) and the percentage of school-aged and preschool-aged children within the family increased. Fifty-five percent of the 20 houses with four occupants had two non-retired adults and two children.

The number of years in which each family had resided at their present address varied between 1 and 60 years, the mean being 18 years.

4.2 HOUSE CHARACTERISTICS

An average house participating in the field test was approximately 47 years of age and had two floors built above a concrete block basement.

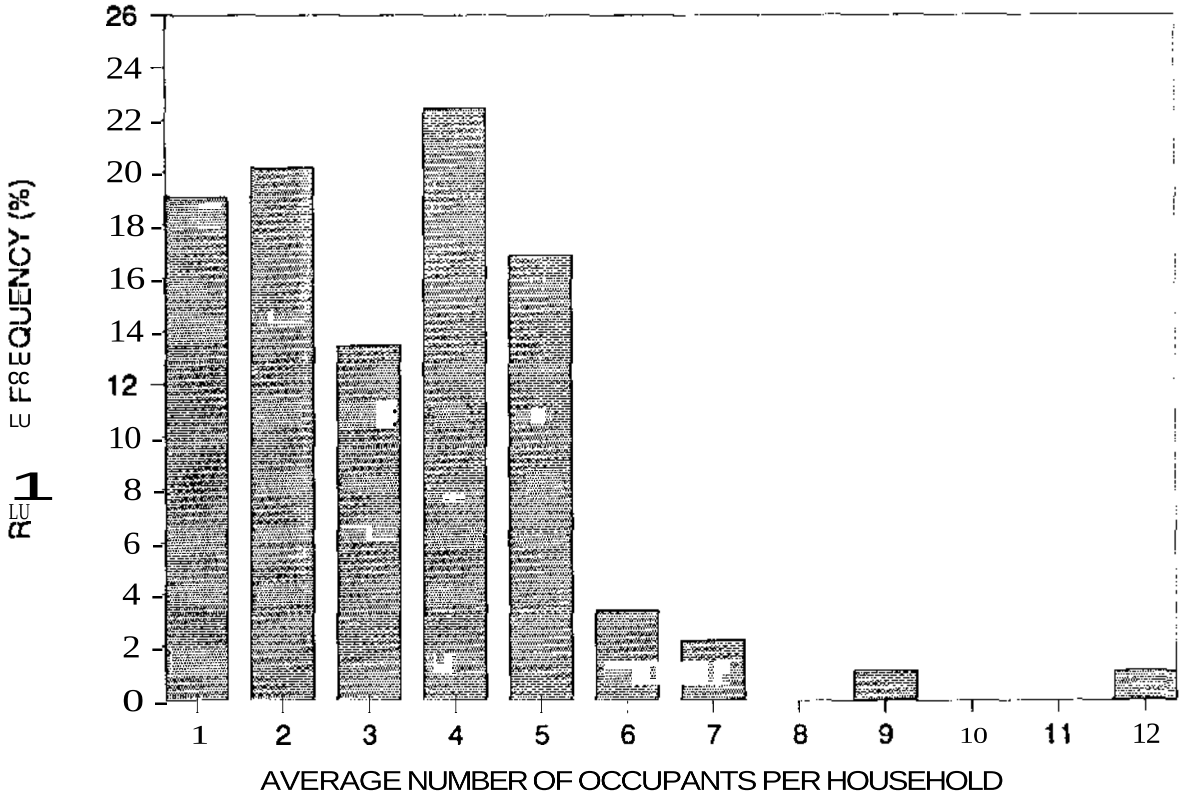

Fig. 4.1. Histogram of number of occupants for the field test houses.

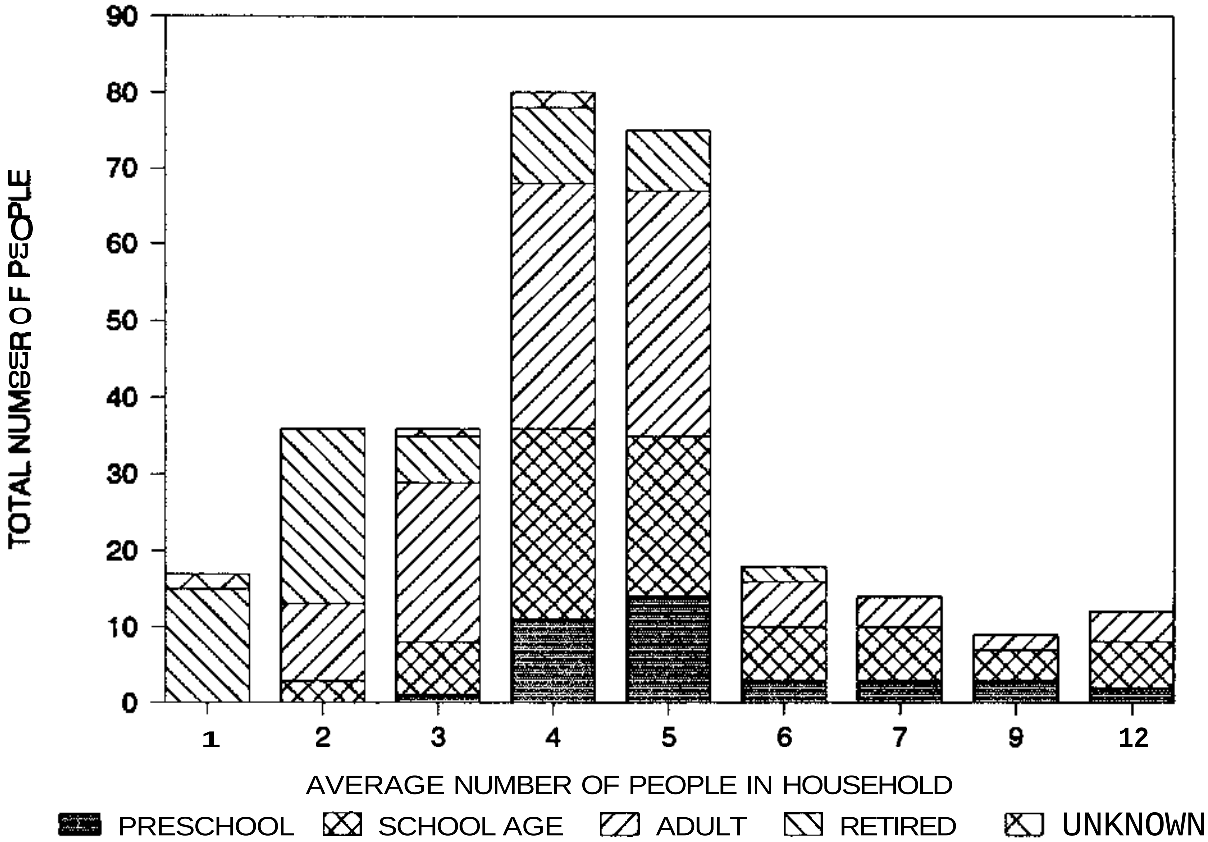

Fig. 4.2. For each occupancy level, total number of people by age group. For example, there were a total of 11 preschoolers, 27 school age, 30 non-retired adults, 10 retired adults, and 2 people of unknown age living in houses with four occupants.

The non-basement floor area of the house (which, in most, was the main living area) was 1305 ft^2 and the total floor area of the house (which includes the basement) was 2082 ft^2. The house was heated with a 19-year old gas furnace and no auxiliary heat was used. The house had some fiberglass batt insulation in the attic but no insulation on the exterior walls, floors, or foundation.

Most houses in the field test were neither new nor very old, having been built during the 1930's through the 1960's. Their ages ranged between 15 and 90 years and their average age was 47 years. Eighty-two percent of the houses were between 26 and 65 years old with a concentration of 34% being between 26 and 35 years old (see Fig. 4.3). Only four houses were built in the last 25 years, and only 12 were built more than 65 years ago.

A majority of the houses (84 of 89) had basements and most of the houses were multi-story. If basements are counted as a floor, four houses had four floors, 61 had three floors, 20 had two floors, and only four had a single floor. The basements were typically made of concrete block, with concrete structures being the second most popular construction type. For the 84 houses with a basement, the basement floor areas varied between 525 and 1240 ft^2 and averaged 824 ft^2. The ratio of the basement floor area to total floor area ranged from 24 to 50%, with the average being 39%.

The non-basement floor area of the 89 field test houses averaged 1305 ft^2. Although the non-basement floor areas varied among the individual houses by as much as 1659 ft^2 (637 to 2296 ft^2), approximately 70% of the houses were between 1000 and 1600 ft^2. This distribution is shown in Fig. 4.4. Total floor areas ranged from 866 to 3424 ft^2 and averaged 2082 ft^2 (the difference between this value and the average non-basement floor area is not equal to 824 ft^2, the average basement floor area, because the basement value is averaged over only 84 houses).

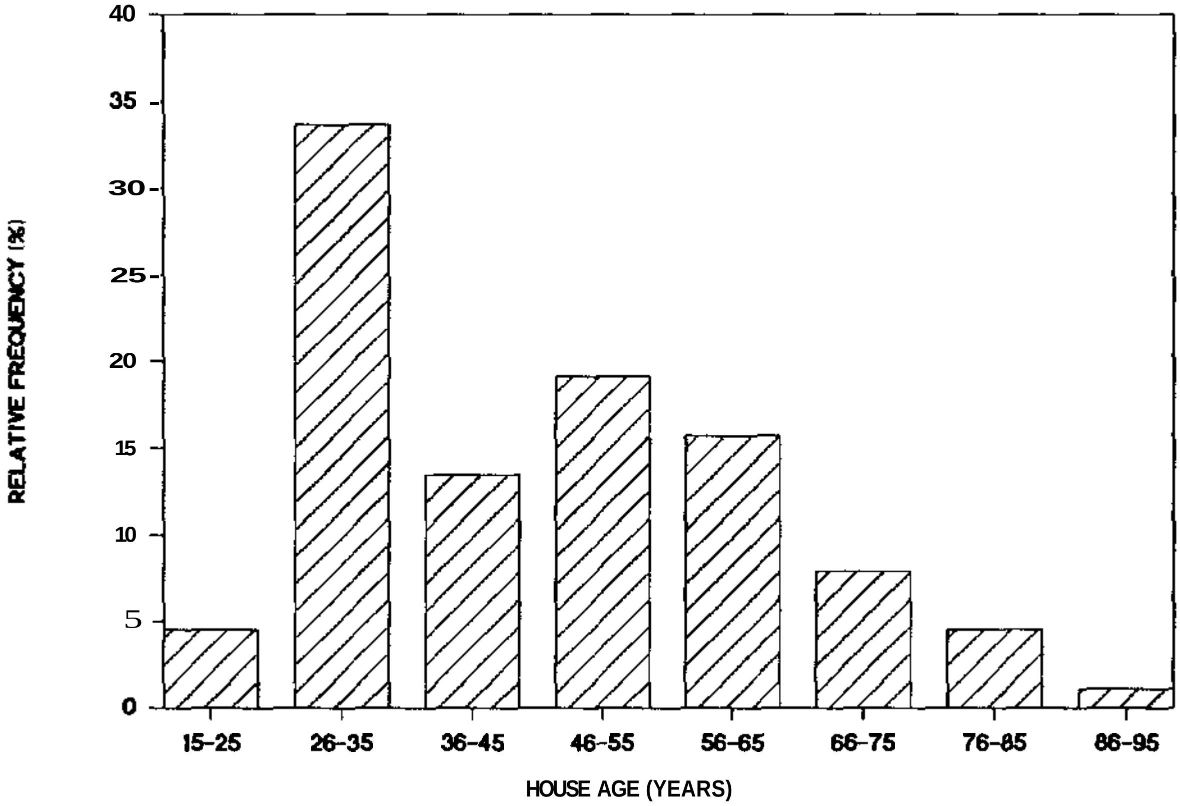

Fig. 4.3. Histograa of house age for the field test houses.

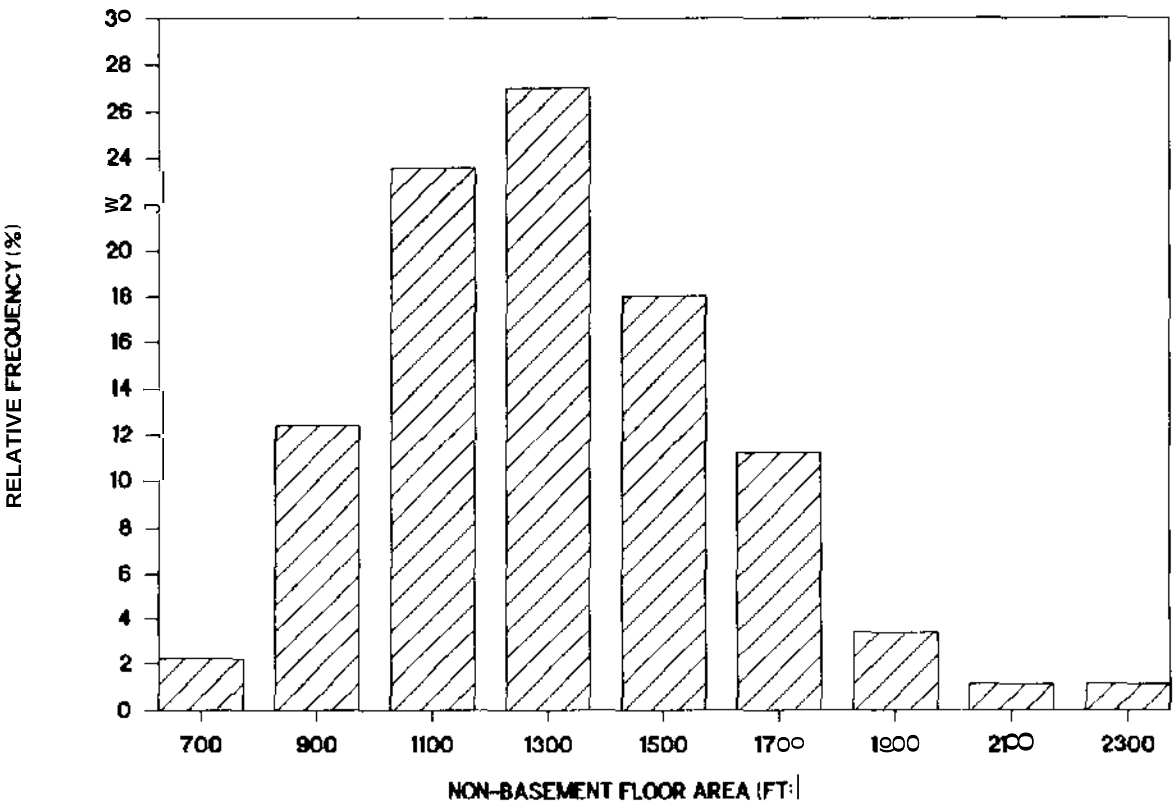

Fig. 4.4. Histogram of non-basement floor area for the field test houses. Listed floor areas represent ranges (i.e., 700 represents a range of 600-799 ft^2, etc.)

Considering only the floor areas presented above does not give an accurate picture of the floor area that is heated. Twenty-four percent of the homeowners reported that they typically closed off one or more rooms of their house. In addition, some homeowners did use their basements as living area. Thus, neither non-basement nor total floor area adequately represents heated floor area. Among the 84 houses having basements, the basements in 73 houses were not intentionally heated, less than two-thirds of the basement area was heated in five houses, and the entire basement was heated in the remaining six houses. Figure 4.5 illustrates the percentage of total floor area that was heated. This graph shows that only eight participants heated their entire house and that two heated as little as one-third of the total floor area of their house. In the majority of the houses, between 50 and 75% of the total floor area was heated; this range was expected because basement floor areas are typically between 30-50% of the total floor area. On average, 67% of the total floor area of the houses was heated. Heated floor areas ranged between 623 and 2514 ft^2 and averaged 1315 ft^2.

As specified by the house selection criteria presented in Sect. 3.2, all primary space-heating systems were fueled by natural gas. Eighty-seven percent of the houses had furnaces and the remaining had boilers. Average age of the furnaces was 19 years while the boilers were slightly older, with a mean of 21 years. An intermittent ignition device was already installed on 18% of the systems at the start of the field test, and 13% of the systems were already equipped with a vent damper (11% were thermally-activated vent dampers and the remaining were electrically-activated). The majority of the participants (75 of 89) did not use any type of auxiliary heat. Only six participants reported using a portable electric heater or a fireplace more than 15 hours a week. Among the eight families that reported using either a fireplace insert, wood stove, kerosene or liquid petroleum gas room heater, or built-in zone heater, seven used this type of heater 12 hours or less a week.

All of the houses had water-heating systems fueled by natural gas as stipulated by the house selection criteria. The typical water-heating

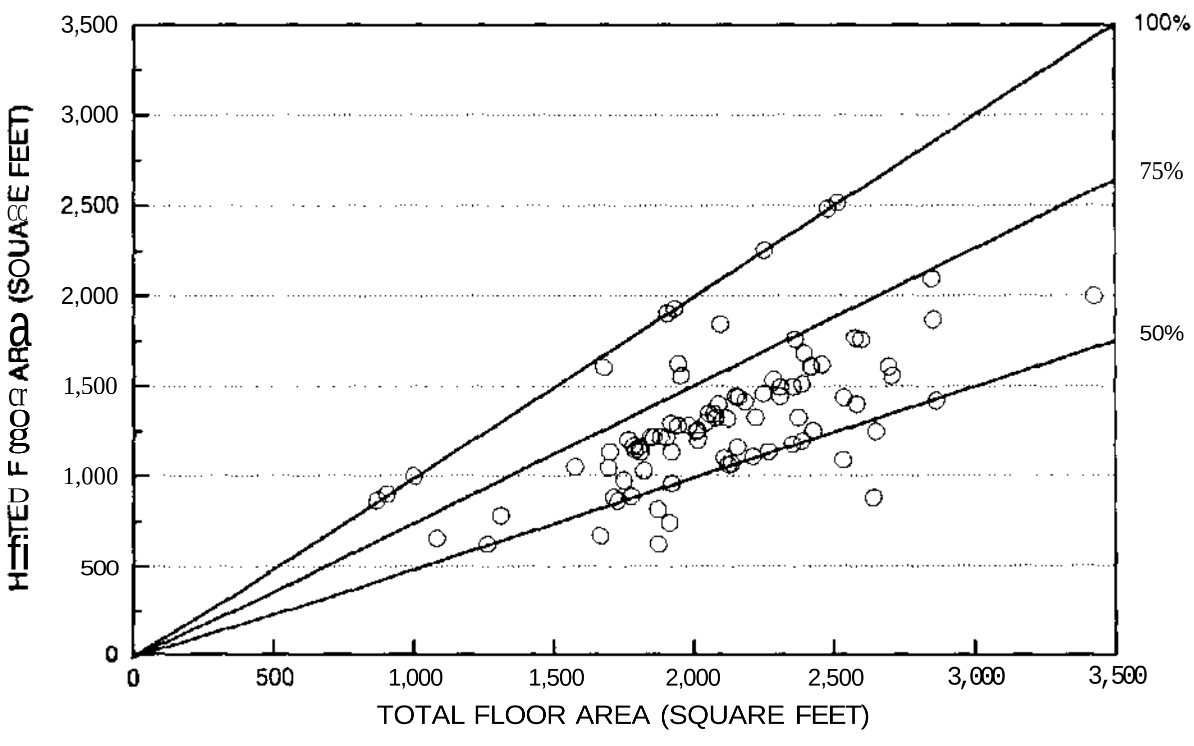

Fig. 4.5. Comparison of heated floor area of each house to its total floor area (including basement floor area). The solid lines indicate where the heated areas are 100, 75, and 50% of the total areas.

system had a 40 gallon storage tank, an input fuel capacity rating of 36,332 Btu/h, and no blanket Insulation. The storage tank was typically located in an unintentionally conditioned area (area maintained unintentionally at more than 55°F such as a basement).

A summary of the appliances found in the houses is provided in Table 4.1. All houses had a cooking range and most had an oven, clothes washer and dryer, and a conventional refrigerator/freezer. Approximately two-thirds of the cooking ranges and ovens and three-fourths of the clothes dryers were gas. Less than half the houses had a separate freezer or dishwasher, and about two-thirds had a microwave oven.

The initial thermal condition of the 89 houses is shown in Fig. 4.6. Ninety percent of the houses had no foundation insulation, 62% had no exterior wall cavity insulation, and 18% had no attic insulation; 15 houses in the study did not have any envelope insulation whatsoever. Because most of the houses had basements, few had any floor insulation.

The floor areas of the attics averaged 916 ft^2, varying between 518 and 1604 ft^2. Most of the attics had a typical attic floor construction as opposed to kneewall or sloped ceilings. Fifty-six percent of the houses had their entire attic floor area insulated. Overall, approximately 73% of the total attic floor area was insulated. Excluding the 16 houses with no attic insulation, this percentage increases to 90%. A distribution of the average R-value of the attic insulation in the 89 houses is shown in Fig. 4.7. Average R-values of 0, 6, and 18 $^{\circ}F\text{-}ft^2$-h/Btu (representing 0, 2, and 6 in. of insulation installed uniformly across the attic) were the most common individual insulation levels. The mean value for the 73 houses with some attic insulation (predominately fiberglass batt) was 9 $^{\circ}F\text{-}ft^2$-h/Btu with extremes of 0.4 and 27 $^{\circ}F\text{-}ft^2$-h/Btu. The average UA of the attics for all 89 houses was 150 Btu/h-°F, and 114 Btu/h-°F for the 73 houses with some attic insulation (the UA values include consideration of film coefficients and building boards).

Table 4.1. Appliance use and fuel type

Appliance	Number of houses	% Gas	% Electric
Cooking range	89	68.5	31.5
Conventional oven	85	69.4	30.6
Microwave	61	0.0	100.0
Clothes washer	84	0.0	100.0
Clothes dryer	77	72.7	27.3
Refrigerator/freezer	85	0.0	100.0
Separate freezer	34	0.0	100.0
Dishwasher	31	0.0	100.0

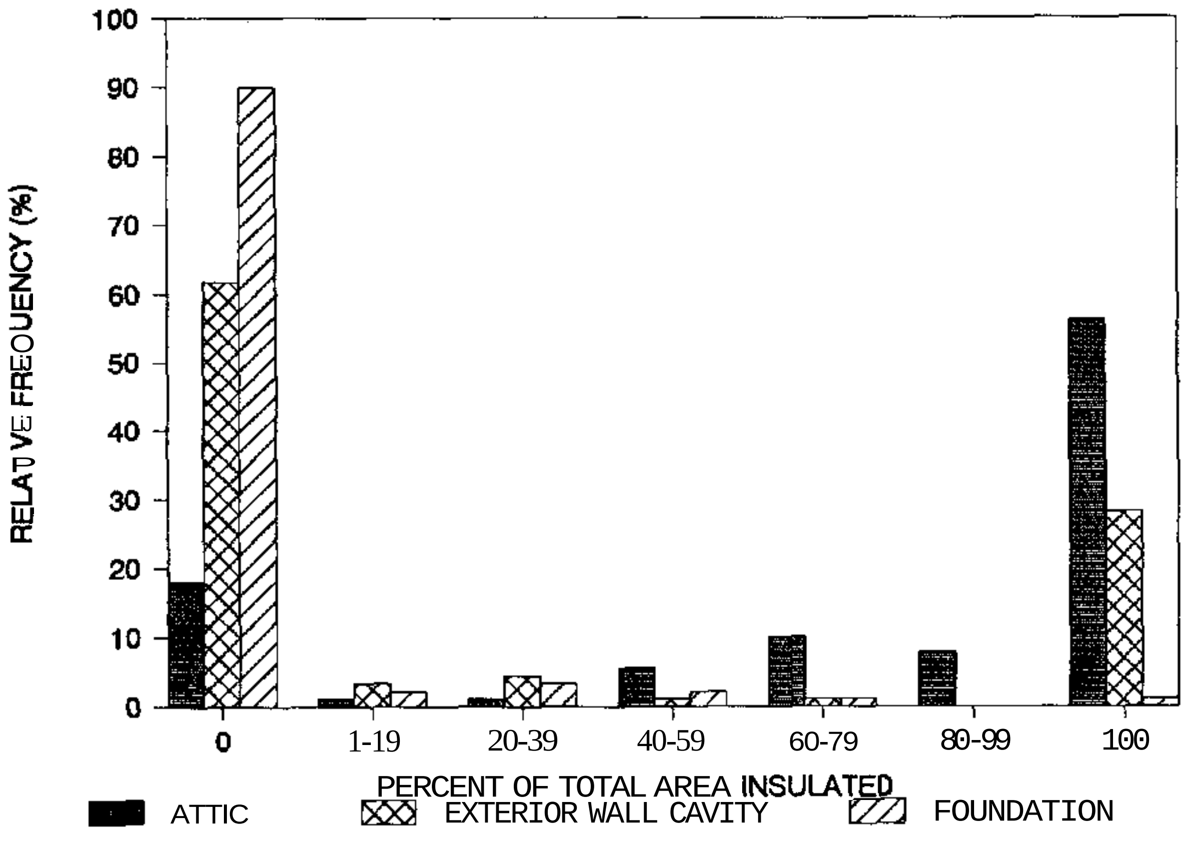

Fig. 4.6. For different building envelope areas (attic, exterior walls, and foundation), percentage of field test houses with specified percentages of total area insulated at the start of the experiment. For example, approximately 10% of the houses had 60-79% of their total attic area insulated and approximately 60% of the houses did not have insulation in exterior wall cavities.

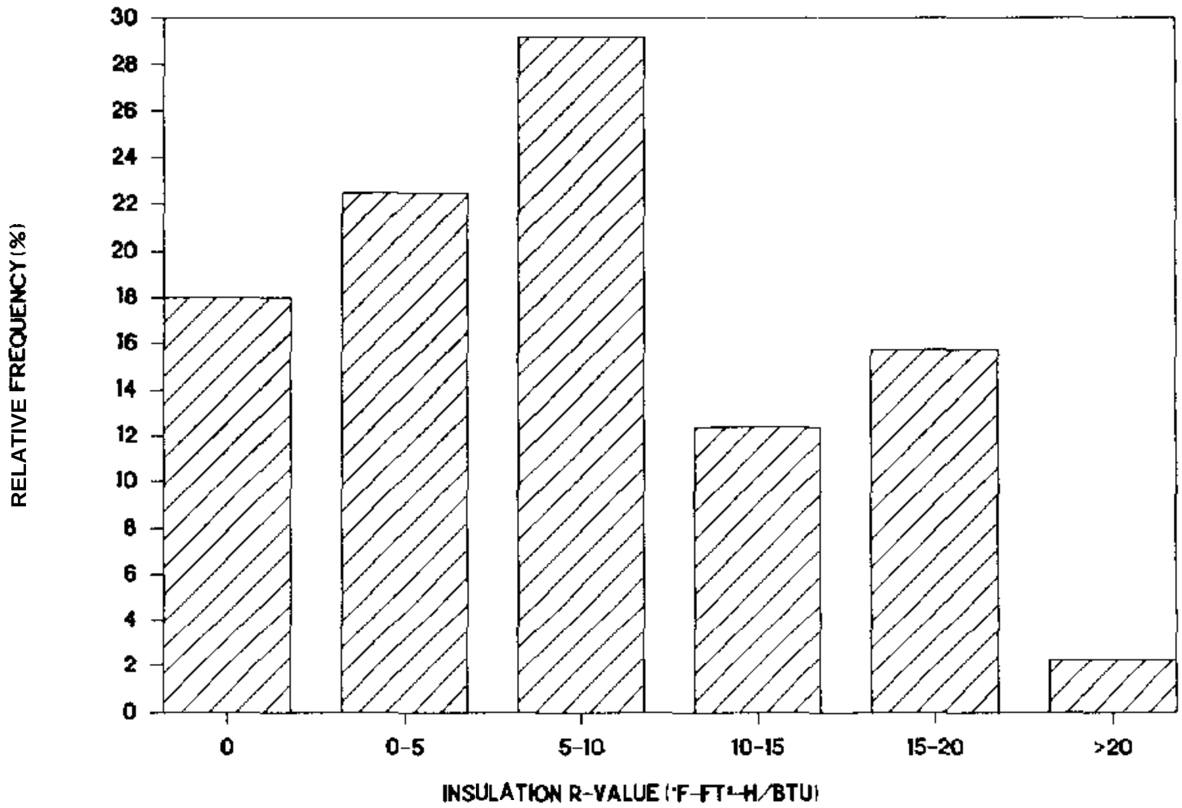

Fig. 4.7. Histogram of amount of attic insulation (average R-value of the insulation only) present in the field test houses at the start of the experiment.

The houses were, with only one exception, made of a frame structure and were sided with either shingles, wood, slate, brick, aluminum, steel, or vinyl. Total exterior wall area averaged 1372 ft^2, ranging from 736 to 2170 ft^2. The wall cavity in approximately 31% of the total exterior wall area of the houses was insulated. Considering only the 34 houses that had at least part of their wall cavities insulated, this percentage increases to 80%. A distribution of the average R-value of the wall cavity insulation in the 89 houses is shown in Fig. 4.8. The average R-value range of >10 °F-ft^2-h/Btu represents houses having about 3.5 in. of insulation in all exterior wall cavity areas. The two ranges of 0-5 and 5-10 °F-ft^2-h/Btu represent houses with Incomplete coverage and/or with less than 3.5 in. of insulation in the wall cavities (it was common practice in previous years to only insulate wall cavities with 1-2 in. batts). The mean value of the wall cavity insulation (predominately fiberglass batt or blown cellulose) in the 34 houses with some wall insulation was 6 °F-ft^2-h/Btu. The average UA of the walls was 313 Btu/h-°F for all 89 houses and 182 Btu/h-°F for the 34 houses with some wall cavity insulation.

Because only nine houses had foundation insulation, the amount of foundation area insulated in the 89 houses averaged only 4%. The nine houses with foundation insulation had, on the average, only 40% of the foundation insulated with a mean thickness of 2.8 in. Sill boxes were found in 91% of the houses and were insulated in only 16% of the houses.

Total window area for each house averaged 179 ft^2, varying between 85 and 305 ft^2. The predominant type of window used in the participating houses was single-pane with a storm window; seventy-eight of the 89 houses had more than half of their house window area installed with this type window. The amount of window area in each house for each category was compared to total window area and averages were computed with the following results: 8% of total window area was single-pane without a storm window, 81% was single-pane with a storm window, 9% was multi-pane without a storm window, and 3% was multi-pane with a storm window.

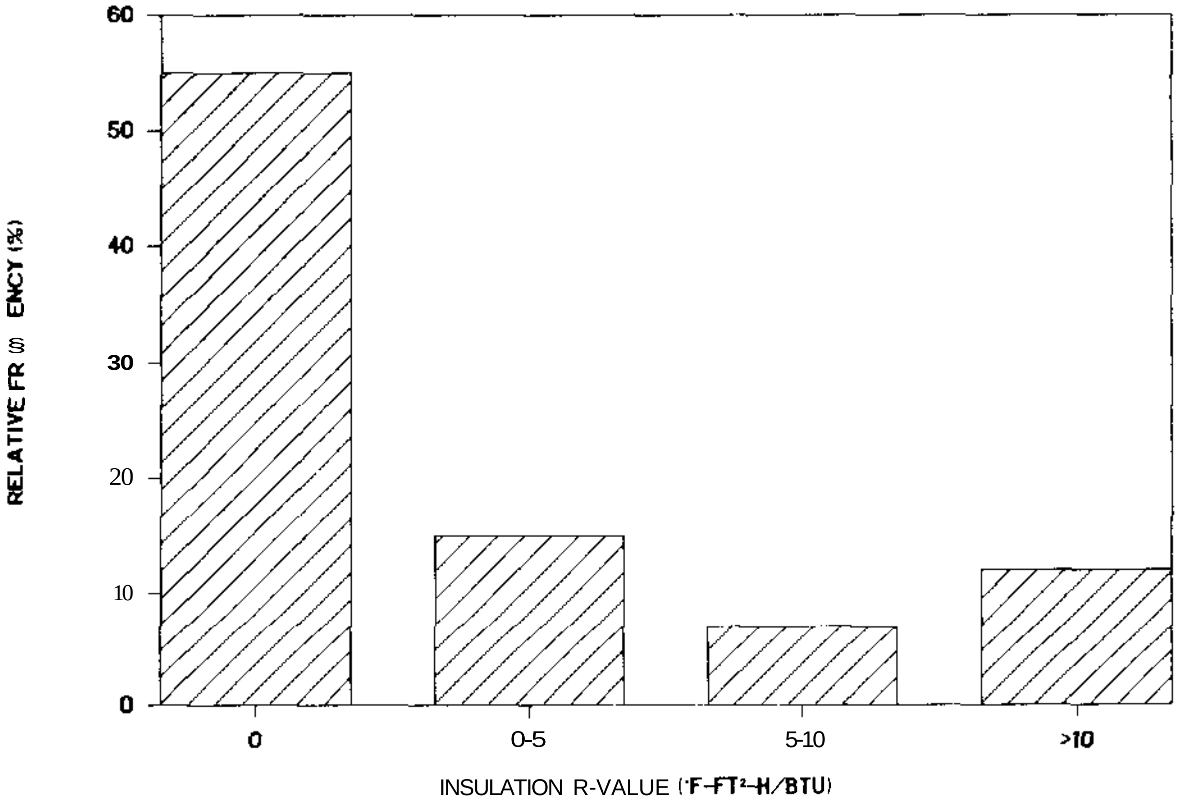

Fig. 4.8. Histogram of **amount** of wall cavity insulation (average R-value of the wall cavity insulation only) present in the field test houses at the start of the experiment.

4.3 COMPARISON OF AUDIT AND CONTROL GROUPS

As discussed in Sect. 3.2, the field test houses were divided into audit and control groups at the end of the first heating season using a stratified random assignment procedure to help achieve pre-weatherization equality between the two groups.

After assignment, important house characteristics other than the two used in the assignment procedure (type of space-heating system and pre-weatherization house gas consumption) were compared to determine whether any significant differences existed between the two groups. The means of the following variables were compared using a two-sample t test: total floor area, non-basement floor area, basement floor area, heated floor area, attic floor area, percent of attic floor area insulated, UA of the attics, U of the attics, wall area, percent of wall cavity area insulated, UA of the walls, U of the walls, foundation type, area of foundation insulated, percent of foundation insulation insulated, presence of sill box insulation, window area, percent of window area represented by different window types, percent of exterior door area with a thermal door or storm door, age of the space-heating system, presence of an intermittent ignition device, presence of a vent damper, house age, number of floors of the house, and number of occupants. To verify an assumption of the t test that the variances of the two groups are equal, the variances of the control group were compared to those for the audit group to check for equality. Other variables such as house type and types of auxiliary heat used were examined by comparing their distributions.

At a significance level of 95%, the only difference found between the two groups involved the level of wall cavity insulation present at the start of the field test. In the control group, 42% of the wall cavity area was insulated, whereas only 19% of the wall cavity area was insulated in the audit group. The mean U-factor for the walls was 0.21 Btu/h-ft^2-$^\circ$F for the control group and 0.25 Btu/h-ft^2-$^\circ$F for the audit group.

This difference should not affect adjustment of audit house savings by the control group savings (as will be discussed in Sect, 8.2) because the presence of wall cavity insulation should not significantly influence changes in occupant behavior. This difference may make the pre-weatherization space-heating energy consumption of the control houses less than the audit houses. Additionally, the percentage of audit houses receiving wall insulation may be more than what would occur in a larger sample.

5. MEASURE SELECTION TECHNIQUE IMPLEMENTATION

5.1 DEFAULT VALUES AND IMPLEMENTATION APPROACHES

Nineteen ECMs identified in Sect. 2.2 were considered in the measure selection technique. Options included in the technique for lowering thermostat settings for space-heating systems were excluded as discussed in Sect. 5.3. Options for installing low-flow shower heads and faucet flow restrictors were excluded for programmatic reasons.

The technique was tailored to use local installation costs for ELMs provided by NF (see Table 5.1). The range of cost values for wall, attic floor, and sloped ceiling insulation are due to the different materials that can be used (blown cellulose and blown or batt fiberglass), attic constructions, and siding types. The costs for interior foundation insulation cover a wide range depending on the method required to install it. Fiberglass batts were assumed to be used to insulate attic kneewall areas, floors, and sill boxes. Lifetimes of the ECMs assumed in the technique are presented in Table 5.1.

A weather file containing average daily outdoor temperatures from 1988-1989 was compiled by WECC for Buffalo for use by the selection technique. The annual heating degree days (base 65°F) used for Buffalo was 6910.

The cost of natural gas assumed in the technique was $5.10/MBtu. This was NF's current residential retail price of natural gas at the time the technique was set-up for the experiment in early 1988. (The price increased to $5.79/MBtu on October 12, 1988). The discount rate used in the economic calculations was 5%.

Multiple contractors were used to implement the measure selection technique in the field and to install recommended ECMs. The contractor employed by NF to perform their current audit system was used to audit the houses and to perform infiltration reduction work. This contractor's

Table 5.1. Installation costs and lifetimes of energy conservation measures assumed in the measure selection technique

	Cost[a,b] ($)	Lifetime (years)
Building-envelope measures:		
wall insulation (3.5 in.)[c]	0.72-0.99/ft^2	20
attic insulation[d]		
attic floor	0.026-0.042/ft^2/R	20
sloped ceiling	0.056-0.09/ft^2/R	20
kneewall	0.026/ft^2/R	20
infiltration reduction	30/h	10
storm windows		
exterior	6.00/ft^2	15
interior	7.16/ft^2	15
floor insulation	0.05/ft^2/R	20
sill box insulation	0.029/ft^2/R	15
interior foundation insulation[e]	0.05-0.37/ft^2/R	20
Space-heating system measures:		
space-heating system tune-up	45 each	2
intermittent ignition device	225 each	10
thermal vent damper	66 each	10
electro-mechanical vent damper	220 each	10
gas power burner		
outdoor reset control scheme	250 each	15
continuous circulation pump	50 each	15
new high-efficiency equipment		
83% SSE boiler	2060 each	15
90% SSE condensing boiler	2450 each	15
85% SSE furnace	1375 each	15
95% SSE condensing furnace	1900 each	15
Water-heating system measures:		
insulation blanket	43 each	15
thermal vent damper	60 each	10
low-flow shower heads	16 each	10
faucet flow restrictors	7.50 each	10
hot water line insulation	0.82-0.92/ft	10
reduced hot water temperature	2.40 each	3

[a]R used in column means per R-value of insulation installed.
[b]These costs were the average costs estimated for the three insulation, three heating system, and one blower door contractors.
[c]Cost ranges due to different siding types and insulation materials.
[d]Cost ranges due to different attic constructions and insulation materials.
[e]Cost ranges due to different installation techniques.

personnel were experienced auditors trained to perform NF's current audit, which is computerized and requires a level of information similar to the tested measure selection technique. After a bidding process, three local contractors were selected to install building envelope (insulation) ECMs recommended by the selection technique and three different contractors were selected to install space- and water-heating system ECMs.

For the field test, the infiltration reduction work was performed before the remaining ECMs were installed. The initial air-leakage rate measured at the start of the infiltration procedure was used in the selection technique to predict the energy savings of this work. This simulated the approach where the auditor would measure the rate at the time of the initial visit. The BCR for the infiltration work was set equal to 2.0 for two reasons. First, infiltration work should be recommended by the selection technique in all houses with an initial air-leakage rate greater than the minimum guideline. Because the BCR cutoff value was expected to be less than 2.0, a BCR of 2.0 was selected for the infiltration reduction work. Second, results from prior research has indicated that expenditures for infiltration work are large but the savings achieved are hard to predict and may be much smaller than expected. In order to reduce expenditures on infiltration reduction work (freeing funds for other ECMs) and to help ensure that the infiltration reduction work performed would be cost effective, a high BCR was selected. The minimum ventilation guideline for the houses was usually between 1500 and 1800 cfm50. The BCR guideline was generally 650 cfm50 reduction per $100 expenditure.

5.2 BENEFIT-TO-COST RATIO CUTOFF SELECTION

The average amount of money spent on a house in the weatherization program and the overall BCR of a program can be controlled indirectly through the selection of the BCR cutoff used by the technique. If a high cutoff value is chosen, only ECMs with high BCRs will be Installed in each house. This reduces the average amount of money spent per house on

ECMs but also reduces the total savings for the house. Overall, the ratio between total savings and costs of the ECMs only increases. If a lower cutoff value is chosen, more ECMs will be installed, on average, in the houses. This increases the average amount spent per house on ECMs but also increases the savings for the house; the ratio between total savings and costs of the ECMs only decreases.

The effect of administration costs and cutoff values on the BCR for a program is shown, hypothetically, in Fig. 5.1. The BCR for the program can be defined as the present value of the benefits expected from the recommended ECMs divided by the total estimated cost associated with installing the ECMs. Considering total cost to be just the costs required to install the recommended ECMs, the BCR for the program increases as the value of the BCR cutoff is increased (although both savings benefits and costs decrease as the BCR cutoff is increased, the savings benefits decrease more slowly than the costs of the ECMs). For this case, the BCR for the program is always higher than the cutoff value because all individual ECMs with a BCR equal to or greater than the cutoff are performed. Considering total cost to be the cost of the ECMs plus administration costs (costs associated with identifying houses, checking eligibility, auditing houses, inspecting installations, and program operation), a maximum BCR for the program will result. Choosing a BCR cutoff greater than the value that maximizes the program BCR causes the program BCR to decrease because there are fewer ECMs and, hence, fewer benefits to offset the fixed costs associated with each house. Selecting a cutoff less than the maximizing value causes the program BCR to decrease because the new recommended ECMs have BCRs less than the maximum.

The value for the BCR cutoff to be used in a weatherization program depends on objectives of the weatherization program (such as a desire to maximize the BCR for the program or install all cost-effective ECMs) and program constraints (such as expenditure guidelines). For the field test, the cutoff value was chosen to be 1.0 because all cost-effective ECMs are performed in the house once it is identified as being eligible

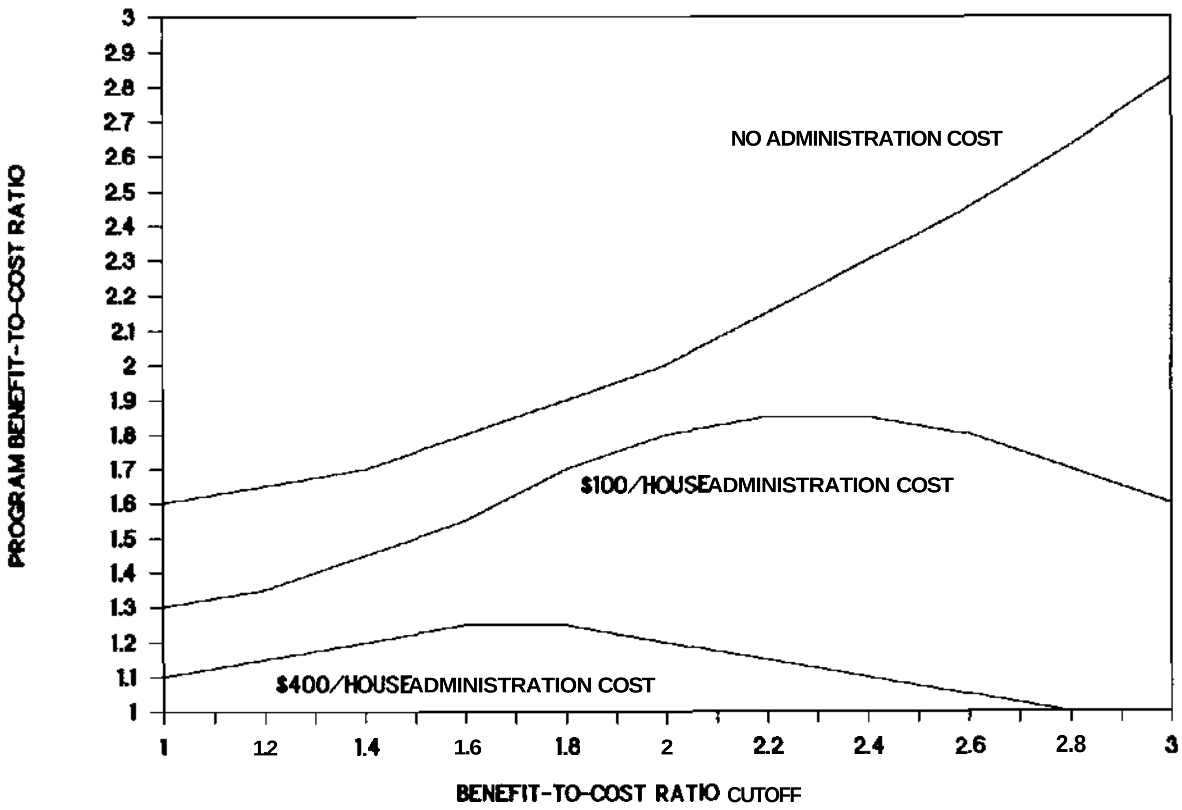

Fig. 5.1. Benefit-to-cost ratio (BCR) for a hypothetical weatherization program *as a* function of the BCR cutoff used in the measure selection technique for three different administration costs.

for the program. At this value, the average anticipated expenditures per house for ECMs only ($1500) remained within the original budget for the field test. One possible problem with this choice is associated with the uncertainty of the energy savings predicted for the ECMs with BCRs near 1.0. ECMs with a BCR near 1.0 are marginally cost effective. If the energy savings for these ECMs are just slightly less than predicted, the cost savings may not be sufficient to justify their installation.

A logical choice for the cutoff value could have been the value that maximized the BCR for the program. Two problems with this approach may make the program administratively unattractive. First, expenditures for ECMs (and, hence, expected savings) among the audited houses become very unequally distributed: a large portion of the expenditures are concentrated in a small set of the homes and little money is spent in many homes. Second, in the homes in which little money is spent, the administration costs are more than the costs associated with installing the ECMs. Additional discussion of BCR cutoff and its selection is provided by Zimmerman (1990).

5.3 FIELD EXPERIENCE

Two ECMs included in the technique were not used in the field test: having the occupants maintain a reduced thermostat setting for all hours of the day and employing a night or day setback strategy (depending on occupancy patterns) either through occupant control of the thermostat or installation of a clock thermostat. Under the selection technique, the auditor estimates the occupants' current thermostat setpoint practices through discussions and visual observations, determines whether these ECMs are applicable, and estimates the extent to which the occupants would follow recommendations for altering their current practices. Despite these steps and regardless of the experience level of the auditor, we felt that the savings from these ECMs could not be accurately predicted because of the uncertainty regarding the occupants' current behavior and the extent to which they would alter this behavior. We also felt that the level of training needed to make these ECMs effective would not be provided under the planned weatherization program. A supplemental analysis to be discussed in Sect. 6.1 indicated that only one clock thermostat would have been recommended if it had been considered.

If the two ECMs identified in the previous paragraph had been used in the field test, the selection technique would not have been flexible enough for our needs. At the time information is entered, the auditor must select whether to reduce the thermostat setting manually (by the occupants) or automatically (by a clock thermostat). Both options cannot be compared within the technique at the same time.

One limitation of the measure selection technique is that the addition of different levels of insulation cannot be examined for a particular ECM (especially noticeable for attic insulation). At the time information is collected by the auditor (or while it is input to the computer), the auditor must select the level of insulation to be added. If the BCR of the ECM at the selected level is less than the cutoff value, the ECM is not recommended even though the BCR at a lower insulation level might be acceptable. If the BCR of the ECM at the selected level is greater than the cutoff value, the possibility that a higher level of insulation would also be acceptable is not known. A lower or higher level of insulation can only be studied by editing the input file and rerunning the program for the house.

In identifying windows to be considered for storm windows, the presence and condition of existing storm windows should be taken into account. If, in an auditor's opinion, an existing storm window has deteriorated to the point that it is no longer effective, then the window should be assumed to be without a storm.

A 60°F balance point temperature was assumed for all houses because a unique value for each house could not be identified using the method provided in the technique. In about 75% of the audit houses, a 58°F balance point temperature would have been selected by the auditors. This result and other information obtained from examination of the method indicate that an auditor is not able to discern differences between selected balance points from visual examinations of data plots. A 60°F temperature was recommended by WECC to be reasonable based on their experience with the measure selection technique.

The length of the training courses provided to field personnel on the selection technique (4 days) and the infiltration reduction procedure (2 days) were likely not adequate. The four-day training on the selection technique centered on entering information into the personal computer and performing the computer calculations. Although previous experience with spreadsheet programs is not required to use the technique, NF personnel felt that having some experience allowed a more thorough understanding. This training was well received and, for the experience level of the personnel, was adequate. NF personnel felt, though, that additional time spent in the field training auditors on how to collect the information (especially that peculiar to this technique), to complete audit forms, and to make decisions regarding emergency repairs could have reduced problems encountered in the field test.

The two-day training course on the blower-door guided infiltration reduction procedure centered on the theory behind infiltration, operation of the blower door, and making measurements. Training on locating and sealing leakage sites was also covered through slide demonstrations, limited field demonstrations, and discussions. This latter training may not have been sufficient to train crews on how to cost-effectively seal leaks, as will be discussed in Sect. 7.1.

The work order produced by the selection technique was not useful for the field test. The work order is designed for use in programs in which a single crew will be performing the work or contractors will be paid the same price for a given job. In the field test, multiple heating and insulation contractors were selected to install the same ECMs, and their costs were slightly different for the same work performed. The work order was not used because separate work orders for the two types of contractors employed (insulation and heating system) could not be produced, average prices were listed on the printed work orders instead of contractor specific prices, and it took too long to use the work order software.

The use of multiple contractors to install identical ECMs also affects the accuracy of the installation costs predicted by the technique. Only a single material and hourly installation cost can be assigned to each ECM in the technique. If multiple contractors are used, an average value between contractors is used for the material and hourly costs.

Two facets of implementing foundation wall insulation in the selection technique affected the frequency this ECM was recommended (to be discussed in Sect. 6.1). First, the feasibility of this ECM for a particular house was determined by the auditor based on personal judgments after observing whether the house was of balloon construction (such a house has no foundation exposed to the outside air), moisture was leaking through the basement walls, and there was considerable shelving installed along the foundation walls. Second, a typographical error occasionally occurred when inputting the percent of foundation wall area above grade. Instead of typing 0.34 (to represent 34%), a 34 was entered, making the percentage 3400%.

In New York, an insulation jacket and vent damper cannot both be installed on the gas water heater according to local codes and without invalidating the manufacturer's warranty. Under the measure selection technique, both ECMs could be recommended. However, both ECMs were never recommended simultaneously in the field test because of actions taken by the auditors in the field. On the audit data form, the auditors would indicate that a vent damper could not be installed on all old water heaters without a jacket. This action was taken under the assumption that blanket insulation was a higher priority ECM.

In evaluating a reduction In the hot water setpoint temperature, the technique does not specifically consider whether a dishwasher is present and if it has its own water heating element. In the field test, the auditors considered this in evaluating the potential of this ECM. Because of the number of calls received concerning the hot water temperature after being reduced in the houses, it is likely that occupants readjusted the temperature to a higher temperature.

During the field test, NF personnel were concerned that a recommendation on a proper size for a new space-heating system was not included in the technique. A properly sized space-heating system should be installed to achieve expected savings and maximum efficiency. The size of the present space-heating system, the degree that it may be incorrectly sized, and the energy load reductions that will occur due to the installation of other ECMs in the house need to be considered in sizing the new system. Because only a few new space-heating systems were installed, this was not a problem during the field test.

Approximately 4 person-hours were required to perform the technique per house. These hours were broken down as follows: 2.5 person-hours to collect the field data (including driving time); 0.75 person-hours at the office to interpret field drawings, perform calculations in the audit form, and complete the audit form; and 0.75 person-hours to input the information into the computer, perform the computer calculations, and obtain the recommended ECMs. A detailed drawing of each house was prepared in the field which increased the field time. Although such a drawing was not a requirement of the selection technique, it proved to be very valuable, especially to explain differences between the amount of work to be performed as determined by the contractor and the technique.

6. ENERGY CONSERVATION MEASURES

Information on the ECMs installed in the audit houses, the costs of the installations, and the energy savings predicted by the selection technique for the ECMs are summarized in Tables 6.1-6.3. This information is presented for the individual houses in Tables 6.1 and 6.2, and summarized by individual ECMs in Table 6.3. As discussed in Appendix C, an error found in the selection technique adversely affected the ECMs installed in nine of the 45 audit houses: ECMs that were not cost effective were incorrectly recommended for installation and, conversely, ECMs that were cost effective were not. Table 6.1 presents information on the audit houses that were not affected by this error; Table 6.2 presents information for the nine affected houses. The information in Table 6.3 is that for the 36 unaffected houses only. Information collected on the nine houses remains useful in studying the accuracy of algorithms used in the selection technique to predict energy savings and installation costs; information from these houses cannot be used, though, to represent the energy savings that would result from use of the corrected technique or the types of ECMs that would be installed.

6.1 RECOMMENDED AND INSTALLED MEASURES

As shown in Fig. 6.1, only 11 of the 19 ECMs considered by the technique were actually installed in any of the 36 audit houses (a new water heater is not considered an ECM within the technique but was installed in one house as a repair item). Three water-heating system ECMs (pipe insulation, tank insulation, and temperature reduction) as well as attic, wall, and sill box insulation were frequently performed. Space-heating system tune-ups were frequently performed in the audit houses to ensure that the systems were operating safely and to avoid any liability issues (a programmatic decision implemented through the measure selection technique), although energy savings were still expected. In only a few cases was a tune-up recommended based only on the cost effectiveness of the expected energy savings. A tune-up was not performed in a few houses because of an error in the measure selection

Table 6.1. **House-by-house listing** of energy **conservation** measure **information for** the 36 **audit** houses **unaffected** by an error **in** the **measure** selection **technique**

House	Energy conservation measures installed[a]: Measures with estimated savings >75 therms each	Energy conservation measures installed[a]: Measures with estimated savings <75 therms each	Measures recommended but not installed	Installation cost: Actual ($)	Installation cost: Estimated ($)	Predicted savings (therms/year): Installed	Predicted savings (therms/year): Recommended
1	IF,AI	WB,WP		791	1123	373	430
3	AI,WI	IF,WB,RT,WP,TU	FL,SI	1521	1483	473	397
14	AI,WI	IF,WB,SI,RT,WP,TU		1851	1674	357	327
16		IF,SI,WP,RT,WH,TU		615	449	94	70
26	WI,AI	WB,SI,WP,TU	IF	1956	1085	266	261
28	AI,WI	IF,SI,WB,TU,RT,WP		1449	1503	365	359
48	AI	WI,WB,TU,RT,WP	IF	439	403	160	187
59		WB,IF,SI,WP,RT,TU	AI	253	199	67	97
68	WI.AI	IF,WB,WP,TU		2144	2346	453	665
70	AI,WI	WB,WP,RT,TU,IF	WD,SI	1476	1258	396	451
72		WB,TU,IF,SI,WP,RT		291	220	97	137
76		IF,RT,SI,WP,TU	FW	265	335	67	143
79	AI,WI,IF	TU,WB,WP		2080	3172	795	932
84	WI,AI	SI,WP,RT,TU	IF	1436	1310	270	280
86	WI,AI,FL	IF,RT,WP,TU		2585	2428	499	625
88	WI	AI,WB,RT,IF,FL,WP,TU		2909	2895	484	714
91	WI,AI	IF,SI,TU,WP,RT		2100	2477	582	658
105	AI,WI	WB,IF,WP,TU		1560	1556	297	403
106	WI.AI	TU,IF,WB,WP,RT	SI	1738	1933	453	501
110	WI,AI	IF,TU,WP	WD	2131	1875	438	456
113		TU,WP	WD,IF	97	121	20	69
115	WI	AI,TU,WB,RT,IF,SI,WP		1111	850	224	227
120	AI	WB,IF,WP,RT	FL	686	1148	250	407
124	AI,WI	SI,TU	IF,WP	2086	1730	358	390
129		WB,AI,WP,IF,TU		583	459	69	209
143	WI	WB,IF,RT,WP,TU	AI	1505	1859	319	386
146	WI	AI,IF,WB,WP,RT,TU		2466	1964	471	481
147	FW	WB,FL,IF,SI,RT,WP	AI	656	580	312	356
148	WI,AI	WB,TU,IF,RT,WP,SI		2474	2049	557	539
154	AI	IF,WB,SI,RT,WP,TU		701	790	265	346
155	CF,AI,IF	WB,SI,RT,WP	FW	2474	3008	800	921
156	AI,FW,WI,IF	RT,WP,TU		2691	2666	803	989
165	AI	FL,IF,RT,WP,TU	WI	935	1206	320	467
167	WI	IF,WB,TU,AI,WP		1672	1590	294	377
170	WI	AI,WB,SI,WP,RT,TU,IF	FL	1634	1583	285	355
172	AI	IF,SI,WB,WP,TU	WI	942	1716	173	381

[a]Energy conservation measures are listed in order of largest estimated **savings**

AI - attic insulation
CF - condensing furnace
FL - floor insulation
FW - foundation insulation
IF - infiltration reduction work
MB - *mid-efficiency* boiler
RT - reduce water heater temperature
SI - sill box insulation
TU - **space-heating** system tune-up
VD - thermal vent damper
WB - water heater tank insulation
WD - water heater vent damper
WH - water heater
WI - wall insulation
WP - water heater pipe insulation

Table 6.2. House-by-house listing of energy conservation measure information Cor the nine audit houses affected by an error in the measure selection technique

House	Energy conservation measures installed[a]: Measures with estimated savings >7S therms each	Measures with estimated savings <75 therms each	Measures recommended but not installed	Installation cost: Actual ($)	Estimated ($)	Predicted savings (therms/year): Installed	Recommended
9	MB,WI,AI	WB,IF,WP	TU,FL,SI	4139	2976	995	769
29	WI	AI,IF,WP,TU		1842	1638	311	407
73	AI	WB,SI,WP,RT	IF	462	377	150	177
89	WI	IF,WB,TU,WP		1557	1819	305	438
131		IF,WB,SI,WP		212	158	63	71
141	WI	WB,IF,SI,WP,TU		1242	1677	230	395
153		RT,WP,TU	IF	155	81	31	84
166	AI,WI	WB,IF,SI,RT,TU		1352	1333	369	373
169		IF,AI,SI,WB,WP,TU		315	220	100	101

[a]Energy conservation measures are listed in order of largest estimated savings

AI - attic insulation
CF - condensing furnace
FL - floor insulation
FW - foundation insulation
IF - infiltration reduction work
MB - mid-efficiency boiler
RT - reduce water heater temperature
SI - sill box insulation
TU - space-heating system tune-up
VD - thermal vent damper
WB - water heater tank insulation
WD - water heater vent damper
WH - water heater
WI - wall insulation
WP - water heater pipe insulation

Table 6.3. Summary of information on conservation measures installed in the 36 audit bouses unaffected by an error in the measure selection technique

Measure	Number of houses		Average installation cost ($)				Average predicted energy savings (therms/year)[c]			
	Installed	Recommended	Actual[a]	Estimated[a]	Actual[b]	Estimated[b]	Installed[a]	Recommended[a]	Installed[b]	Recommended[b]
Hall insulation	23	25	1187	1126	758	749	193	185	123	123
Attic insulation	29	32	473	449	381	366	145	148	117	121
Infiltration	31	36	70	175	61	153	36	88	31	77
Floor insulation	4	7	159	144	18	21	44	44	5	6
Sill box insulation	17	20	60	34	28	18	15	13	7	7
Interior foundation insulation	2	4	382	253	21	20	214	225	12	15
Space heating-system tune-up	32	32	67	45	60	40	8	24	8	21
Condensing furnace	1	1	1755	1900	49	53	516	516	14	14
Hater heater	1	1	351	275	10	8	0	0	0	0
Mater heater tank insulation	26	26	56	43	40	31	25	25	18	18
Hater heater vent damper	0	3	0	0	0	5	0	0	0	2
Water heater pipe insulation	35	36	22	9	22	9	6	6	6	6
Reduce water heater temperature	25	25	7	2	5	1	9	9	6	6

[a]Average based on data from only the houses in which the particular energy conservation measure was actually installed.

[b]Average based on data from all 36 audit houses.

[c]Recommended savings is based on all energy conservation measures initially recommended by the measure selection technique. The installed savings excludes the savings of measures that were not installed and uses re-estimated savings based on the degree to which each measure was installed (for example, the actual area insulated or the actual amount of infiltration reduction achieved).

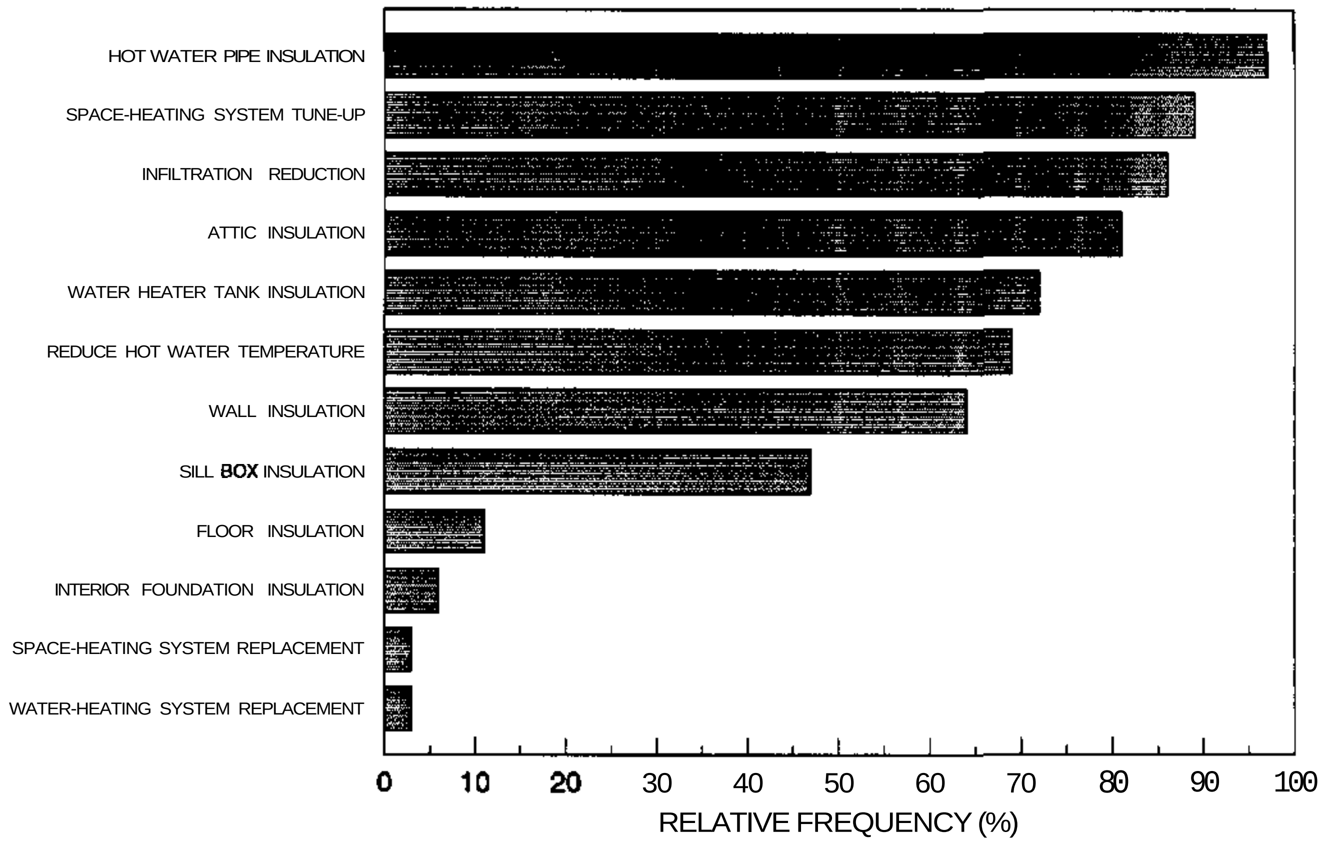

Fig. 6.1. Installation frequency of energy conservation measures in the 36 audit houses. (A new water heater was not considered a measure within the measure selection technique but was installed in one house as a repair item.)

technique. Infiltration reduction work was also a commonly performed ECM. The infiltration procedure was applied to all 36 houses, but sealing work was not performed in 5 houses because the infiltration rate was already below the minimum guideline. Floor insulation, foundation insulation, and space-heating system replacement were ECMs infrequently performed in the audit houses. Floor insulation was infrequently recommended because most of the audit houses were built with basements, for which floor insulation is generally not considered to be an appropriate ECM.

Foundation insulation was not frequently installed because of the aspects identified in Sect. 5.3. Based on the auditor's observation of basement conditions (moisture and wall shelving) and house construction (balloon type), foundation insulation was determined to be feasible in only eight of the 36 houses. In all eight of these houses, only small portions of the foundation area (less than 200 ft^{9}) were being considered; full foundation insulation was determined to be unfeasible in all the houses. In four of the eight houses, foundation insulation was not recommended by the measure selection technique because the wall percentage above ground was input incorrectly (this error decreased the energy savings to nearly zero, but did not affect the cost, making the BCR about equal to zero). Of the remaining four houses, the ECM was installed in only two houses because of an additional input mistake regarding the house construction.

Even though space-heating system replacement can save a significant amount of energy, this ECM was performed in only one house. In a previous field test of the selection technique in Wisconsin (McCold et al. 1988, Ternes et al. 1988), approximately a third of the houses received space-heating system replacements (although, in this test, ECMs with BCRs less than 1.0 were installed to achieve an average expenditure of $1400/house). In this study, space-heating system replacement was cost effective if considered by itself in six of the 36 audit houses (25%), with BCRs ranging from 1.0 to 1.7. After interacting the energy savings of this ECM with those of other ECMs appropriate for the house with higher BCRs, only one replacement was recommended. For a space-heating system replacement to be cost effective, the space-heating energy consumption of the house must be high or the efficiency of the space-heating system must be low, and preferably both.

Considering the eight audit houses with high pre-weatherization space-heating energy consumption (greater than 1375 therms/year as determined by the selection technique using billing data), space-heating system replacement was cost effective in six if considered by itself (all houses in which the space-heating system replacement was cost effective by itself had a space-heating energy consumption greater than 1375 therms/year). Of the two houses where the ECM was not cost effective, one house had a steam boiler and no space-heating system replacement option for it was included in the technique, and the BCR for the ECM was 0.98 in the other. After interacting the energy savings of this ECM with those of other ECMs with higher BCRs, the BCR for space-heating system replacement dropped below 1.0 in five of the six houses; with the present space-heating systems operating at their current efficiencies, the other ECMs decreased space-heating energy consumption in the five houses to the point that replacement of the systems was not cost effective. The house in which replacement of the space-heating system was cost effective had the highest space-heating energy consumption of the 36 houses (2371 therms/year), a space-heating system efficiency of 73.5% (a typical average value), and little energy savings from ECMs with higher BCRs.

Considering the six houses with steady-state space-heating system efficiencies less than 72%, space-heating system replacement was cost effective by itself in only one house but not cost effective after energy interactions were accounted for. Of the five houses in which the ECM was not initially cost effective, one house was equipped with a steam boiler (and no replacement option was considered for it in the selection technique) and the other four were characterized by having low space-heating energy consumptions (ranging from 589 to 1006 therms/year).

Eight ECMs were never installed: storm windows, intermittent ignition device, thermally-activated vent damper, electrically-activated vent damper, gas power burner, outdoor temperature reset control, continuous circulation pump, and water-heating vent damper. As discussed in Sect. 5.3, the primary reason that water-heating vent dampers were not installed is that both it and water-heater tank insulation could not be present on a gas-fired system with a pilot (according to local codes), and tank insulation was assumed to be the higher priority ECM. Algorithms used to estimate the savings of storm windows, intermittent ignition device, and all three vent damper applications were reviewed and found to be reasonable compared to measured and estimated savings reported in the open literature. Thus, the costs required to install these ECMs under the field test were too great to justify their installation.

As identified in Table 6.1, ECMs recommended by the selection technique were not always installed in the houses. Reasons for this varied. For attic, wall, floor, and sill box insulation, the areas were usually already insulated to the extent possible or access could not be gained to insulate the areas. Interior foundation insulation was not installed in two houses because they were of balloon construction and "sill box" insulation was already being installed (mutually exclusive ECMs for this type house). Even though an actual pre-weatherization air-leakage rate was used in the selection technique, infiltration reduction work was recommended in all 36 houses because the minimum air-leakage rate guideline is not used in the selection technique.

Although temperature setback using a clock thermostat was an option in the selection technique that was not used in the field test, subsequent analysis showed that it would not have been a frequently selected ECM if considered. Assuming a 5°F setback for 8 hours/night, a clock thermostat would have been recommended in only one house; with a 7.5°F setback, it would have been recommended in only three houses.

Houses that did and did not receive attic insulation followed a consistent pattern based on the average R value of the attic insulation presently installed. Houses with an average R value less than 10 always received some attic insulation. In most cases, the insulation added was extensive (costing more than $100) because large attic areas were either not insulated or insulated below R-11. Houses with an average R value greater than 10 did not receive additional attic insulation except for a few isolated instances. Generally in these few cases, small attic areas (such as kneewalls or additions) that were not previously insulated were upgraded.

A similar but not as definitive pattern also occurred with wall insulation. Insulation was installed in all wall cavity area that was not previously insulated in 23 of 31 houses (the wall cavity area of the remaining 5 houses was already completely insulated). Only two of the 31 houses had brick or stone siding; in both cases, adding wall insulation was not a cost-effective ECM. In three additional houses, wall insulation was not installed because the ECM was not cost effective: the BCR of wall insulation was less than 1.0 in one house before interaction with other ECMs and in two houses after interaction. In the three remaining houses, the ECM was determined to be not applicable for an unknown reason and, thus, was not considered by the selection technique.

Foundation insulation was installed in the only two houses in which the ECM was determined to be feasible and information was input correctly. The estimated BCRs for these two installations ranged from 4.8 to almost 7.0. Additional investigation showed that the BCR for foundation insulation would almost always be greater than 2.0 if information were input correctly, implying that the measure selection technique would always recommend this ECM if it was feasible. Recent research results of foundation insulation (Robinson et al. 1990) indicate that this ECM is only marginally cost effective, if at all, implying that the BCR estimated by the selection technique is overly optimistic. Thus, it may be fortunate that foundation insulation was not more frequently installed.

The infrequent recommendation for space-heating system replacements could be due to incorrect estimates of the energy savings from this ECM, although previous testing (McCold et al. 1988, Ternes et al. 1988) indicated that these estimates are, on average, correct. In estimating the energy savings of a space-heating system replacement, the change in steady-state efficiencies (reduced several percent to account for seasonal factors) is used. It is likely that a correction of a few percent is not sufficient to fully account for seasonal factors. Additionally, a smaller correction may be needed for the replacement system than the present system because the replacement system would be properly sized, installed, and adjusted.

If envelope and water-heating system ECMs only were to be installed in homes similar to those tested, and under conditions similar to those encountered in the field test (same climate conditions, fuel costs, installation costs, etc.), a simpler selection technique than the one tested might produce near equivalent results. This occurs because the consistency of the housing and the other factors allow patterns to develop regarding correct installations. Such a technique could require less input data and, thus, reduce administration costs. As previously discussed for these houses and conditions, decisions to install attic and wall insulation can be made correctly in most cases based on currently installed insulation levels and building characteristics. Sill box insulation, although not as thoroughly studied as attic and wall insulation, likely follows a similar pattern to that for walls: if no insulation is present and the ECM is applicable, the ECM should be performed in most cases. Infiltration reduction work would be performed in each house the same as under this technique: by following the infiltration reduction procedure. Decisions regarding the remaining two envelope ECMs installed in this study (floor insulation and interior foundation insulation) might be harder to determine on a general basis; nevertheless, a simple calculation procedure may be used for these ECMs. A generalized approach to performing the water-heating system ECMs could also be developed. In the field test, most houses received water heater pipe insulation if insulation was not present, tank insulation in preference to vent dampers on all water heaters without extra insulation, and water heater tank temperature reduction if the temperature was above 120°F.

If space-heating system ECMs are also to be considered, a simpler technique may not be able to be developed. As clearly demonstrated, proper decisions regarding the replacement of the space-heating system can be made only after the energy savings of the ECM are interacted with the savings of other ECMs appropriate for the house that have higher BCRs. If a simpler technique were to be developed, current space-heating energy consumption appears to be a more important screening criterion than space-heating system efficiency, although the latter must still be considered before making a final decision (if the space-heating system energy consumption of a house is estimated to be greater than 1750 therms/year after other ECMs are installed, a space-heating system with an efficiency up to 80% might still be a good candidate for replacement).

6.2 ACTUAL AND ESTIMATED COSTS

The amount of money spent on each house averaged $1453 for the 36 audit houses but varied over a large range as shown in Fig 6.2: less than $500/houses was spent in five houses and more than $2000/house was spent in 11 houses. In using a selection technique designed to maximize program energy savings per investment dollar, such a distribution results because houses with low energy efficiencies receive many ECMs and little work is performed in houses that are efficient.

For the audit houses as a group, expenditures were predominately for envelope ECMs, with equally small amounts spent, on average, for space- and water-heating system ECMs (see Fig. 6.3). As shown in Fig. 6.4, an average of about $750 and $400 was spent in each of the 36 houses for wall and attic insulation, respectively, while less than $75 was spent (on average) on each of the remaining ECMs.

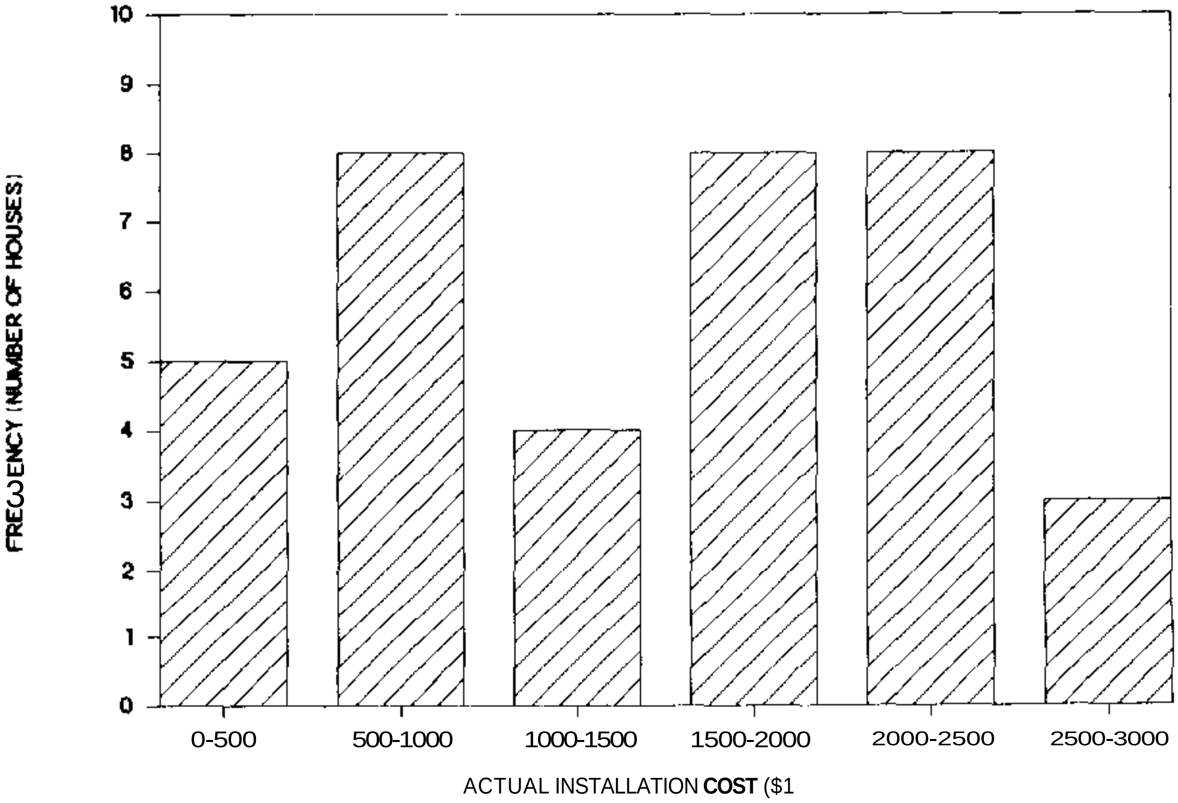

Fig. 6.2. Histogram of actual installation costs for the 36 audit houses.

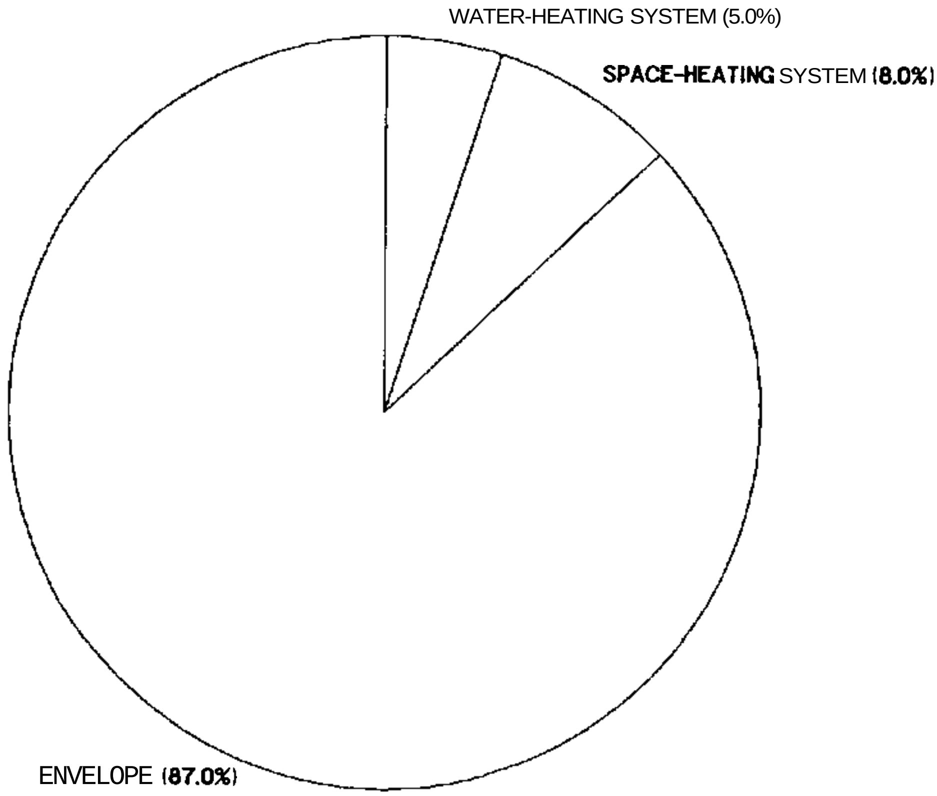

Fig. **6.3.** Distribution of actual expenditures for the 36 audit houses by type of energy conservation measure.

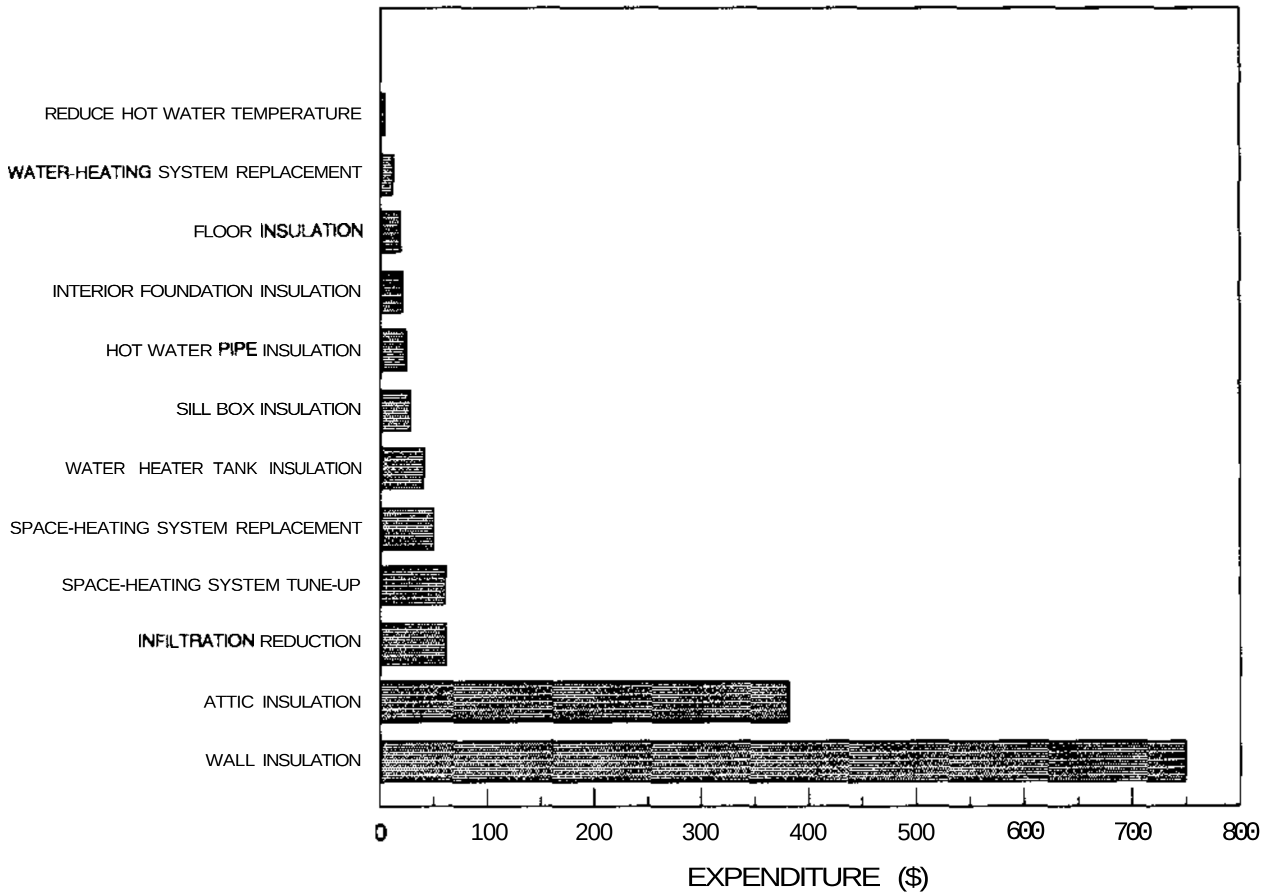

Fig. 6.4. Average actual expenditure in the 36 audit houses for each energy conservation measure (total expenditure for each measure divided by 36, the total number of audit houses).

The cost for performing the ECMs were, on average, estimated quite reliably by the selection technique on a per house and per ECM basis. The actual cost to install the ECMs in the 36 audit houses listed in Table 6.1 was $1453/house as compared to the estimated cost of $1473/house; similarly, for the nine houses identified in Table 6.2, the actual cost of $1253/house is about equal to the estimated cost of $1142/house. Comparisons for individual houses (Fig. 6.5) varied more widely than this average comparison may indicate, although good agreement is still evident. Not being able to install recommended ECMs contributes to individual house fluctuations in only some cases because the ECMs that were not installed were usually inexpensive ECMs.

Figure 6.6 shows that, except for infiltration reduction work and the replacement space-heating system, the costs required to install each ECM were, on average, higher than that estimated by the selection technique (this figure only compares the actual and estimated costs from houses in which the ECM was actually installed as listed in Table 6.3). On an absolute basis, the underprediction of cost is most serious for foundation wall insulation; on a relative basis, the costs for water heater pipe insulation and reducing tank temperature were much higher than estimated. The use of contractors to perform these ECMs and to install water heater insulation likely inflated the costs really necessary to perform these ECMs. Because only one space-heating system was replaced, the overestimation of costs for this ECM is not significant. The large overestimation of costs for infiltration reduction work is explained in Sect. 7.1. Table 6.4 compares costs assumed in the selection technique to estimate the costs of ECMs to actual costs.

6.3 PREDICTED ENERGY SAVINGS

In Tables 6.1-6.3, two savings estimates are provided: installed and recommended. In both cases, the savings are based on energy savings estimates calculated by the selection technique. The recommended savings estimate is based on all ECMs initially recommended by the technique; on

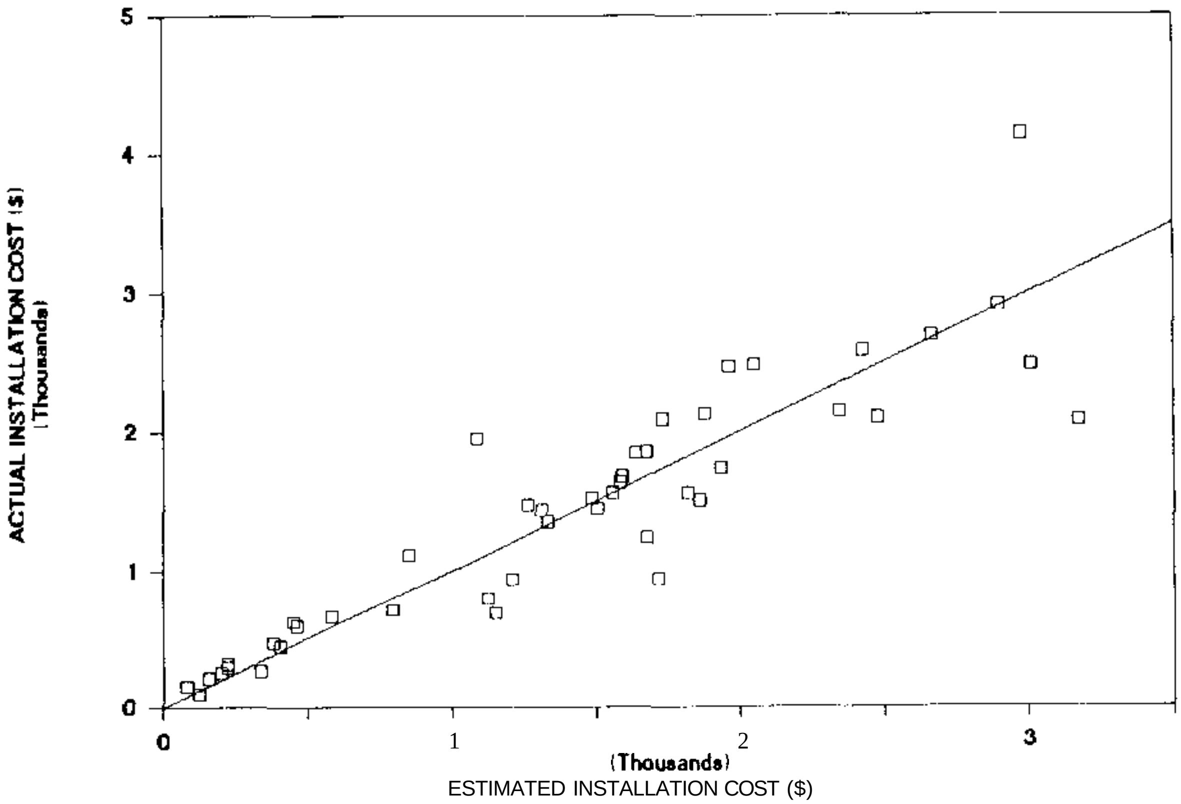

Fig. 6.5. Comparison of the actual installation cost of energy conservation measures for each house to the installation cost estimated by the measure selection **technique.** The solid line indicates where actual and estimated costs are equal.

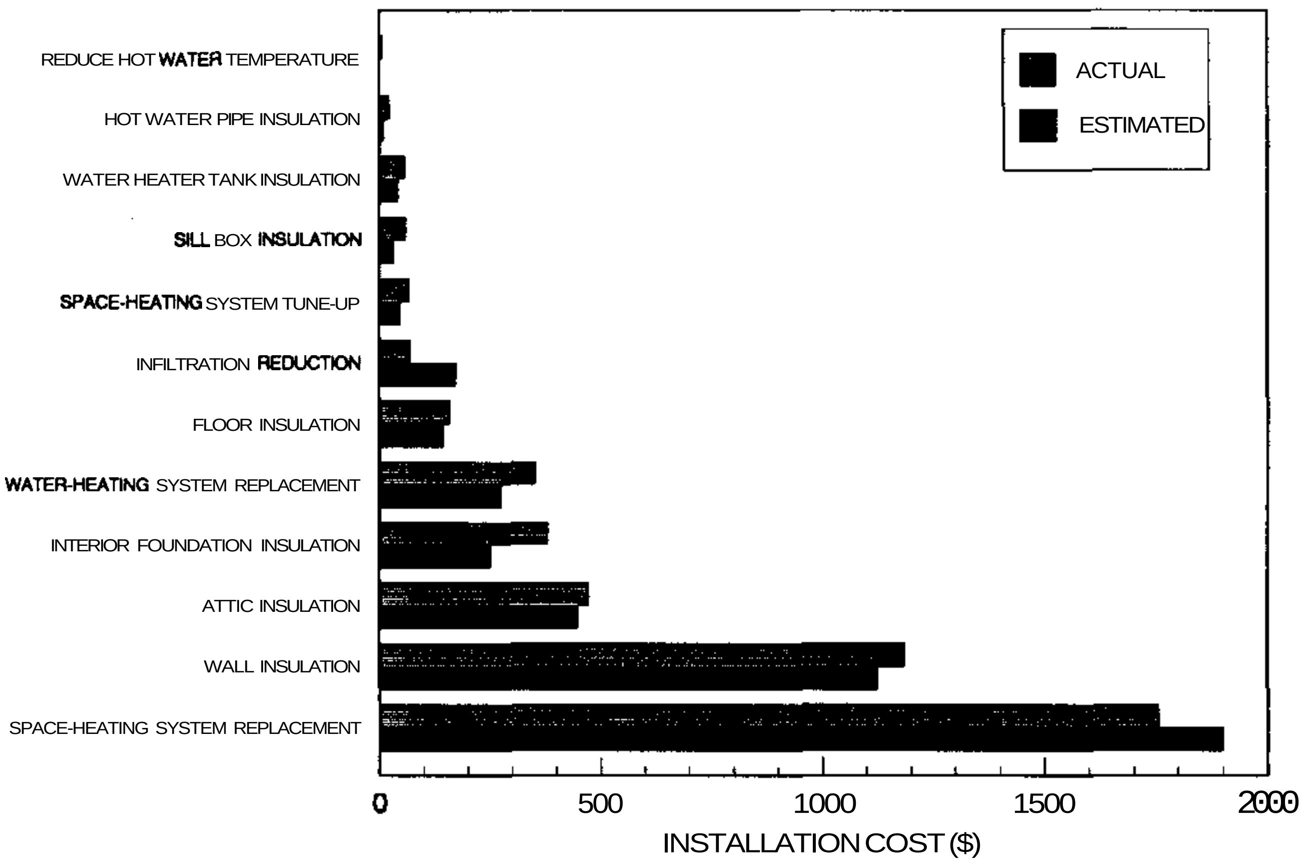

Fig. 6.6. Average cost to install each energy conservation measure in houses receiving that measure (total cost for each measure divided by the number of houses in which the measure was installed).

Table 6.4. Comparison of actual and assumed costs for energy conservation measures

	Assumed Cost[a] ($)	Actual Cost[a] ($)
Building-envelope measures:		
wall insulation (3.5 in.)	0.72-0.99/ft^2	0.65-0.95/ft^2
attic insulation		
attic floor	0.026-0.042/ft^2/R	0.026-0.055/ft^2/R
sloped ceiling	0.056-0.090/ft^2/R	0.026-0.068/ft^2/R
kneewall	0.026/ft^2/R	0.032-0.086/ft^2/R
infiltration reduction	30/h	33/h
floor insulation	0.050/ft^2/R	0.050-0.063/ft^2/R
sill box insulation	0.029/ft^2/R	0.026-0.045/ft^2/R
interior foundation insulation	0.05-0.37/ft^2/R	0.073-0.086/ft^2/R
Space-heating system measures:		
space-heating system tune-up	45 each	45-81 each
95% SSE condensing furnace	1900 each	1755 each
Water-heating system measures:		
insulation blanket	43 each	54-58 each
hot water line insulation	0.82-0.92/ft	2.25-2.41/ft
reduced hot water temperature	2.40 each	0-11 each

[a]R used in column means per R-value of insulation installed

the other hand, the installed savings estimate excludes the savings of ECMs that were not installed and uses re-estimated savings based on the degree to which each ECM was installed (for example, the actual area insulated or the actual amount of infiltration reduction achieved). The recommended savings estimate is useful in examining the overall accuracy of the selection technique. In examining the accuracy of energy savings algorithms used in the selection technique, a comparison of measured savings to the installed savings estimate provides the greatest insight.

The average energy savings predicted for the 36 audit houses, based on the ECMs actually installed in the houses, was 347 therms/year. As shown in Fig. 6.7, the predicted energy savings of each house varied over a large range. Most houses were predicted to save between 200 and 500 therms/year; however, six houses were predicted to save less than 100 therms/year while five houses were expected to save over 500 therms/year. As with the house expenditures, this distribution results from using a selection technique designed to maximize program energy savings per investment dollar: houses with low energy efficiencies receive many ECMs that should save significant levels of energy while few ECMs are performed in other houses that are comparably efficient, resulting in little energy savings. As shown in Fig. 6.8, there is a strong relation between the predicted savings and the actual cost of the weatherization work in each house.

The average estimated energy savings of the audit houses, based on all the ECMs initially recommended by the selection technique, was 416 therms/year. Examination of Table 6.3 shows that the difference between the recommended and installed savings is due primarily to less energy savings predicted from infiltration reduction work and space-heating system tune-ups once the actual level of improvement from these ECMs was known. These are discussed more in Sects. 7.1 and 7.2, respectively.

For the audit houses as a group, energy savings were expected to result principally from attic and wall insulation (Fig. 6.9), even though many of the other ECMs were performed in most of the houses. This is

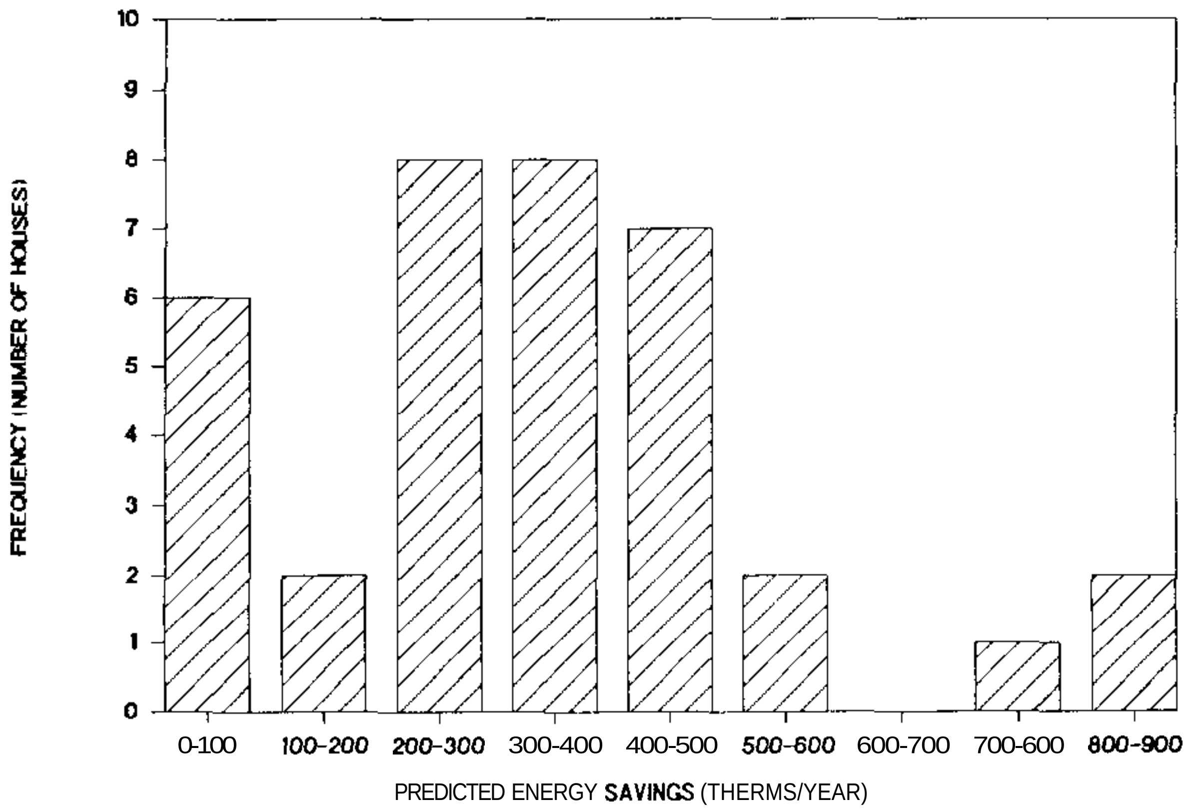

Fig. 6.7. Histogram of predicted energy savings for the 36 audit houses, based on the energy conservation measures actually installed in the houses.

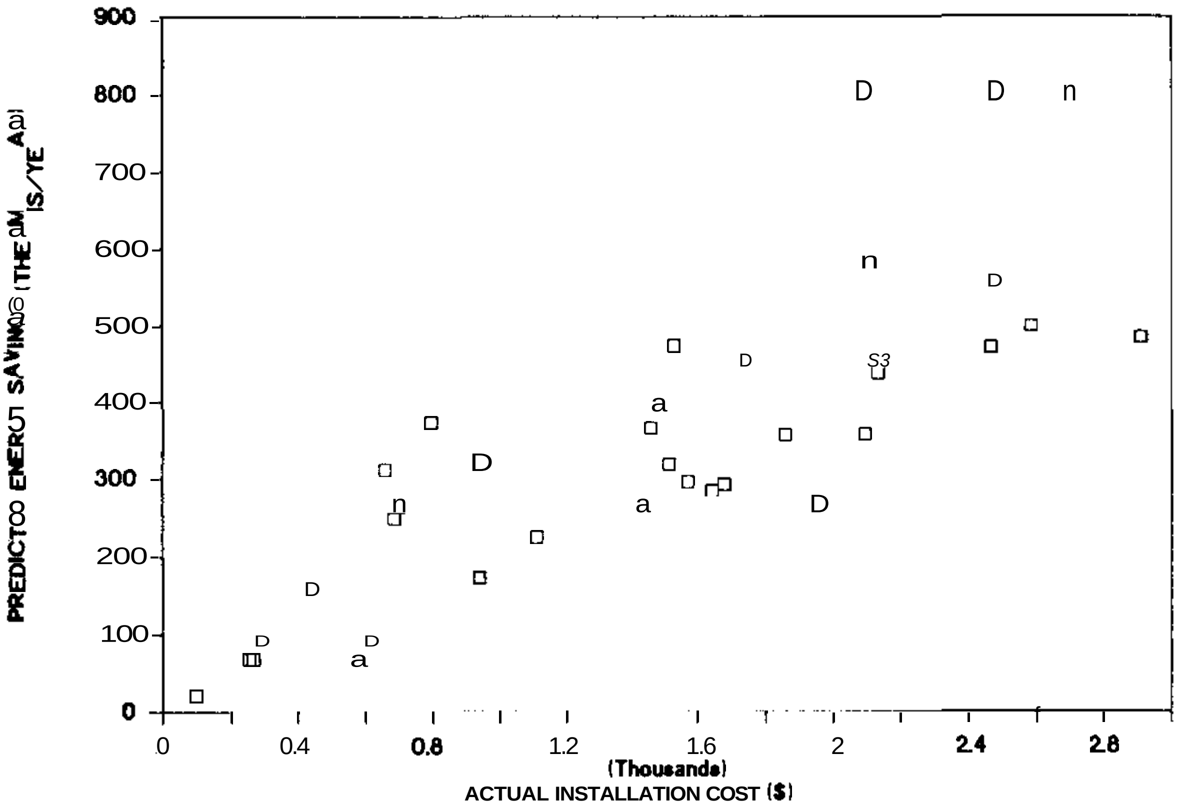

Fig. 6.8. Comparison of the predicted energy savings for each audit house (based on the energy conservation measures actually installed) to the actual installation cost.

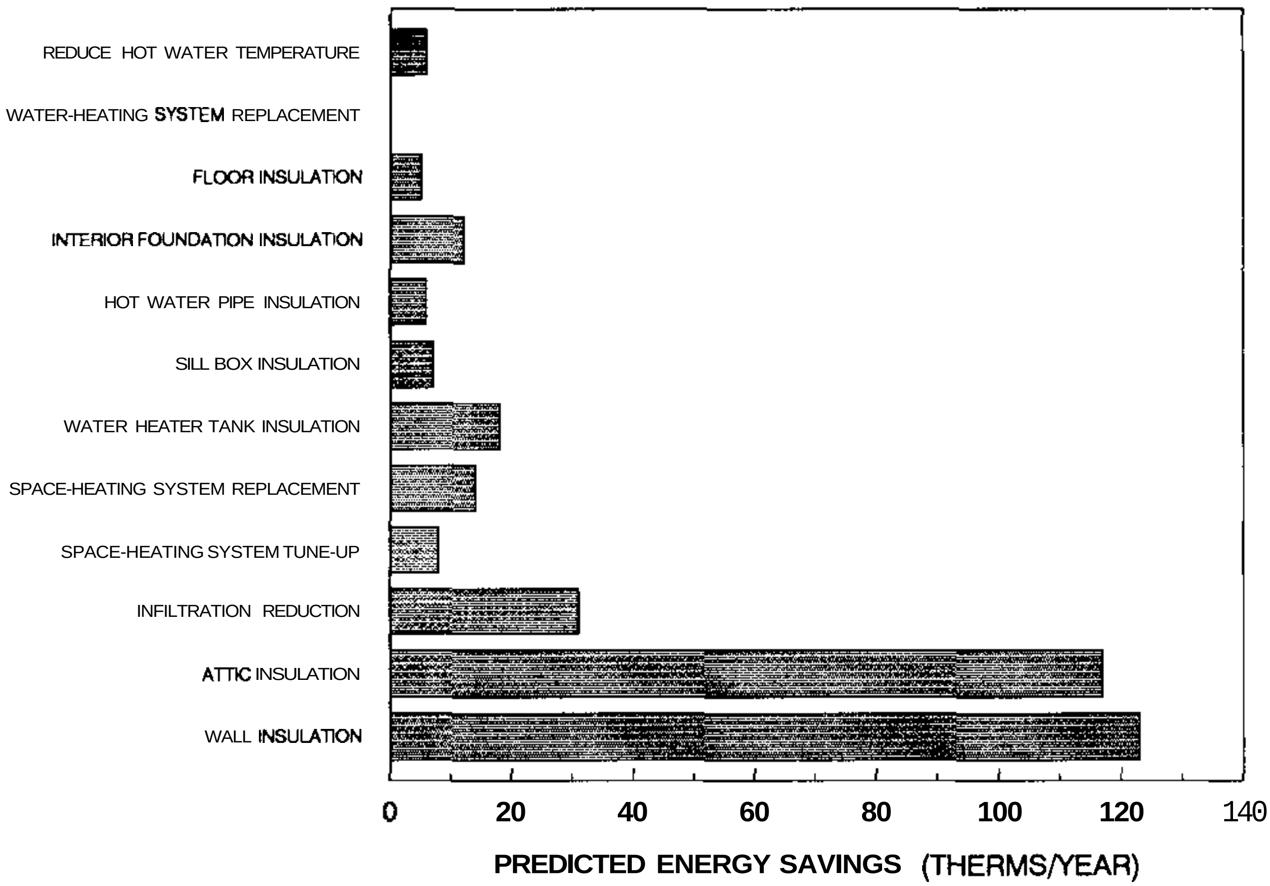

Fig. 6.9. Average predicted energy savings in the 36 audit houses for each energy conservation measure (total predicted savings for each measure actually installed divided by 36, the total number of audit houses).

consistent with the cost expenditures where the largest expenditures were for these same two ECMs. Large savings were predicted from interior foundation wall insulation and space-heating system replacement in the houses where these ECMs were installed, but, because they were installed in only two and one house, respectively, their savings impact on the entire audit group is small.

7. NON-ENERGY RESULTS

7.1 AIR-LEAKAGE MEASUREMENTS AND REDUCTIONS

Air-leakage rates were measured three times in each of the audit houses: before weatherization, after blower-door-guided infiltration work, and after weatherization. Infiltration reduction work was always performed before other ECMs were installed. The first two measurements were made on the same day by the crew performing the infiltration work (in July or August 1988 for most houses). The third measurement was taken after all weatherization work had been installed and inspected (usually in November 1988). In the control houses, two measurements were taken at approximately the same time as the audit houses to correspond to the pre- and post-weatherization measurements.

Air-leakage rate measurements for the control and audit houses are summarized in Tables 7.1 and 7.2, respectively. These rates represent the rate of air flow (units of cubic feet per minute) through the house when the house is depressurized 0.20 in. H_2O (50 Pa) below ambient pressure (cfm50). Fan pressurization (blower door testing) was used to measure these air-leakage rates, generally following a standard technique (ASTM 1981). A series of air-leakage rates were measured in each house at different levels of depressurization [nominally 0.04 in. H20 (10 Pa) to 0.24 in. H_2O (60 Pa) in increments of 0.04 in. H_2O (10 Pa)]. These data were then fit to a power curve, allowing the air-leakage rate at 0.20 in. H_2O (50 Pa) depressurization to be determined.

The average pre-weatherization air-leakage rate of the control houses was 3034 cfm50 and the average post-weatherization rate was 2989 cfm50. The change of -46 cfm50 in the average air-leakage rate was not significant: the rate in most houses changed less than 200 cfm50, although changes as large as 500 cfm50 were observed. Because no work was performed on the control houses, a change in the individual or average rates were not expected. Changes observed in the individual house rates are likely due to random measurement errors, possibly induced

Table 7.1. Control house air-leakage measurements

House	Pre-weatherization (cfm50)	Post-weatherization (cfm50)	Change (cfm50)
2	2330	1844	-486
6	2226	2362	136
7	2220	2175	-45
8	2981	3026	45
11	3475	3831	356
12	3412	3466	54
27	3538	3412	-126
30	3320	3281	-39
31	1963	1798	-165
51	4852	4779	-73
58	2222	2264	42
65	3178	3054	-124
75	5542	5049	-493
78	6678	6779	101
81	3202	3336	134
85	2139	2224	85
87	4429	4023	-406
92	2084	1783	-301
93	3556	3551	-5
94	5604	5797	193
95	1829	1916	87
103	1393	1404	11
108	1865	1875	10
109	2297	2363	66
111	3180	3193	13
114	2003	2058	55
116	3227	3091	-136
121	2000	2057	57
122	2816	3205	389
127	1347	1313	-34
134	4461	4495	34
135	2744	2457	-287
140	5056	4750	-306
142	3511	3650	139
144	2303	2291	-12
145	1635	1625	-10
149	2001	1954	-47
150	1937	1912	-25
152	2390	2340	-50
159	3707	3302	-405
160	2942	3115	173
161	3459	3340	-119
163	1538	1424	-114
174	4914	4535	-379
Average:	3034	2989	-46

Table 7.2. Audit **house air leakage measurements**

House	Pre-weatherization Estimate[1] (cfm50)	Pre-weatherization Measured (cfm50)	Pre-weatherization Difference (cfm50)	Post-infiltration Measured (cfm50)	Post-infiltration Change Measured (cfm50)	Post-infiltration Change Estimated[2] (cfm50)	Post-weatherization Measured (cfm50)	Post-weatherization Change Pre - post (cfm50)	Post-weatherization Change Other measures[3] (cfm50)	Infiltration reduction work cost ($)	Infiltration reduction work cost effectiveness (cfm50/$100)	Infiltration reduction work cost effectiveness BCR[4]
1	4000	6815	2815	4741	-2074	-2698	4322	-2493	-419	133	1559	5.0
3	4200	3498	702	3188	-310	-578	3081	-417	-107	66	470	1.5
9	6000	4168	1832	3992	-176	-928	3373	-795	-619	88	200	0.6
14	3000	2216	784	1687	-529	-273	1491	-725	-196	100	529	1.7
16	3300	2370	930	1726	-644	-314	1574	-796	-152	83	776	2.5
26	3400	1475	1925	1475	0	-104	1519	44	44	0	ERR	—
28	4200	1950	2250	1627	-323	-211	1498	-452	-129	66	489	1.6
29	5700	4466	1234	4060	-406	-1129	3439	-1027	-621	83	489	1.6
48	4200	1533	2667	1533	0	-136	1431	-102	-102	0	ERR	—
59	3500	2080	1420	1932	-148	-232	1626	-454	-306	60	247	0.8
68	4200	5870	1670	5579	-291	-2338	3721	-2149	-1858	70	416	1.3
70	4000	1762	2238	1762	0	-160	1578	-184	-184	16	0	0.0
72	5000	2786	2214	2584	-202	-424	2772	-14	188	66	306	1.0
73	3900	1868	2032	1868	0	-185	1709	-159	-159	0	ERR	---
76	3500	2983	517	2778	-205	-485	2678	-305	-100	66	311	1.0
79	4300	6826	2S26	5932	-894	-2429	5622	-1204	-310	66	1355	4.3
84	4100	1570	2530	1570	0	-118	1094	-476	-476	0	ERR	—
86	3700	5233	1533	4970	-263	-1743	3081	-2152	-1889	66	398	1.3
88	4200	6025	1825	5837	-188	-2065	5003	-1022	-834	66	285	0.9
89	6000	5217	783	4646	-571	-1659	3990	-1227	-656	66	865	2.8
91	5500	5621	121	4930	-691	-1713	4108	-1513	-822	66	1047	3.4
105	4200	3168	1032	3007	-161	-566	2756	-412	-251	66	244	0.8
106	4200	3124	1076	2799	-325	-590	2326	-798	-473	66	492	1.6
110	4800	3275	1525	2842	-433	-603	2029	-1246	-813	83	522	1.7
113	3600	853	2747	853	0	-25	917	64	64	0	ERR	—
115	4000	2390	1610	2248	-142	-302	2330	-60	82	66	215	0.7

Table 7.2. (continued)

House	Pre-weatherization			Post-infiltration			Post-weathetization			Infiltration reduction work cost	Infiltration reduction work cost effectiveness	
					Change			Change				
	Estimate[1] (cfm50)	Measured (cfm50)	Difference (cfm50)	Measured (cfm50)	Measured (cfm50)	Estimated[2] (cfm50)	Measured (cfm50)	Pre - post (cfm50)	Other measures[3] (cfm50)	(S)	(cfm50/$100)	BCR[4]
120	4300	4417	117	4226	-191	-1140	4181	-236	-45	66	289	0.9
124	3800	1473	2327	1473	0	-88	1497	24	24	0	ERR	---
129	4300	4871	571	4829	-42	-1288	4745	-126	-84	50	84	0.3
131	3000	2208	792	1923	-285	-271	1945	-263	22	100	285	0.9
141	4000	2801	1199	2647	-154	-480	2175	-625	-471	66	233	0.7
143	3700	3006	694	2813	-193	-521	2158	-848	-655	66	292	0.9
146	4300	3638	662	3305	-333	-771	2832	-806	-473	66	505	1.6
147	6000	2891	3109	2724	-167	-451	2786	-105	62	66	253	0.8
148	6800	2821	3979	2660	-161	-472	2348	-473	-312	66	244	0.8
153	6000	1596	4404	1596	0	-125	1440	-156	-156	0	ERR	---
154	4000	2657	1343	2350	-307	-368	2080	-577	-270	66	465	1.5
155	4500	5303	803	4444	-859	-1721	3247	-2056	-1197	100	859	2.8
156	4000	5811	1811	5031	-780	-1794	4386	-1425	-645	100	780	2.5
165	4300	4470	170	4206	-264	-1407	4139	-331	-67	66	400	1.3
166	4000	1877	2123	1659	-218	-207	1510	-367	-149	41	532	1.7
167	6400	3988	2412	3629	-359	-939	2838	-1150	-791	55	544	1.7
169	3800	2212	1588	1858	-354	-273	1623	-589	-235	66	536	1.7
170	4500	2378	2122	2378	0	-294	2298	-80	-80	66	0	0.0
172	3500	1874	1526	1725	-149	-192	1703	-171	-22	66	226	0.7
Average:	4353	3321	1653	3014	-306	-774	2644	-676	-370	60		
Average (excluding the eight houses in which no work was performed)					-372	-920				73		

1. value estimated by auditor
2. value estimated by the measure selection technique using the pre-weatherization measured air-leakage rate
3. post-infiltration value minus post-weatherization value
4. benefit-to-cost ratio

by differences in weather conditions between the two periods, and thus have no net affect on the average. These results confirm that average changes observed in the audit houses are real and not due to measurement errors or biases, although some degree of change observed in individual audit houses could be due to measurement errors.

The average pre-weatherization air-leakage rate of the audit houses was 3321 cfm50. The close agreement between this value and the pre-weatherization rate for the control houses indicates that the two groups were equivalent with regard to their air tightness.

The measured pre-weatherization air-leakage rate of each house was used in the measure selection technique to estimate energy savings and costs associated with the infiltration work. An alternative method is to use a value of the air-leakage rate estimated by the auditor based on the visual appearance of the house. This approach was tested and found to be unreliable for an individual house as well as a group of houses. The average estimated value was 4353 cfm50, which is 1032 cfm50 greater than the average measured value (an error of approximately 30%).

The average post-infiltration air-leakage rate of the audit houses was 3014 cfm50, which was 306 cfm50 less than the pre-weatherization rate. One result of following the infiltration reduction procedure was that infiltration work was not performed in eight houses (Houses 26, 48, 70, 73, 84, 113, 124, and 153) because their air-leakage rates were already at or below the minimum ventilation guideline (no reduction was achieved in House 170 even though the two person crew worked one hour in the house). Considering only the houses in which work was performed, the average air-leakage rate reduction was 372 cfm50.

Through use of the infiltration reduction procedure, expenditures for infiltration reduction work were limited to an average of $60/house (excluding $70/house set up cost) for all the houses or $73/house for those in which work was performed ($16 was spent on House 70, perhaps for some minor repair, even though no reduction work was performed). The charge of $66 occurring frequently in Table 7.2 indicates that a two person crew spent an hour in the house performing infiltration reduction work (the charge for each crew member was $33/h, which includes labor and materials). These costs do not include a set-up cost of $70/house charged by the contractor that performed the infiltration work because this cost should be more properly labeled an "audit cost" rather than a cost of performing the ECM and this cost was excessive and only paid because of the research nature of the field test ($30/house would be a more reasonable value). In implementing the procedure, an initial air-leakage rate must be measured to determine whether work should be performed in the house (much like the level of attic insulation must first be determined before the effectiveness of adding more can be established). Depending on who makes this measurement and when, the cost of this measurement may be small to almost negligible.

The energy savings from the infiltration reduction work in each house was estimated using the measured change in air-leakage rate. This energy savings was then used with the installation cost to estimate a BCR for the work. These estimates were made using equations presented by Schlegel (1990) (the same equations used to develop the BCR guideline for the infiltration reduction procedure) and the following assumptions:

1. 6910 heating degree days (base 65°F) for the area,
2. a degree day correction factor of 0.6,
3. a factor equal to 20 to convert cfm to cfm50,
4. a fuel cost of $0.579/therm,
5. a space-heating system efficiency of 75%,
6. a lifetime for the measure of 10 years, and
7. a discount rate of 5%.

The estimated BCR was greater than 2.0 in seven houses, greater than or equal to 1.0 and less than 2.0 in 16 houses, and less than 1.0 in 14 houses (infiltration work was not performed in eight houses). A BCR greater than or equal to 1.0 indicates that the estimated savings was achieved cost effectively under the stated assumptions. Even though the work performed on only about 20% of the houses remained above the original goal (BCR - 2.0), the work performed on 60% was cost effective based upon these estimates.

The infiltration reduction procedure was generally adhered to in performing the infiltration reduction work. No work was performed in any house once the minimum air-leakage rate of the house was obtained (usually between 1500 and 1800 cfm50). Additionally, no work was performed once the effectiveness of the latest work (usually the last hour's work) fell below the guideline for the house (generally 650 cfm50 reduction per $100 expenditure) as indicated from an examination of the BCR and hours of work performed on each house. (The effectiveness shown in Table 7.2 represents the overall effectiveness of the work and not the effectiveness of the latest increment of work. Data taken at intermediate intervals to check the effectiveness of the latest work were not recorded). Examination of these same data indicates that work may have been stopped prematurely in three houses (Houses 1, 79, and 91). One reason that work may have been stopped prematurely in Houses 79 and 91 was that the set up cost for performing the infiltration work was included with the cost of performing the first hour of work. This mistake dropped the apparent effectiveness of the work below the guideline for the house.

Although the infiltration reduction procedure was adhered to, crews may not have been proficient at locating and sealing major leakage sites particular to each house. In 11 of the 14 houses with a BCR less than 1.0, the air-leakage rates remained considerably above the minimum ventilation guideline following the work, indicating that significant leakage area remained. As shown in Fig. 7.1, there is little correlation between the pre-weatherization air-leakage rate of a house and the measured reduction. Although these results could indicate that few leakage sites existed in the houses that could be sealed cost effectively, they more likely indicate a lack of crew proficiency. The

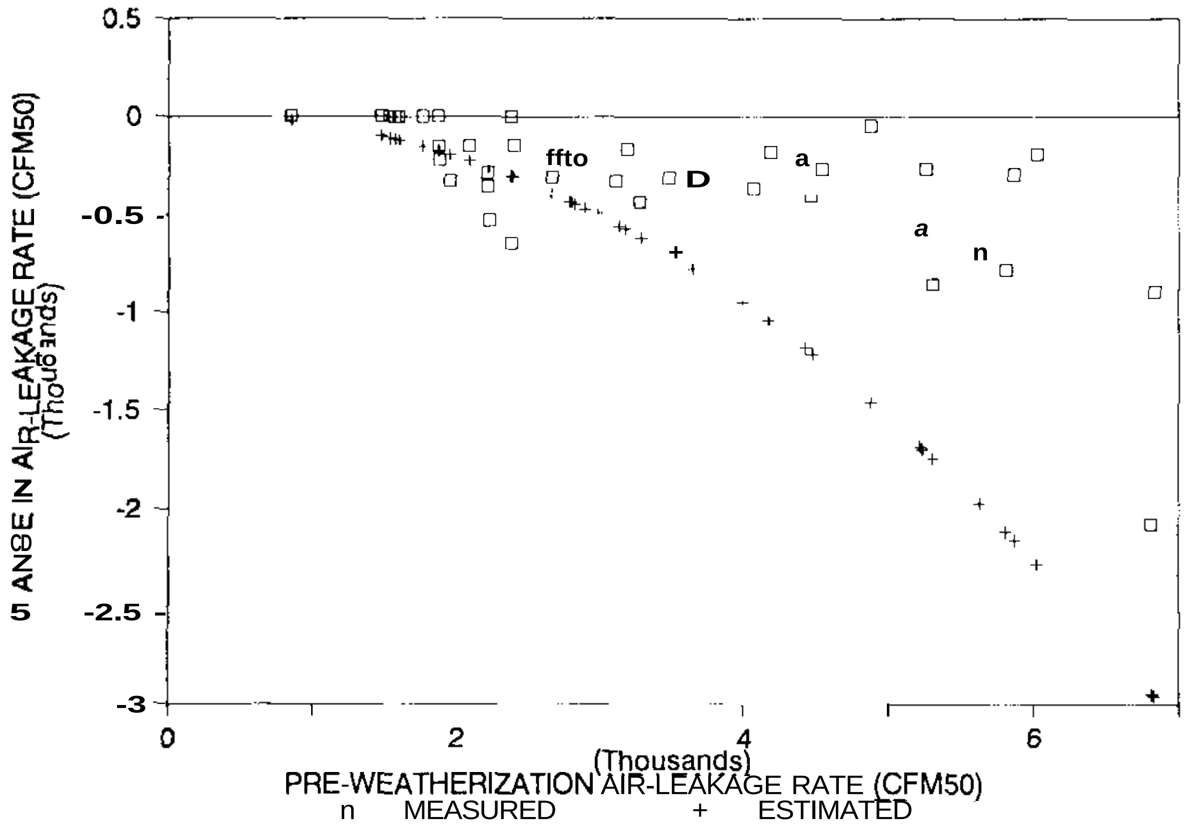

Fig. 7.1. Comparison of the measured and estimated change in air-leakage rate in the audit houses due to infiltration reduction work to the pre-weatherization air-leakage rate.

crews used In the study were trained in the use of blower doors, leak detection, and sealing techniques but had no prior experience with either the procedure or sealing.

In most houses, the air-leakage rate reductions achieved were considerably less than estimates of achievable reductions made in the measure selection technique, as shown in Fig. 7.1. (In this figure, the reductions were estimated assuming an interior volume in each house of 15,000 ft2 in order that a smooth curve would result. Use of the actual volume would make the figure harder to interpret without adding more information.) An average reduction of 774 cfm50 was estimated by the selection technique for all the houses and 920 cfm50 for just the houses in which infiltration work was performed.

The major factor contributing to the discrepancy between achieved and estimated reductions is the estimation method. An equation developed by WECC is used in the measure selection technique to estimate the reduction achievable in a house based on the present air-leakage rate. This equation was developed from their experience regarding reductions achievable by experienced crews in houses with different pre-weatherization air-leakage rates. Because the only two variables used in the equation are the pre-weatherization air-leakage rate and house volume, the estimate is independent of the BCR chosen for the work; the same reduction is estimated If the work must be performed at a BCR of 2 or 1, for example. Realistically, less work can be performed and, thus, a smaller reduction should be achieved when a higher BCR for the work is stipulated. The value estimated by the selection technique may be better interpreted as a typical maximum reduction that can be achieved if the work is performed at a BCR of 1. Because the BCR chosen in this study for the infiltration work was 2.0, the measure selection technique estimates of the reductions are too high.

A second factor that contributed to the discrepancy is the use of inexperienced infiltration reduction crews in the study. Using the same cost-effective guidelines, an experienced crew can work longer in a house and achieve greater air-leakage reductions than an inexperienced crew because the experienced crew can identify and seal leaks more effectively.

A third factor that contributes to the discrepancy is that the minimum guideline used in the infiltration procedure is not considered in the selection technique. Consequently, a reduction is estimated in houses in which no work will be performed if the infiltration procedure is followed correctly. Although not a factor in this study, a maximum expenditure guideline may be used in the infiltration procedure which is also not considered in the measure selection technique.

The expenditures for infiltration work were less than predicted by the measure selection technique. Cost estimates made in the measure selection technique were based on the estimated reductions to be obtained and the BCR stipulated for the work. Because the estimated reductions were high, the cost estimates would also be high. Use of inexperienced crews would tend to decrease the differences because inexperienced crews would spend more money than planned.

The BCR guidelines for the houses were established assuming a BCR of 2.0. Because the BCR cutoff used in the measure selection technique was 1.0, use of the same value for the infiltration reduction work might have been a more appropriate choice. Such a choice would have allowed more work to be performed at a greater expenditure, improving the comparisons between actual and estimated reductions and costs. With a BCR of 1.0, the guideline for the houses would have been approximately 325 cfm50 reduction per $100 expenditure. The available data indicates that with this guideline additional work would have been performed in only 21 houses (eight houses should still receive no work and the effectiveness of the work performed in the remaining 16 houses was less than or equal to even this lowered guideline).

The average post-weatherization air-leakage rate was 2644 cfm50, a reduction of 676 cfm50 from the pre-weatherization rate and 370 cfm50 from the post-infiltration rate (representing the reduction due to ECMs other than the infiltration work installed in the houses). On average, the reductions due to the other ECMs were equal to the reductions achieved from infiltration reduction work.

As shown in Fig. 7.2, the type of insulation ECMs installed and the air-leakage rate before the ECMs were installed (the post-infiltration rate) affect the reductions obtained from the other ECMs in individual houses (in identifying the type of ECMs installed in the houses in Fig. 7.2, differences in the areas insulated were not considered). Houses that did not receive attic or wall insulation (the two main insulation ECMs installed in the study) all had pre-weatherization and post-infiltration air-leakage rates below 3000 cfm50. Because all these houses had attic insulation and half had wall insulation, this begins to indicate that insulation does lead to lower house air-leakage rates. Furthermore, the reductions obtained from the other ECMs in these houses only averaged 47 cfm50 and were always less than 310 cfm50 (increases in the air-leakage rate in several houses likely represent measurement errors as mentioned in the previous discussion of the control houses). Reductions occurring in houses receiving attic insulation but not wall insulation were less than 420 cfm50 in all but one house (the only unique feature of the one house is that it received a condensing furnace), averaged 278 cfm50 (160 cfm50 excluding the one house), and were not dependent on the post-infiltration air-leakage rate. The greatest reductions were obtained in houses receiving both attic and wall insulation. These reductions were dependent on the post-infiltration air-leakage rate, with larger reductions occurring at higher air-leakage rates and almost no reductions occurring at the lower rates (2500 cfm50 or less). The average reduction of the houses with air-leakage rates above 2500 cfm50 was 721 cfm50. Because only three houses received just wall insulation and not attic insulation, statistics for such a small group must be evaluated cautiously. For these three houses, the average reductions for the other ECMs was 594 cfm50, which is consistent with the reductions observed in the houses receiving both attic and wall insulation.

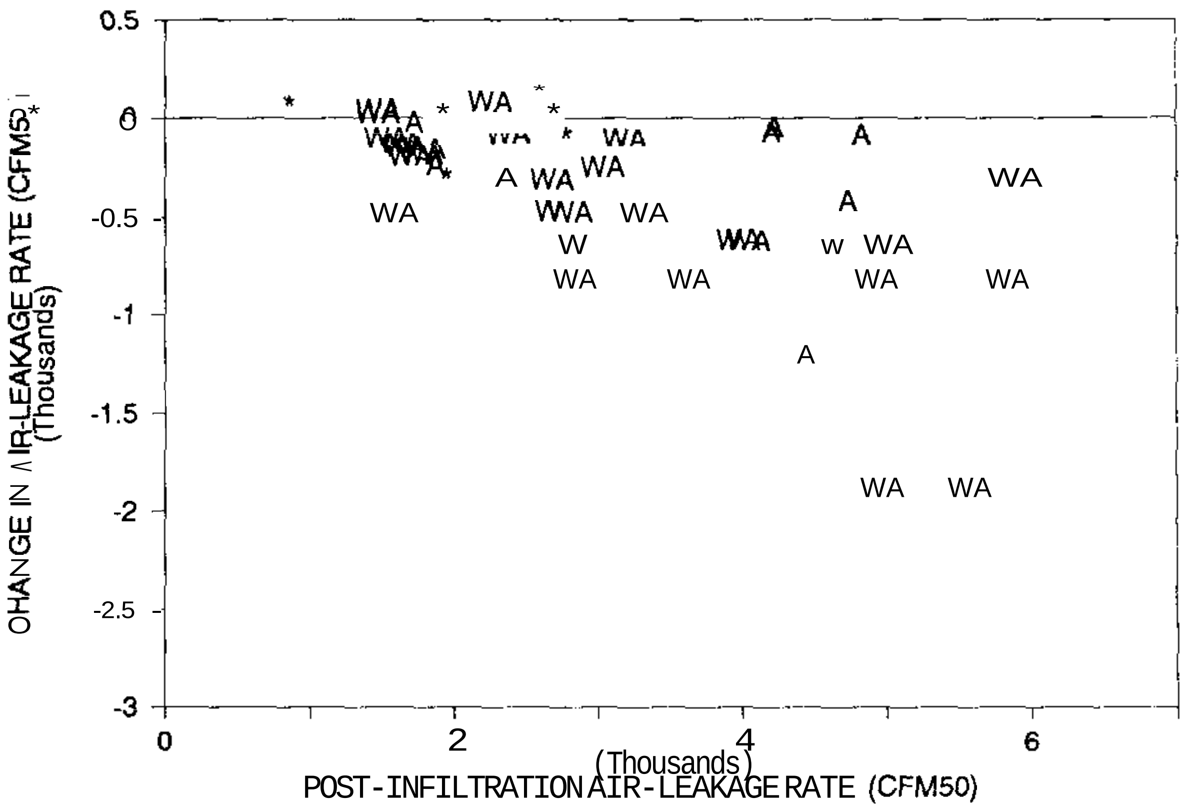

Fig. 7.2, Comparison of the change in air-leakage rate in the audit **houses** due to the installation of energy conservation measures other than infiltration reduction work to the air-leakage rate after infiltration reduction work was performed. An A indicates a house in which attic insulation with a predicted savings greater than 75 therms/year was installed, a W in which wall insulation with a predicted savings greater than this value was installed, a WA that both wall and attic insulation (each meeting this savings criterion individually) was installed, and a * that neither was installed.

The results presented above indicate that significant air-leakage rate reductions can result from the installation of wall insulation (walls were insulated in the field test by blowing cellulose into the wall cavities). If the present air-leakage rate of the house is above 2500 cfm50, reductions on the order of 500 cfm50 are likely to result from the installation of wall insulation alone. In general, only minor reductions (less than half the above value) are likely to be obtained from the installation of wall insulation if the present air-leakage rate is less than 2500 cfm50 and from the installation of other insulation ECMs.

Because the infiltration reduction work was performed before the insulation ECMs were installed, greater reductions might be obtained from the insulation ECMs if performed before the infiltration work. Reversing the order of installation would not have decreased the number of houses requiring infiltration reduction work.

7.2 SPACE-HEATING SYSTEM EFFICIENCY

Space-heating system steady-state efficiencies were measured in the audit houses in June and July 1988 before any ECMs were installed (as part of the audit input data requirements) and again between October and November 1988 following weatherization. Efficiencies in the control houses were also measured in June and July 1988. The pre-weatherization efficiencies were measured by a single company using either chemical or electronic combustion test equipment. The post-weatherization efficiencies were measured by three companies, two using electronic equipment and the other chemical equipment.

The measured pre-weatherization steady-state efficiencies of both the audit and control houses are shown in Fig. 7.3. From a visual inspection, the audit and control groups appear to be equivalent. Efficiencies generally ranged between 70 and 80% for all system ages, with a dip in efficiency occurring for units about 10 years old.

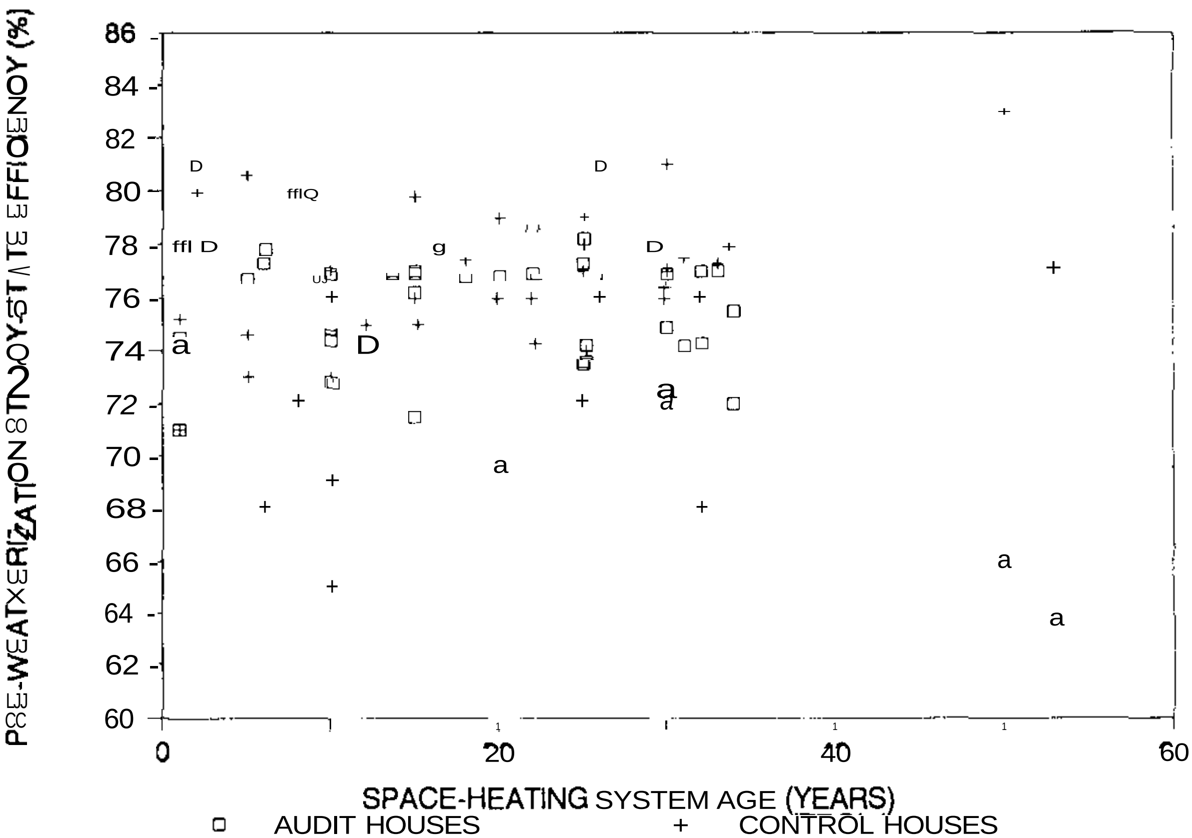

Fig. 7.3. Comparison of the pre-weatherization steady-state efficiency of the space-heating systems installed in the field test houses to the age of the system.

Space-heating system tune-ups were the only mechanical ECMs performed in 43 audit houses that would affect the steady-state efficiency of the systems (two audit houses received new space-heating systems). This tune-up consisted of cleaning the space-heating system as needed, inspecting blower belts and air filters, and adjusting for proper flame and maximum steady-state combustion efficiency under the guidance of flue gas analysis equipment. Adjustments to controls (such as blower speed, fan, and limit switches) were not performed.

Efficiency changes measured in 40 of the 43 houses (post-weatherization efficiencies were not measured in three houses) were compared to values predicted in the measure selection technique to quantify the benefit of space-heating system tune-ups performed in these houses and to determine the accuracy of the prediction method. The change in steady-state efficiency was predicted[1] assuming that no change would occur if the pre-weatherization efficiency was greater than or equal to 79%, the efficiency could be increased to 79% if the pre-weatherization efficiency was between 73 and 79%, and the efficiency could be increased 6% if the pre-weatherization efficiency was less than or equal to 73%.

As shown in Fig. 7.4, measured changes in steady-state efficiency were less than predicted in all but three houses. More importantly, the measured efficiency decreased (identified as negative changes) in about half the houses, especially those with pre-weatherization efficiencies greater than 76%. In houses with pre-weatherization efficiencies less than 72%, though, the measured efficiency always increased. (The line in the figure is a least squared fit to the data ignoring the data point with a pre-weatherization efficiency of about 64%.) An apparent difference of 2-4%, on average, between the predicted and measured

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[1]In the measure selection technique, a seasonal efficiency is calculated from the steady-state efficiency (the steady-state efficiency is reduced up to several percentage points depending on space-heating system characteristics) and used to predict a change in seasonal efficiency. This discussion outlines an equivalent procedure to determine the change in steady-state values.

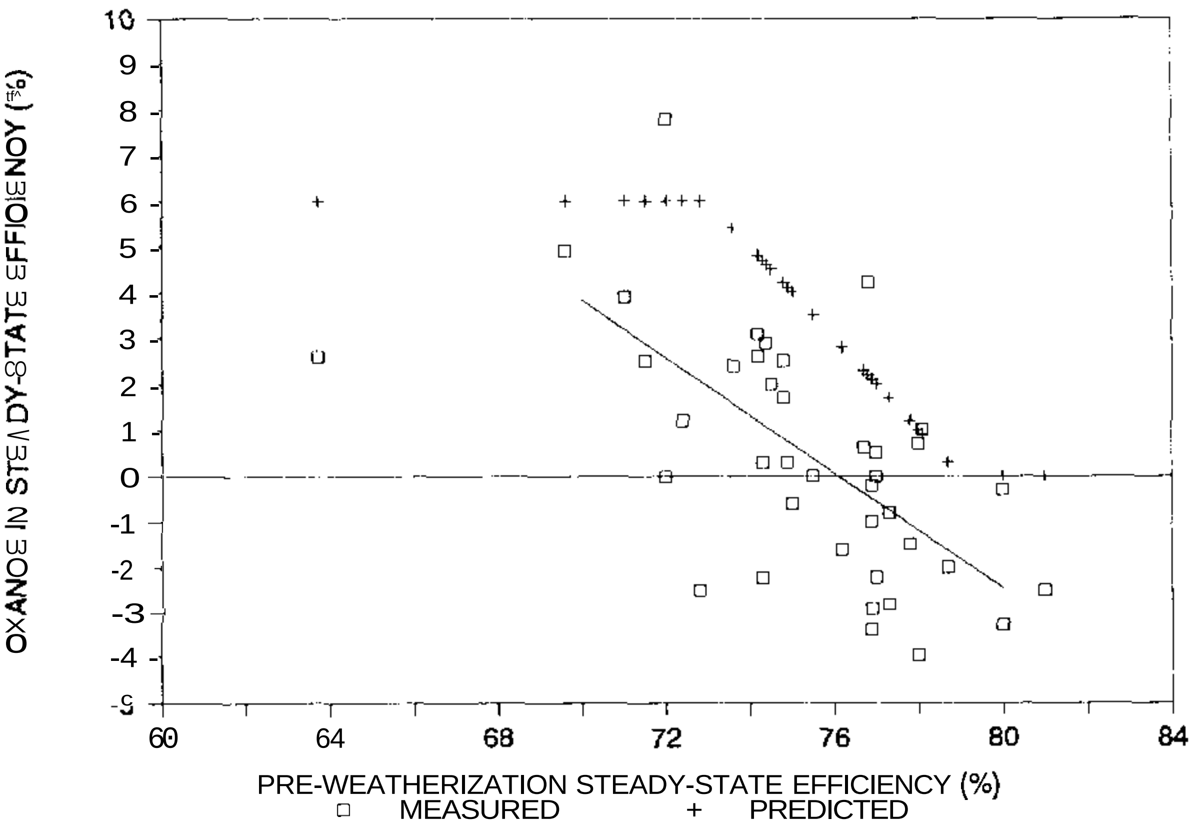

Fig. 7.4. Change in steady-state efficiency of the space-heating systems in the audit houses following tune-up as a function of the pre-weatherization steady-state efficiency. The solid line is a least fit regression line for the measured data (excluding the data point with a pre-weatherization steady-state efficiency of about 64%).

efficiency change of each house is demonstrated in Fig. 7.5, where the solid line represents points where the measured change equals the predicted change and the dashed line is a least squared fit to the data. Similar figures identifying the contractor making the post-weatherization measurements revealed no consistent pattern (measurements for all three contractors were randomly scattered about the regression line). Additionally, no general affect of system age on the measured change in efficiency was observed.

The frequent occurrence of negative changes in the measured efficiencies are difficult to explain. Attempting to tune-up systems already in good operating condition (such as those that had an efficiency greater than 76%) could have resulted in a decrease in performance. Another plausible explanation is that the pre-weatherization steady-state efficiencies were biased on the high side because the strength of chimney drafts were less in the summer than the winter, steady-state conditions were more likely achieved before measurements were made in the winter than the summer, or all the test equipment used by the single contractor to make the pre-weatherization measurements (more than one analyzer was used) was out of calibration. Use of different contractors with different equipment more likely introduced scatter in the results than a 2-4% bias. Additionally, the difficulty in making consistent readings on equipment with built-in draft diverters introduces scatter rather than a bias.

Conclusions regarding the benefit of tune-ups and the accuracy of the prediction method are difficult to make because of the frequent occurrence of negative changes in the measured efficiencies. Assuming the data are correct, tune-ups increase the steady-state efficiency only on systems with steady-state efficiencies presently less than 76% (a tune-up performed on systems with efficiencies greater than 76% would usually result in a decrease in performance) and the prediction method overpredicts efficiency increases. Assuming efficiency measurements made in the summer were higher than those made in the winter due to measurement bias improves the observed performance of tune-ups and the

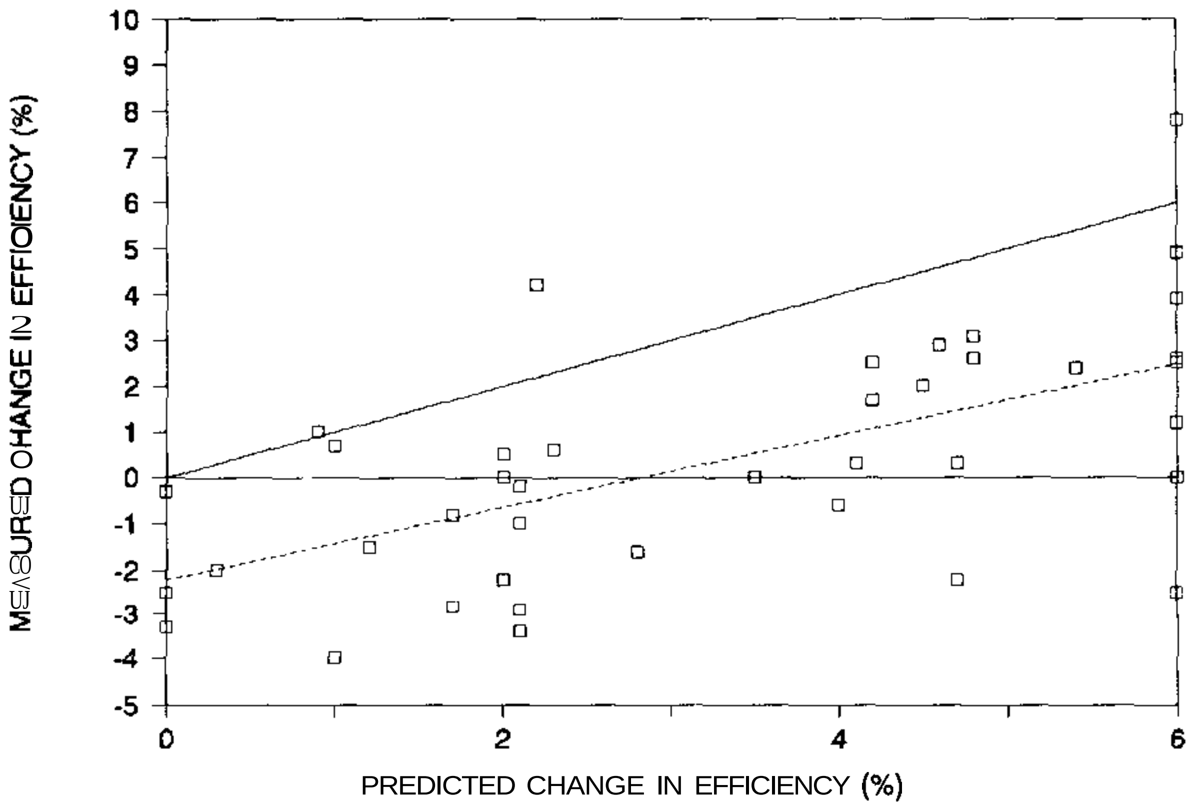

Fig. 7.5. Comparison of the measured change in steady-state efficiency of the space-heating systems in the audit houses following tune-up to the predicted change. The solid line indicates where measured and predicted savings are equal. The dashed line is a least fit regression line for the data.

accuracy of the prediction method, although the value of such a bias is unknown. From Figs. 7.4 and 7.5, a bias of 2% might be assumed because of the likelihood that no actual change in efficiency occurred, on average, in houses with efficiencies greater than 79% (predicted change of 0%). Thus, in this case, tune-ups may increase efficiency on systems with steady-state efficiencies less than 78%.

Recommendations for future measurements of efficiencies in field tests include:

1. calibrate combustion efficiency test equipment before making pre-and post-weatherization measurements,
2. use the same instrument for all houses,
3. use the same instrument for the pre- and post-measurements,
4. document locations within the space-heating system where pre-weatherization temperature and gas sample readings were taken and take post-weatherization readings in the same locations,
5. make pre- and post-weatherization measurements during identical seasons,
6. make pre- and post-weatherization measurements in control houses, and
7. have the heating contractor record efficiencies immediately before and after performing all work.

7.3 HOUSE INDOOR TEMPERATURE CHANGES

Increased house indoor temperatures following weatherization has often been a primary explanation for why measured savings from weatherization are less than predicted savings. Indoor temperatures were monitored in the field test specifically to study and account for this possible behavior. In analyzing the measured savings, changes in indoor temperature were accounted for directly in the analysis methods. However, insight can be gained as to the changes that are occurring from a direct analysis of the indoor temperature data.

For each house, an average pre- and post-weatherization indoor temperature was calculated by averaging data collected in the months of January through April. These temperatures and their changes are listed in Table 7.3 for the control houses and Table 7.4 for the audit houses.

Average pre-weatherization indoor temperatures ranged from about 60 to 78°F. The average for the control houses was 68.9°F and the average for the audit houses was 68.1°F, a difference that is not statistically significant at a 95% confidence level. Considering the fact that the temperature recorders read about 0.75°F low, the average indoor temperature maintained by the occupants during the pre-weatherization winter was about 69°F.

Following weatherization, the indoor temperature increased or decreased in both control and audit houses by as much as 8°F, although changes were less than 2°F in more than 70% of the houses. These changes are shown in Fig. 7.6, where no noticeable difference between control and audit houses is evident. On average, the indoor temperature increased in the audit houses by 0.5°F and decreased in the control houses by 0.1°F. However, neither of these changes nor the difference between changes are statistically significant at the 95% confidence level (although the change in the audit houses is significant at a 90% confidence level).

These results confirm conclusions drawn from previous ORNL experiments (Ternes and Stovall 1988) that indoor temperature and its change does not contribute significantly to lower than expected savings observed in weatherization programs but does contribute to the variation in measured savings observed in individual houses. As in these previous experiments, the average temperature maintained in the audit houses is about that expected (68-70°F), and the average change in indoor temperature for the audit group of houses is nearly zero and about equal to that observed in the control group. Indoor temperatures maintained in individual houses and changes in the temperature following weatherization are unique for each house, which introduces variability in energy consumption and savings among houses.

Table 7.3. **Control house indoor** temperatures

House	Average Indoor Temperature Pre-weatherization (°F)	Post-weatherization C°F)	Change (°F)
2	78.13	71.16	-6.97
6	73.36	73.79	0.43
7	76.06	75.38	-0.68
8	71.75	70.72	-1.02
11	76.38	78.33	1.95
12	63.84	64.43	0.59
27	66.96	62.34	-4.62
30	71.03	71.07	0.04
31	66.76	68.50	1.74
51	71.78	69.93	-1.85
58	69.59	70.26	0.68
65	62.77	64.85	2.09
75	69.08	70.81	1.73
78	70.64	70.40	-0.23
81	65.05	65.22	0.17
85	70.61	70.04	-0.57
87	72.81	74.38	1.57
92	67.13	68.81	1.68
93	64.04	65.83	1.79
94	66.06	66.98	0.92
95	73.17	71.49	-1.69
103	65.97	66.39	0.43
108	67.22	67.93	0.70
109	68.07	67.53	-0.54
111	66.31	69.54	3.22
114	67.47	68.03	0.57
116	61.70	61.09	-0.61
121	71.81	72.54	0.73
122	65.89	65.51	-0.38
127	68.11	67.50	-0.61
134	75.07	75.48	0.42
135	69.87	68.94	-0.94
140	63.38	64.55	1.17
142	66.86	69.41	2.55
144	71.94	72.06	0.12
145	71.67	71.32	-0.35
149	64.73	57.28	-7.46
150	65.35	65.51	0.16
152	72.00	70.38	-1.62
159	66.62	66.60	-0.02
160	67.49	68.12	0.63
161	73.02	73.61	0.59
163	63.09	62.69	-0.40
174	71.69	71.83	0.14
Average:	68.92	68.83	-0.09

Table 7.4. Audit house indoor temperatures

House	Average Indoor Temperature Pre-weatherization C°F)	Post-weatherization (°F)	Change (°F)
1	62.06	62.13	0.06
3	62.71	60.37	-2.34
14	66.58	69.84	3.27
16	68.38	64.98	-3.39
26	67.62	69.77	2.14
28	72.39	71.62	-0.76
48	68.96	70.55	1.59
59	66.29	66.40	0.11
68	71.90	66.29	-5.61
70	70.20	73.79	3.58
72	70.65	70.39	-0.27
76	67.28	66.57	-0.70
79	70.19	69.48	-0.71
84	67.25	69.53	2.29
86	66.11	67.73	1.62
88	64.61	64.87	0.26
91	67.60	68.21	0.60
105	70.05	69.65	-0.41
106	66.43	71.82	5.39
110	63.23	63.94	0.72
113	64.12	63.93	-0.19
115	65.45	65.48	0.03
120	67.90	69.37	1.46
124	62.86	64.41	1.54
129	69.27	71.13	1.86
143	74.54	74.66	0.11
146	68.08	69.19	1.11
147	70.90	70.57	-0.33
148	67.90	73.05	5.15
154	70.69	70.58	-0.11
155	70.76	68.43	-2.33
156	65.13	66.18	1.05
165	68.21	70.27	2.06
167	63.42	65.84	2.42
170	70.23	70.57	0.34
172	60.33	61.09	0.76
9	71.05	71.13	0.07
29	68.09	68.28	0.20
73	76.90	77.06	0.16
89	64.66	67.05	2.38
131	69.86	69.16	-0.70
141	70.76	72.44	1.68
153	70.67	69.79	-0.88
166	73.18	74.01	0.83
169	71.03	69.22	-1.81
Average:	68.14	68.68	0.54

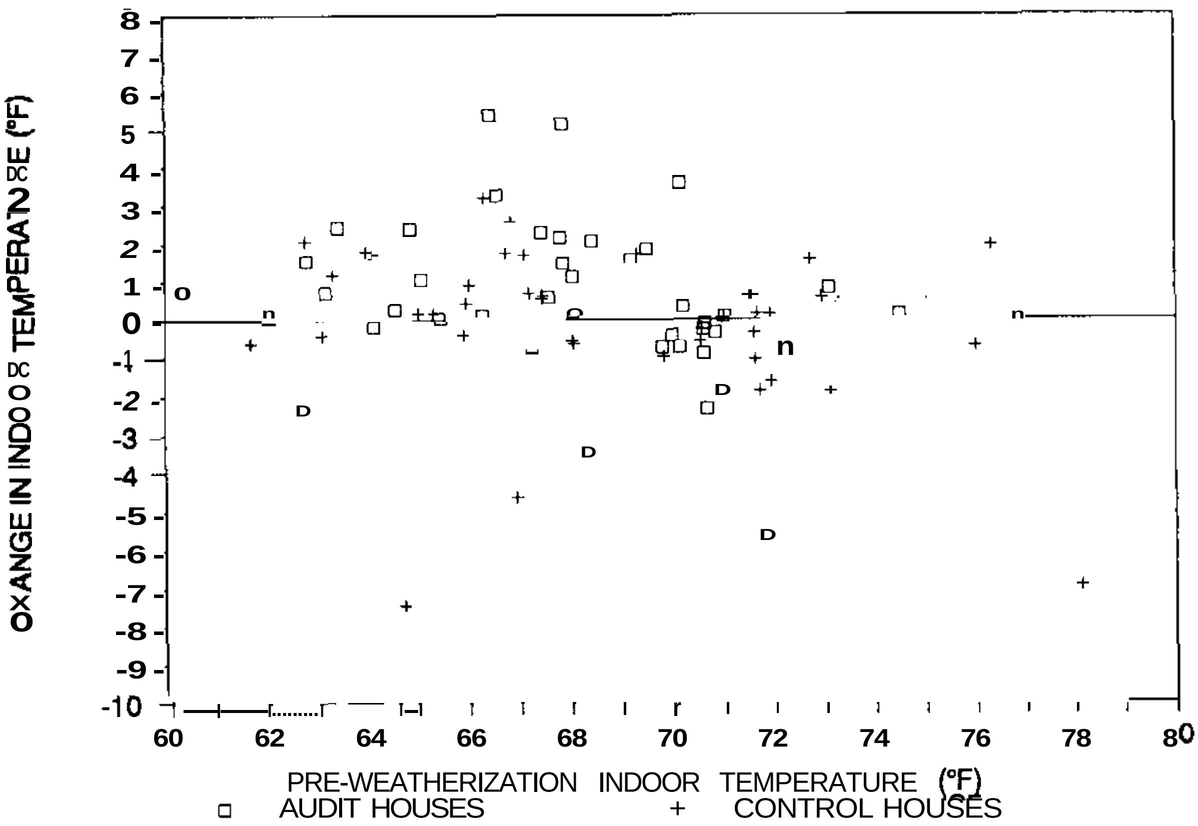

Fig. 7.6. Comparison of indoor temperature changes (average post-weatherization temperature minus average pre-weatherization temperature) to the average pre-weatherization indoor temperature for the field test houses.

7.4 HOUSE INTERNAL ENERGY CONSUMPTION

For each house, average weekly gas consumption by appliances other than the space- and water-heating systems (stove and/or dryer) and average weekly electricity consumption were calculated for the pre- and post-weatherization periods by averaging data collected in the months of January through April. Electricity consumptions and changes for the control and audit house are listed in Tables 7.5 and 7.6; gas consumptions and their changes are listed in Tables 7.7 and 7.8.

Determining the internal load of a house is complicated because energy sources other than those identified above (such as water-heating energy consumption and the occupants themselves) contribute to the load. Determining internal load is further complicated because only a portion of the energy consumption of the different sources represents useful heat entering the house, a portion that must be estimated and is likely different for each house. Nevertheless, because the consumptions identified in the above paragraph significantly affect house internal load, examination of their changes does indicate if a change in internal load likely occurred.

For both the control and audit houses, electricity consumption did not change on average; average weekly consumptions of 128 and 127 kWh were maintained during both winters for the two groups of houses, respectively. Large changes did occur, though, in several individual houses which could affect measured space-heating energy consumption.

Similarly, gas consumption of stoves and dryers in the audit houses did not change on average (the change observed in the control houses is not statistically significant at the 95% confidence level) but did change in individual houses, especially House 2 (a control house).

Table 7.5. Control house electricity consumptions

House	Average Weekly Electricity Consumption Pre-weatherization (kWh/week)	Post-weatherization (kWh/week)	Change (kWh/week)
2	125	204	79
6	67	67	0
7	74	77	3
8	71	66	-5
11	182	178	-5
12	52	60	7
27	166	139	-28
30	91	91	0
31	168	184	16
51	113	159	46
58	136	144	7
65	56	54	-2
75	293	227	-66
78	218	212	-6
81	166	185	19
85	166	158	-8
87	106	103	-2
92	144	167	23
93	118	114	-4
94	157	149	-8
95	133	126	-7
103	94	102	8
108	160	150	-10
109	109	89	-20
111	199	213	14
114	150	137	-13
116	136	163	27
121	233	221	-11
122	53	58	5
127	91	114	24
134	134	136	2
135	134	112	-22
140	127	128	0
142	83	95	13
144	119	108	-11
145	116	107	-9
149	157	60	-96
150	109	113	4
152	100	101	1
159	84	103	19
160	83	93	10
161	104	108	4
163	103	101	-1
174	122	123	1
Average:	127	127	0

Table 7.6. Audit house electricity consumptions

House	Average Weekly Electricity Consumption Pre-weatherization (kWh/week)	Post-weatherization (kWh/week)	Change (kWh/week)
1	59	58	-1
3	122	123	2
14	168	157	-10
16	90	88	-3
26	35	34	-1
28	125	122	-3
48	93	95	2
59	59	59	0
68	70	81	11
70	70	74	4
72	97	80	-17
76	155	140	-15
79	367	487	120
84	80	76	-5
86	159	140	-19
88	192	157	-34
91	125	113	-12
105	119	110	-9
106	132	158	26
110	53	48	-4
113	88	85	-3
115	192	216	24
120	114	131	17
124	52	54	1
129	151	164	13
143	83	93	9
146	115	122	7
147	163	144	-20
148	144	158	13
154	154	142	-11
155	178	144	-34
156	227	223	-4
165	109	105	-4
167	138	147	9
170	151	160	9
172	53	52	0
9	350	321	-30
29	119	133	14
73	137	126	-11
89	199	176	-23
131	51	49	-2
141	103	103	0
153	164	163	-1
166	85	76	-9
169	88	87	-1
Average:	128	128	0

Table 7.7. Control house appliance gas consumptions

House	Average Weekly Appliance Gas Consumptions Pre-weatherization (therms/week)	Post-weatherization (therms/week)	Change (therms/week)
2	17.0	4.1	-12.9
6	6.6	5.6	-1.0
7	3.0	2.6	-0.4
8	4.0	3.6	-0.4
12	4.0	3.0	-0.9
27		5.3	
30	2.9	2.4	-0.5
31	4.4	4.7	0.2
51	2.3	2.0	-0.3
58	7.4	7.1	-0.4
75	1.7	4.5	2.8
78	6.9	8.1	1.2
81	4.1	3.1	-1.0
85	5.5	6.2	0.7
87	5.5	5.0	-0.5
92	4.2	2.8	-1.4
93	5.0	5.7	0.7
94	3.9	3.0	-0.9
95	1.7	2.2	0.4
103	2.8	0.8	-2.0
108	3.3	3.4	0.0
109	4.1	2.8	-1.3
111	3.0	2.6	-0.3
114	8.8	8.4	-0.4
116	1.7	1.4	-0.2
121	2.5	1.7	-0.9
122	3.6	3.4	-0.1
134	6.9	5.4	-1.4
135	3.9	4.2	0.4
140	4.3	4.2	-0.1
142	5.5	3.7	-1.8
144	5.3	4.4	-0.9
145	4.4	5.2	0.9
149	4.4	4.9	0.5
152	3.9	4.0	0.0
159	2.6	3.2	0.7
160	3.9	3.5	-0.4
161	2.8	3.7	0.9
163	3.2	3.2	0.0
174	3.8	3.7	-0.1
Average:	4.48	3.97	-0.54
Excluding House 2:			
Average:	4.15	3.97	-0.22

Table 7.8. *Audit* house appliance gas consumptions

House	Average Weekly Appliance Gas Consumptions: Pre-weatherization (therms/week)	Post-weatherization (therms/week)	Change (therms/week)
1	2.0	2.3	0.3
3	1.9	1.8	-0.1
14	6.5	4.8	-1.7
16	3.6	4.1	0.6
26	4.7	4.7	0.0
28	2.4	3.0	0.6
48	2.8	3.0	0.2
59	2.6	2.9	0.3
68	3.7	4.7	0.9
70	0.2	3.9	3.7
72	3.7	3.5	-0.2
76	4.2	3.4	-0.8
88	4.3	3.8	-0.5
91	2.1	1.8	-0.3
105	4.1	4.0	-0.1
106	2.4	2.0	-0.4
113	1.9	2.0	0.1
124	4.3	2.8	-1.5
129	3.4	1.7	-1.7
143	2.9	3.8	0.9
146	2.9	3.8	0.9
147	3.3	3.6	0.3
148	4.5	7.7	3.1
154	1.8	2.0	0.1
156	0.8	2.5	1.7
165	7.3	3.5	-3.8
167	4.2	3.3	-0.8
170	3.1	1.5	-1.6
172	5.4	5.8	0.4
29	3.9	4.9	1.0
73	5.8	5.0	-0.8
141	4.2	4.7	0.5
153	4.2	4.1	-0.1
Average:	3.50	3.53	0.03

8. ENERGY SAVINGS ANALYSIS APPROACHES AND MODEL DESCRIPTIONS

8.1 SPACE-HEATING ENERGY SAVINGS DEFINITIONS

The annual energy savings occurring in a weatherized house can be defined in different ways. One generally accepted definition is the annual amount of energy saved if all factors are kept constant before and after weatherization except for the ECMs themselves. This definition is applicable if the savings actually induced by the ECMs only is of interest. The savings defined in this manner is not the same as the observed annual energy savings, because this latter savings is influenced by differences in outdoor and indoor climate, occupant behavior changes (such as changes in internal loads and room closures), and changes in occupancy following weatherization.

Consistent with this definition, the measured space-heating energy savings were normalized in this study to average annual outdoor temperatures and a standard house indoor temperature (68°F for all houses before and after weatherization). In this study, the measured space-heating energy savings are not influenced by changes in occupancy because the few houses that did have new occupants were dropped from the study. Because the space-heating energy savings for most ECMs were estimated by the selection technique assuming typical outdoor temperatures and a standard 68°F indoor temperature (savings for space-heating system ECMs were also based on current space-heating energy consumption), the normalized savings can be compared to the savings estimates because both are determined on a common basis. Additionally, the normalized space-heating energy savings of individual houses can be compared to each other on an equal basis (differences among the pre- and post-weatherization indoor temperatures of the houses are removed by the indoor temperature normalization).

The normalized annual savings for the control houses can be used to adjust the normalized annual savings calculated for the audit houses, especially when group rather than individual house savings are considered. The normalized annual savings for the control houses will verify the normalization ability of the defined approach and may be used to account for occupant behavior changes other than changes in indoor temperature (such as internal load, room closures, and window and door openings) that cannot be considered directly. Consideration was given to normalizing the savings for internal loads directly, but this approach was not pursued because of large uncertainties associated with determining the internal loads from the measured data.

For each house, the measured savings could have been normalized to the actual pre-weatherization indoor temperature maintained in the house rather than to a standard temperature of 68°F. The savings determined under this approach would represent the savings achieved in these houses as they are currently operated and, when averaged, the savings that would be achieved through a large scale implementation of a weatherization program using this technique in similar houses. However, because the savings are not normalized to the same assumptions used to estimate savings, interpreting comparisons between predicted and measured savings to determine the accuracy of the selection technique would be more complicated. Because the average pre-weatherization indoor temperature of the homes was 68°F, the average measured savings of the audit houses normalized to 68°F will represent the average savings that are achieved in these houses as they are currently operated.

8.2 SPACE-HEATING ENERGY CONSUMPTION MODELS AND ANALYSIS APPROACH

Normalized annual space-heating energy consumptions used to calculate savings were estimated from the pre- and post-weatherization data using house energy consumption models and regression analysis to account for the following factors:

1. time periods over which the data were collected were unequal and did not cover the entire winter periods,

2. pre- and post-weatherization outdoor temperatures were different and not equal to the typical outdoor temperatures desired for normalization, and

3. indoor temperatures maintained in each house over the two periods were not the same and were not equal to the standard temperature desired for normalization.

The house energy consumption model assumes that space-heating energy consumption is linearly related to the temperature difference between the inside and outside of the house:

$$EC - A + (B * DT) \,,$$

where

EC - energy consumption of the space-heating system,

DT - indoor minus outdoor temperature difference,

A - intercept coefficient (determined by regression), and

B - slope coefficient (determined by regression).

Linear regression techniques were used to estimate the parameters, A and B, for the pre- and post-weatherization periods for each house using the pre- and post-weatherization data, respectively. Although the energy consumption data were collected primarily on a weekly basis, collection periods did vary in duration (especially if a weekly reading for a given house was missed). Consequently, the energy consumptions used in the regression analyses were normalized to weekly consumptions by dividing the energy consumption for the period by the duration of the period in weeks. The temperature differences used in the analyses were the average difference between hourly indoor and outdoor temperatures for the period.

Pre- and post-weatherization normalized annual space-heating energy consumptions were calculated using the estimated pre- and post-weatherization regression values for A and B found for each house, average outdoor temperatures from a Typical Meteorological Year (TMY) weather tape for Buffalo, (assumed to represent historical conditions), and a 68°F indoor temperature. Weekly average temperature differences were calculated using the TMY outdoor temperature data and 68°F as the indoor temperature. Because positive temperature differences resulted even during the summer months when no space heating was needed, only temperature differences from September 10 to May 27 (representing a 37-week winter period during which space heating was required) were used. Each average weekly temperature difference was then used with values of A and B for each house to estimate a weekly space-heating energy consumption. The weekly values were summed to obtain an estimate of the normalized annual space-heating energy consumption of each house. Normalized annual energy savings were than found by subtracting the post-weatherization consumption from the pre-weatherization consumption.

The normalized annual energy savings of each audit house was adjusted using the normalized annual savings of the control houses to account for factors affecting space-heating energy consumption other than the ECMs themselves. A procedure followed by other researchers (Fels 1986) was used to make this adjustment. First, an adjustment factor was calculated by dividing the average post-weatherization space-heating energy consumption of the control houses by their average pre-weatherization consumption. The adjusted savings of each audit house was then calculated by multiplying the pre-weatherization space-heating energy consumption by this factor and subtracting the post-weatherization consumption from this quantity.

8.3 WATER-HEATING ENERGY CONSUMPTION ANALYSIS APPROACH

The water-heating system ECMs installed in the houses are designed to save energy year round. To determine the annual energy consumption of the water-heating system before and after weatherization, an average weekly energy consumption was determined using water-heating energy consumption data collected from January to April for each period and multiplied by 52. Energy savings were then found by subtracting post-weatherization consumption from pre-weatherization consumption. As with the space-heating energy savings, the water-heating savings of the control houses were used to adjust the savings of the audit houses.

One limitation of this simple analysis is that the seasonality of water-heating energy consumption is not taken into account. Another limitation is that the consumptions and savings are not normalized to any appropriate variables, such as hot water consumption that significantly affect energy consumption. Because data were not collected over the summers or on hot water consumption, these limitations cannot be directly addressed. The latter limitation is addressed indirectly, though, by adjusting the audit house savings with those for the control houses. To perform a proper evaluation, the inlet water temperature, storage tank water temperature, and hot water consumption would need to be monitored in addition to water-heating energy consumption.

9. ENERGY CONSUMPTIONS AND SAVINGS

9.1 SPACE-HEATING ENERGY SAVINGS

Using the models and analysis approach presented in Sect. 8.2, normalized annual pre- and post-weatherization space-heating energy consumptions and space-heating energy savings were estimated for each house. Results for 43 control houses are presented in Table 9.1 and for 38 audit houses in Table 9.2. Because of inadequate space-heating energy consumption data or indoor temperature data, space-heating energy consumptions and savings could not be determined using the desired analysis approach in eight houses (one control and seven audit houses).

Coefficients of determination (R^2) for the regressions are presented in these tables. Coefficients for the pre-weatherization regressions were greater than 0.8 (and generally greater than 0.9) for all but three control houses. Coefficients for the post-weatherization regressions were generally less than the pre-weatherization values but remained above 0.8 for all except nine control or audit houses.

9.1.1 Control Houses

The annual normalized pre-weatherization space-heating energy consumptions ranged from a low of 320 therms to a high of 1541 therms, with the average being 902 therms. The post-weatherization space-heating energy consumptions increased, on average, by 61 therms/year to 963 therms/year, a change that is statistically significant at a 95% confidence level. Individually, space-heating energy consumption increased in most houses although savings in some houses did occur, as shown in Fig. 9.1. At this same level of confidence, the energy consumption increases of individual houses were significantly different than zero in all but 10 houses.

A reason for the observed increase in the average space-heating energy consumption of the control houses is not known, especially

Table 9.1. Control house space-heating energy consumptions

House	Coefficient of determination Pre	Coefficient of determination Post	Normalized annual heating energy consumption Pre (therms/year)	Normalized annual heating energy consumption Post (therms/year)	Annual energy savings with 95% confidence limits (therms/year)	
2	0.88	0.86	320	741	-421	+/-42
6	0.98	0.93	737	818	-82	19
7	0.98	0.98	639	659	-19	15
8	0.98	0.92	1035	1109	-75	25
11	0.99	0.93	919	783	136	35
12	0.98	0.95	767	791	-25	14
27	0.97	0.95	979	1120	-142	25
30	0.98	0.81	1541	1657	-116	41
31	0.37	0.90	537	455	82	37
51	0.98	0.96	810	823	-13	22
58	0.93	0.78	985	1127	-142	50
65	0.97	0.92	927	990	-63	21
75	0.98	0.83	1020	847	173	47
78	0.98	0.93	1035	1298	-263	33
81	0.99	0.83	911	1119	-208	40
85	0.95	0.91	915	921	-6	31
87	0.98	0.97	886	860	26	21
92	0.96	0.77	1068	1204	-136	42
93	0.97	0.54	1129	1161	-32	55
94	0.77	0.58	1313	1693	-380	80
95	0.98	0.84	904	973	-69	31
103	0.97	0.89	739	773	-34	20
108	0.92	0.84	860	851	9	36
109	0.93	0.86	1103	1136	-33	30
111	0.96	0.92	1129	1235	-106	32
114	0.05	0	839	854	-15	51
116	0.96	0.93	1195	1205	-11	30
121	0.97	0.88	430	447	-17	28
122	0.96	0.81	927	1005	-78	28
127	0.98	0.88	420	438	-18	15
134	0.94	0.96	1229	1250	-21	45
135	0.95	0.91	771	907	-136	26
140	0.92	0.94	867	898	-31	30
142	0.97	0.87	983	1110	-127	34
144	0.92	0.74	700	848	-148	37
145	0.89	0.95	857	873	-15	28
149	0.97	0.94	938	991	-53	19
152	0.95	0.85	392	414	-21	20
159	0.93	0.84	640	681	-41	30
160	0.99	0.94	1324	1289	35	29
161	0.99	0.94	1137	1218	-81	30
163	0.95	0.94	761	775	-14	17
174	0.98	0.89	1176	1059	117	49
Average:			902	963	-61	+/-41

Table 9.2. Audit house space-heating energy consumptions

House	Coefficient of determination Pre	Coefficient of determination Post	Normalized annual heating energy consumption Pre (therms/year)	Normalized annual heating energy consumption Post (therms/year)	Annual heating energy savings Normalized (therms/year)	Annual heating energy savings Adjusted (therms/year)	Annual heating energy savings Predicted (therms/year)	Adjusted minus predicted (therms/year)	95Z confidence limit for normalized savings (therms/year)
1	0.98	0.95	1395	1158	237	331	343	-12	+/-17
3	0.96	0.85	1469	1371	98	196	435	-239	33
14	0.96	0.86	786	580	206	259	324	-65	25
16	0.98	0.91	482	431	50	83	83	0	16
26	0.97	0.97	767	751	16	68	238	-170	18
28	0.97	0.69	697	572	124	171	328	-157	28
48	0.98	0.93	495	498	-3	30	132	-102	13
59	0.96	0.92	1206	1263	-57	24	26	-2	27
68	0.99	0.98	1124	873	251	327	430	-103	18
70	0.97	0.95	882	671	211	270	357	-87	16
72	0.98	0.95	906	956	-50	11	57	-46	18
76	0.96	0.76	735	760	-25	24	41	-17	33
79	0.96	0.85	1103	868	235	310	776	-466	58
84	0.96	0.92	900	484	416	477	257	220	18
88	0.97	0.93	1307	1059	248	336	428	-92	30
91	0.83	0.70	1628	1283	344	454	569	-115	107
105	0.93	0.90	1061	865	196	267	270	-3	34
106	0.95	0.82	1700	694	1006	1120	417	703	42
113	0.97	0.93	508	510	-2	33	15	18	11
115	0.85	0.91	850	674	175	233	178	55	37
124	0.93	0.79	1051	900	151	221	358	-137	31
129	0.97	0.92	911	1003	-92	-30	29	-59	34
143	0.97	0.89	888	635	253	313	275	36	26
146	0.94	0.87	1225	888	337	420	403	17	32
147	0.99	0.94	710	691	18	66	264	-198	17
148	0.99	0.88	1222	607	615	697	508	189	30
154	0.96	0.91	908	827	80	142	224	-82	30
156	0.95	0.96	1802	1266	536	657	782	-125	33
165	0.98	0.81	895	1092	-197	-136	302	-438	34
167	0.97	0.88	948	704	244	306	265	43	28
170	0.96	0.92	873	777	96	155	252	-97	29
172	0.96	0.82	1255	1116	139	224	154	70	33
Average:			1022	836	183	252	298	-46	
Houses to be compared with predicted savings only:									
9	0.91	0.92	1592	900	693	800	956	-156	+/-66
29	0.99	0.83	1166	839	327	406	304	102	50
73	0.98	0.92	306	327	-21	0	109	-109	21
89	0.98	0.93	1356	981	375	466	274	192	25
141	0.98	0.92	862	661	201	259	202	57	22
153	0.96	0.92	510	506	4	38	0	38	21
Average of ail houses:			1013	817	196	264	299	-35	

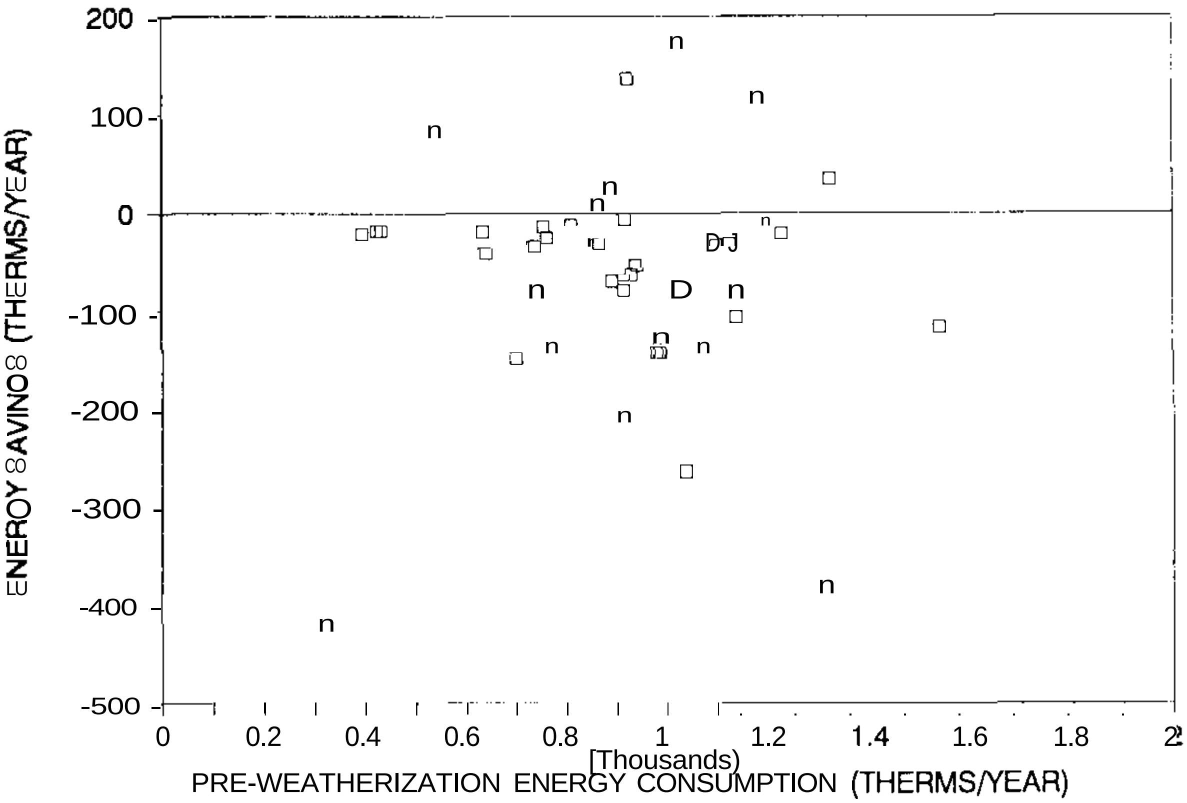

Fig. 9.1. **Comparison of the space-heating energy savings of the control houses to** their pre-weatherization space-heating energy consumption.

considering that no ECMs were performed on the control houses (either as part of the field test or, individually, by the home owners) and the energy consumptions were normalized to constant indoor temperature. Occupant behavior changes other than indoor temperature and internal load changes are a likely cause of the observed increase. Although occupant behavior changes can be induced by many factors (such as increasing or decreasing fuel prices and unemployment), the changes that can occur within the house are predominately limited to indoor temperature, internal load, room closures, and window and door openings. Major factors of indoor temperature and internal load were already either considered in the analysis or shown not to have likely changed (see Sect. 7.4).

The normalized annual savings of the audit houses can be adjusted by the normalized annual savings of the control houses to account for affects that caused the increased energy consumption in the control houses, be it room closures, window or door openings, a bias introduced by the analysis method, or other cause. Because the consumption were normalized using indoor temperature, it was originally thought that this would account for most occupant behavior influences and, thus, eliminate the need for control houses. Because of the average change observed, such a recommendation cannot be made.

9.1.2 Audit Houses

The normalized annual pre-weatherization space-heating energy consumptions of the audit houses ranged from 306 to 1802 therms, with an average of 1013 therms. At the 95% confidence level, this average consumption is not statistically different from that measured for the control houses (902 therms/year), even though wall insulation was more prevalent in the control houses (see Sect. 4.3).

After adjusting the normalized energy savings of the audit houses by the factor developed using the normalized control house savings, the average space-heating energy savings achieved by ECMs selected using the selection technique was 252 therms/year, approximately 25% of the pre-weatherization space-heating energy consumption. The 95% confidence interval for these adjusted savings is +/- 91 therms/year, indicating that the adjusted savings were significantly different from zero. This interval also indicates that widespread weatherization of houses similar to those field tested and using the selection technique would result in average space-heating energy savings between 161 and 343 therms/year. Only 32 of the 38 audit houses listed in Table 9.2 were used to determine the average adjusted savings; the remaining 6 houses were those that were weatherized incorrectly because of the measure selection technique mistake (see Sect. 6 and Appendix C) and were only used to compare predicted and adjusted savings. The average cost to install ECMs designed to reduce space-heating energy consumption (excluding water-heating system ECMs) in the 32 houses was $1,309.

The distribution of adjusted space-heating energy savings for the 32 audit houses is shown in Fig. 9.2. Only two houses with negative adjusted savings were found. In one of these houses, the adjusted energy consumption increased only 30 therms/year; the 95% confidence interval of the change was +/- 34 therms/year, indicating that the increase was not significantly different from zero; and few ECMs (having correspondingly small expected savings) were installed. Reasons for the negative savings in the second house could not be identified.

The wide range of adjusted energy savings shown in Fig. 9.2 and the large number of houses with positive savings less than 100 therms/year results because the selection technique concentrates ECMs in homes that can most benefit from them. As shown in Fig. 9.3, greater savings were achieved in houses receiving the greater degree of conservation effort. Because expenditures for ECMs designed to reduce space-heating energy consumption (excluding water-heating system ECMs) were generally greater in houses with greater pre-weatherization space-heating energy consumption (see Fig. 9.4), greater savings were also achieved in these houses (see Fig. 9.5).

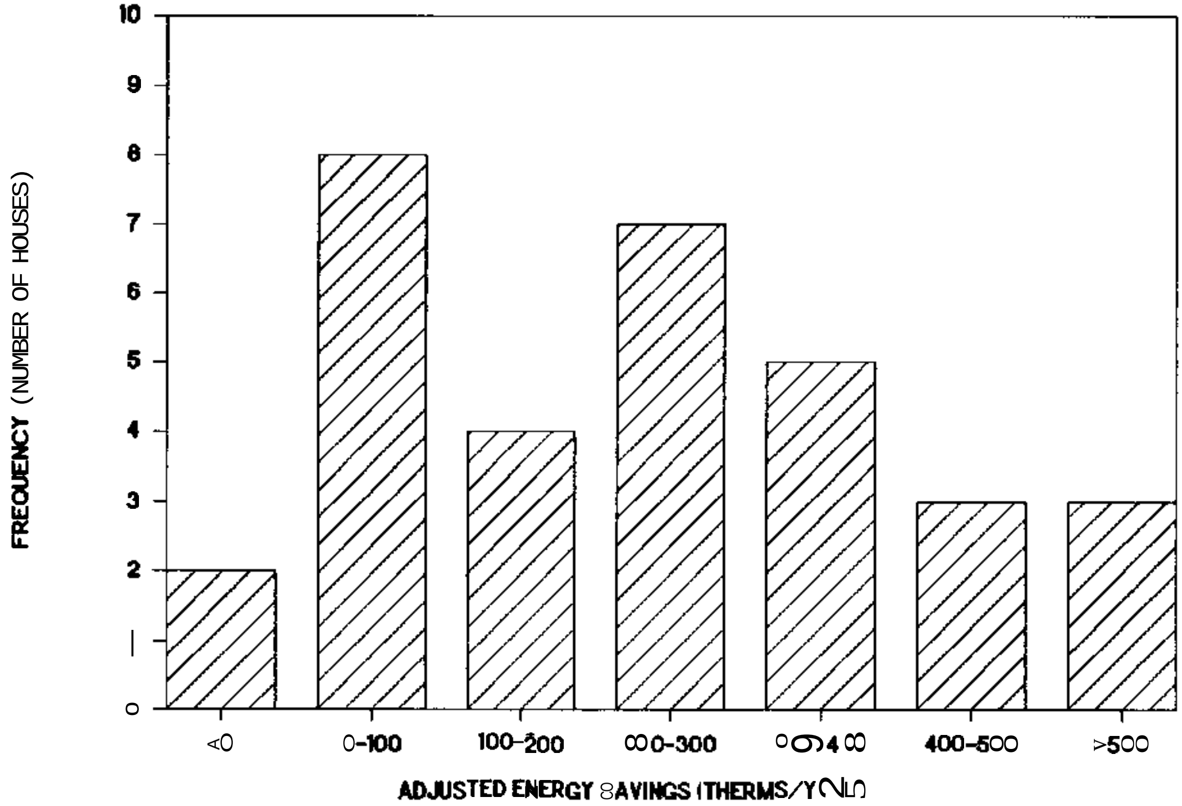

Fig. 2. Histogram of adjusted space-heating energy savings for the 32 audit homes.

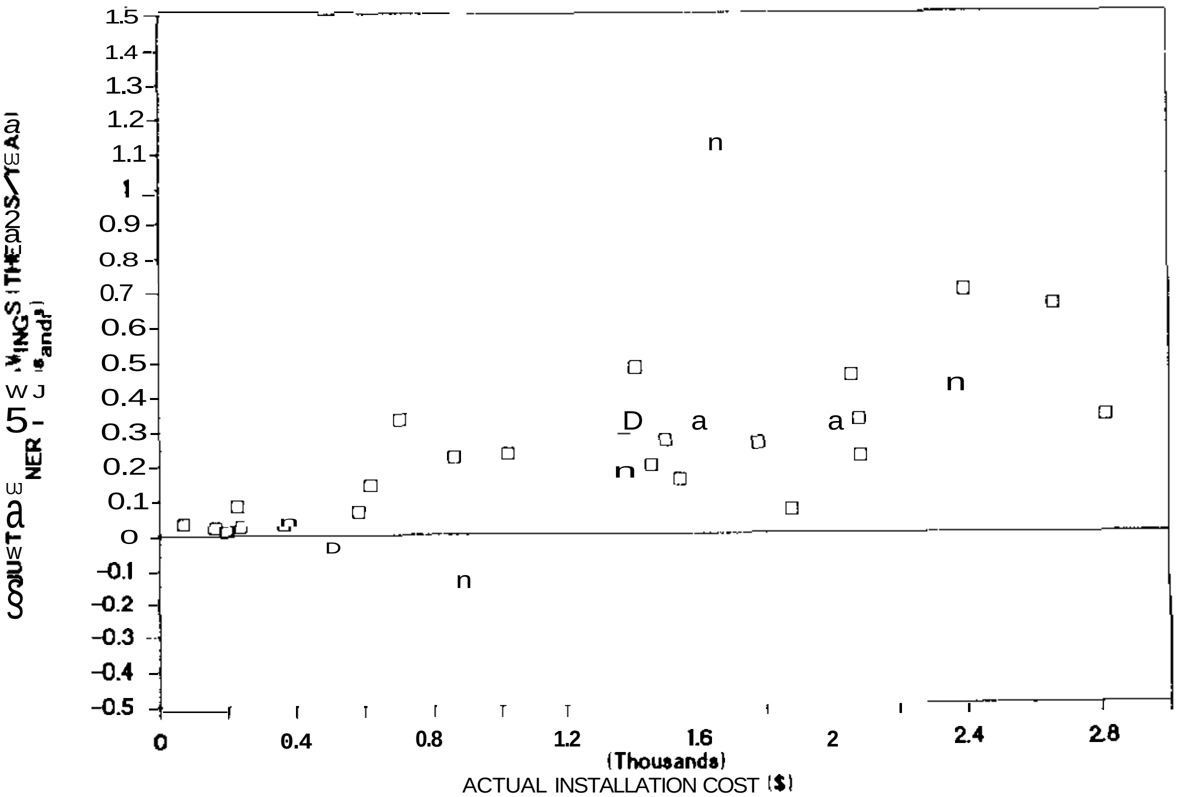

Fig. 9.3. Comparison of the adjusted space-heating energy savings of the audit houses to the actual cost for energy conservation measures designed to reduce space-heating energy consumption (excluding water-heating system measures) installed in the houses.

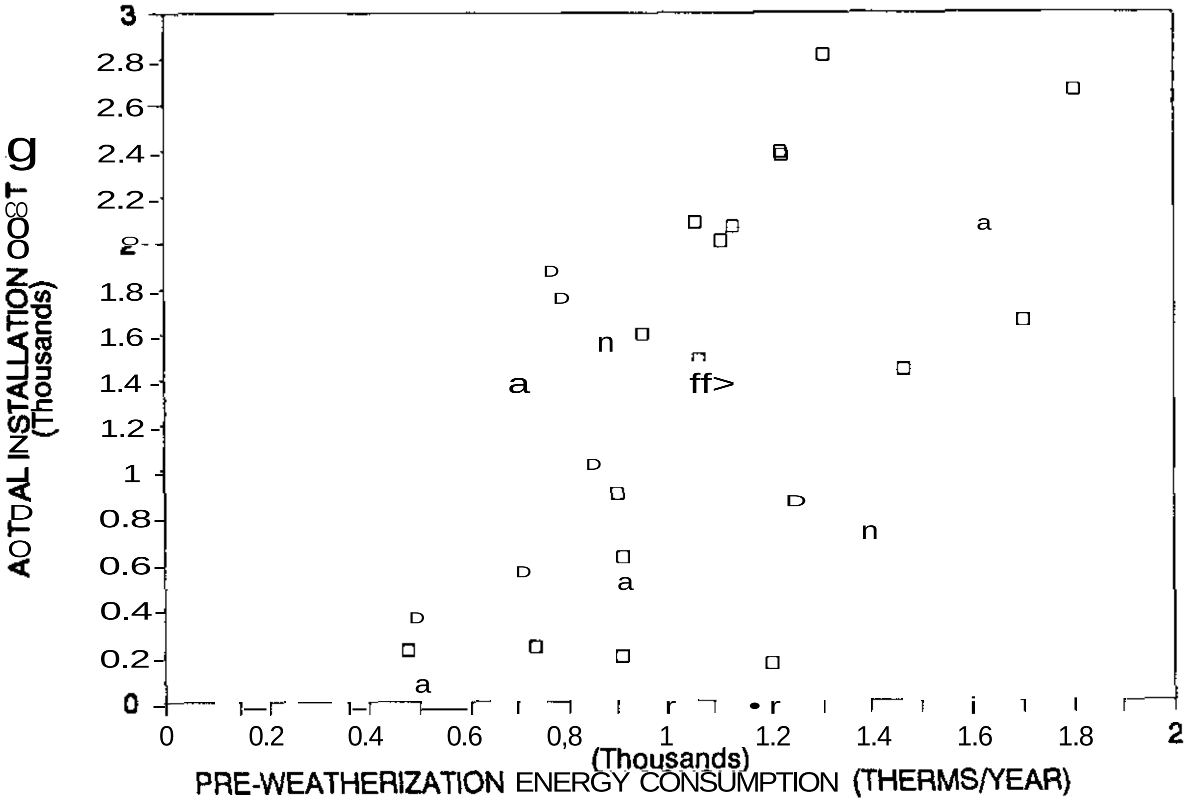

Fig. 9.4. Comparison of the actual cost for energy conservation measures designed to reduce **space-heating** energy consumption (excluding water-heating system measures) installed in the audit houses to the **pre-weatherization space-heating** energy consumption.

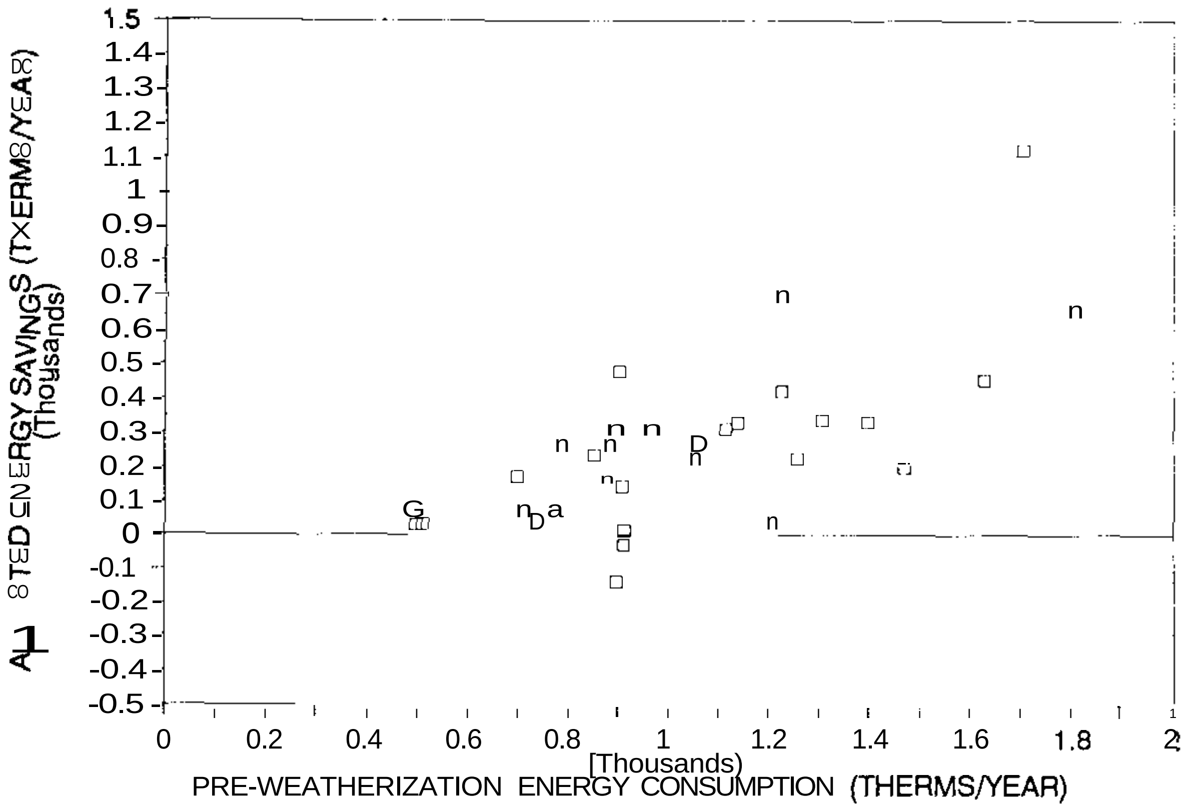

Fig. 9.5. Comparison of the adjusted space-heating energy savings of the audit houses to the pre-weatherization space-heating energy consumption.

Table 9.3 summarizes the adjusted space-heating energy savings and installation costs for ECMs designed to reduce space-heating energy consumption (excluding water-heating system ECMs) for houses with pre-weatherization space-heating energy consumptions greater than the average value for the audit houses (approximately 1000 therms/year). For this select group of houses, the adjusted space-heating energy savings averaged 399 therms/year, approximately 30% of their pre-weatherization space-heating consumption. Consequently, applying the measure selection technique to houses preselected based on pre-weatherization space-heating energy consumption would likely improve program energy savings significantly. Because these savings were achieved at a greater cost ($1772/house compared to $1309/house), the economics of such an approach are further examined in Sect. 9.4.

The predicted energy savings shown in Table 9.2 are based only on ECMs actually installed in the houses and, thus, do not include predicted savings for ECMs recommended by the selection technique that could not be installed. A predicted value defined in this manner is useful in evaluating the accuracy of algorithms used in the selection technique to predict energy savings. The accuracy of the selection technique from the point of view of how many recommended ECMs could be installed was evaluated in Sect. 6.

The selection technique was found to be reasonably accurate in predicting average space-heating energy savings. Using all 38 houses, the average adjusted space-heating energy savings due to the ECMs was only 35 therms/year below the average predicted value of 299 therms/year, or about 88% of predicted. The 95% confidence interval associated with comparing the average predicted and adjusted savings is +/- 6 therms/year (based on the uncertainty of the individual house measurements and not the variance between individual houses). Thus, although the difference of 35 therms/year is small, the difference is statistically significant and not due to measurement errors.

Table 9.3. Audit houses with pre-weatherization space-heating energy consumption greater than 1000 therms/year

House	Normalized pre-weatherization space-heating energy consumption (therms/year)	Adjusted space-heating energy savings (therms/year)	Installation cost[a] ($)
1	1395	331	713
3	1469	196	1443
59	1206	24	161
68	1124	327	2071
79	1103	310	2007
88	1307	336	2817
91	1628	454	2073
105	1061	267	1489
106	1700	1120	1657
124	1051	221	2086
146	1225	420	2378
148	1222	647	2391
156	1802	657	2661
172	1255	224	864
Average:	1325	399	1772

[a]Energy conservation measures designed to reduce space-heating energy consumption only (excluding water-heating system measures).

Although the selection technique is not statistically accurate for individual houses, it was found to predict the space-heating energy savings of most within reason. The difference between predicted and adjusted savings in individual houses is significant at the 95% confidence level in all but six houses. However, as shown in Fig. 9.6, houses are generally grouped near the line representing equality between adjusted and predicted savings (the solid line in the figure). Agreement between predicted and adjusted savings is especially good for houses in which few ECMs were installed (low predicted savings), which reflects the accuracy of the analysis method as well as the accuracy of the selection technique.

As seen from Fig. 9.6, the adjusted savings of only three houses are different from predicted by at least 400 therms/year. The house with a predicted savings of about 800 therms/year used wood heating a considerable part of the day, which likely contributed to the overprediction of gas space-heating energy savings. This house was also the largest audit house, having a non-basement floor area 300 ft^2 greater than the next largest house. Definitive reasons for the deviations in the remaining two houses could not be identified. It was noted that both houses had a boiler space-heating system. The house with a predicted savings of about 400 therms/year was the only audit house with a steam boiler.

The scatter observed in Fig. 9.6 might be reduced if accurate internal loads were included in the analysis; changes in internal load affect space-heating energy consumption which can lead to scatter in the space-heating energy savings. The average savings would not likely be affected because the energy consumptions other than for space- and water-heating did not change, on average, in the audit houses (see Sect. 7.4).

The linear regression model included on Fig. 9.6 (the dashed line) confirms that the data fall around the line of equivalency. Because the regression line is rotated from the line of equivalency with the pivot point near the origin, overprediction of the space-heating energy savings

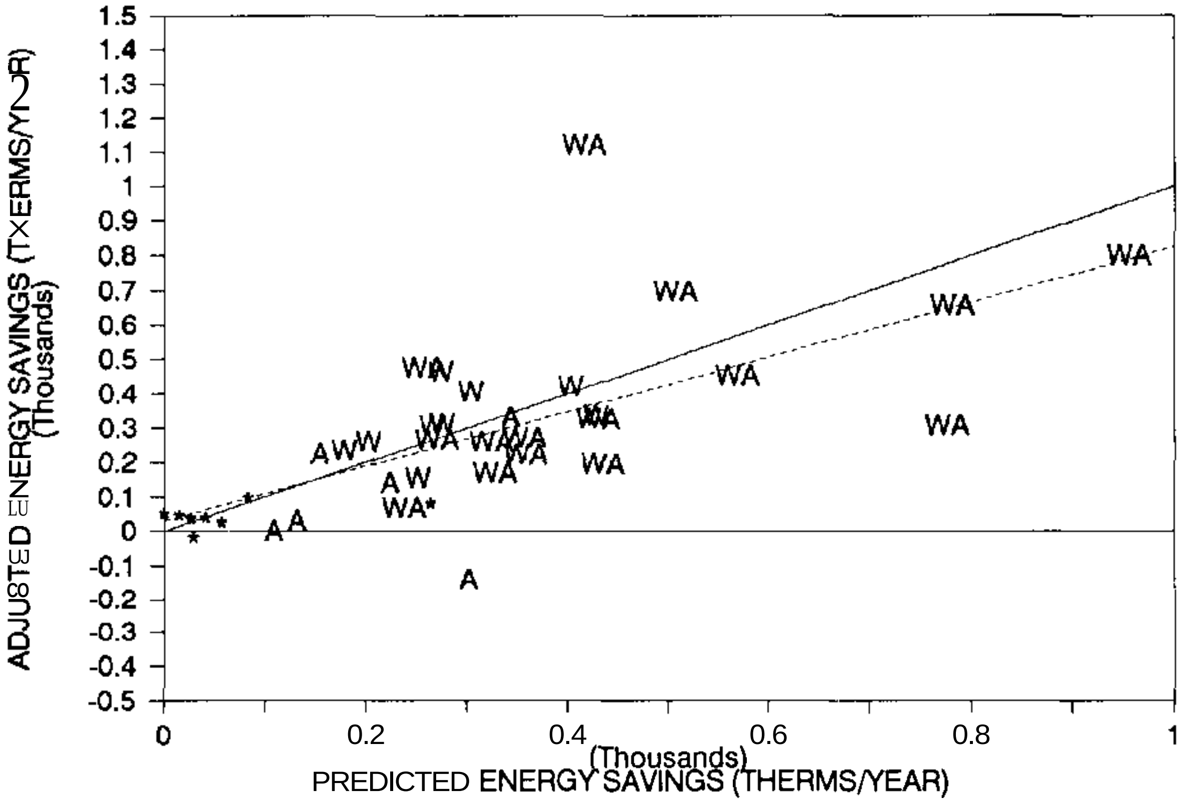

Fig. 9.6. Comparison of adjusted to predicted space-heating energy savings for each audit house. An A indicates a house in which attic insulation with a predicted savings greater than 75 therms/year was installed, a **W** in which wall insulation with a predicted savings greater than this value was installed, a **WA** that both wall and attic insulation (each meeting this savings criterion individually) was installed, and a * that neither was installed. The solid line indicates the points where adjusted and predicted savings are **equal**. The dashed line is a least fit regression line for the data.

by a fixed percentage rather than by a fixed amount is indicated. If the technique overpredicted savings in each house by a fixed amount, the regression line would be more parallel with the equivalency line and shifted downward by the fixed amount.

For this study, the slight overprediction of space-heating energy savings can be eliminated, on average, by using a 57°F balance point temperature rather than 60°F in estimating the savings of envelope ECMs. Savings for envelope ECMs were estimated in the selection technique using a variable-based degree-day method and a 60°F balance point temperature for each house (a unique value for each house was not used as discussed in Sect. 5.3). Using a 57°F temperature, the predicted savings for each house is reduced by approximately the same percentage, making the average predicted value agree closely with the average adjusted savings. Because a majority of the space-heating energy savings achieved in the houses was due to envelope rather than space-heating system ECMs, a change in the method of estimating savings for these latter ECMs would not significantly improve the comparison between predicted and adjusted savings.

The possibility that the inaccuracy of the selection technique in predicting average space-heating energy savings could be due to a specific measure was investigated, but a definitive conclusion could not be reached. As discussed in Sect. 6.3, the majority of the savings were predicted to result from wall and attic insulation. In Fig. 9.6, each house is identified by whether attic or wall insulation with a predicted savings greater than 75 therms/year was installed: an A meaning that attic insulation meeting this criterion was installed, a W that wall insulation was installed, a WA that both wall and attic insulation were installed, and a * that neither was installed. Adjusted savings for houses receiving wall but no attic insulation are generally predicted accurately, with five houses being close to the equivalency line, two above, and two below. Adjusted savings for houses receiving attic but no wall insulation appear to be more generally overpredicted: four of six houses are overpredicted with two having zero or negative adjusted savings. Consistent with this latter result, 11 of 15 houses receiving both attic and wall insulation are overpredicted. Despite these observations, concluding that inaccurate savings predictions are due to poor predictions of attic insulation savings is risky because only six houses are directly involved.

9.2 WATER-HEATING ENERGY SAVINGS

Using the models and analysis approach presented in Sect. 8.3, annual pre- and post-weatherization water-heating energy consumptions and savings were estimated for each house. Results for 41 control houses are presented in Table 9.4 and for 40 audit houses in Table 9.5. Because of inadequate water-heating energy consumption data, water-heating energy consumptions and savings could not be determined using the desired analysis approach in eight houses (three control and five audit houses).

9.2.1 Control Houses

The annual pre-weatherization water-heating energy consumptions ranged from a low of 11 therms to a high of 1125 therms, with the average being 289 therms. The post-weatherization water-heating energy consumption increased, on average, by 6 therms/year to 295 therms/year, a change that is not statistically significant for a group of non-weatherized houses at a 95% confidence level. This change is significantly affected by the large increase in water-heating energy consumption experienced by two houses (Houses 116 and 174). Because these houses appear to be outliers (water-heating energy consumption was much greater in House 174 in January during the second winter than either the first winter or latter part of the second winter), the mean savings of 12 therms/year when these two houses are excluded better represents the average (this mean is not statistically significant at a 95% confidence level but is at 90%). The median savings of 8 therms/year confirms that this latter mean, rather than the mean of -6 therms/year, may better reflect the savings achieved, on average, in the control houses.

Table 9.4. Control house water-heating energy consumptions

House	Annual water-heating energy consumption Pre (therms/year)	Post (therms/year)	Annual water-heating energy savings (therms/year)
2	553	470	82
6	11	5	6
7	113	117	-4
8	226	194	33
12	125	124	1
27	299	296	3
30	231	238	-7
31	356	346	10
51	441	343	98
58	580	523	56
75	1125	1044	82
78	241	219	22
81	383	354	29
85	304	274	29
87	377	394	-17
92	262	309	-47
93	183	183	0
94	190	197	-7
95	278	250	29
103	182	263	-81
108	431	389	41
109	233	219	14
111	331	321	10
114	526	518	8
116	318	710	-392
121	89	186	-97
122	135	94	41
134	468	433	35
135	457	506	-49
140	364	274	90
142	209	177	31
144	308	278	30
145	147	144	3
149	183	150	33
150	282	286	-4
152	164	157	7
159	226	212	14
160	113	140	-26
161	126	140	-15
163	117	132	-15
174	193	500	-308
Average:	289	295	-6
Excluding Houses 116 and 174:			
Average;	292	280	12

Table 9.5. Audit house water-heating energy consumptions

House	Annual water-heating energy consumption: Pre (therms/year)	Annual water-heating energy consumption: Post (therms/year)	Annual water-heating energy savings: Measured (therms/year)	Annual water-heating energy savings: Adjusted (therms/year)	Annual water-heating energy savings: Predicted (therms/year)	Adjusted minus predicted energy savings (therms/year)
1	205	192	13	4	30	-26
3	214	238	-24	-33	38	-71
14	185	182	3	-4	33	-37
16	323	254	68	55	11	44
26	59	43	16	14	28	-14
28	396	317	79	63	37	26
48	154	98	55	49	28	21
59	98	42	56	52	41	11
68	360	386	-26	-41	23	-64
70	68	45	23	20	39	-19
72	206	211	-4	-13	40	-53
76	305	299	6	-7	26	-33
86	398	304	94	78	23	55
88	445	401	44	26	56	-30
91	422	251	172	154	13	141
105	166	147	19	13	27	-14
106	354	402	-48	-63	36	-99
110	76	67	9	6	5	1
113	425	417	7	-10	5	-15
120	124	102	22	17	38	-21
124	107	116	-8	-13	0	-13
129	441	474	-33	-51	40	-91
143	141	132	9	3	44	-41
146	441	393	48	30	68	-38
147	363	325	38	23	48	-25
148	363	378	-15	-30	49	-79
154	217	208	9	0	41	-41
155	625	643	-18	-44	37	-81
156	522	458	65	43	21	22
165	102	128	-26	-30	18	-48
167	396	449	-52	-69	29	-98
170	237	218	18	9	33	-24
172	211	225	-15	-23	19	-42
29	378	476	-98	-114	7	-121
73	343	197	146	132	41	91
131	81	69	12	9	26	-17
141	127	117	10	5	28	-23
153	534	581	-46	-68	31	-99
166	207	169	37	29	33	-4
169	51	66	-15	-17	22	-39
Average:	272	256	16	5	30	-25

9.2.2 Audit Houses

The annual pre-weatherization water-heating energy consumptions of the audit houses ranged from 51 to 625 therms and averaged 272 therms. At the 95% confidence limit, this average consumption is not statistically different from that measured for the control houses (289 therms/year).

The measured energy savings of each audit house was adjusted by the factor calculated using the control house savings (after the two outlier houses were excluded) to account for factors affecting water-heating energy consumption other than the ECMs themselves. The adjusted water-heating energy savings achieved by ECMs selected using the selection technique averaged 5 therms/year, approximately 2% of the pre-weatherization water-heating energy consumption. The 95% confidence interval for these adjusted savings is +/- 16 therms/year, indicating that the adjusted savings were not significantly different than zero.

Additional analyses support the above finding, that little savings were measured in this study due to the water-heating system ECMs. The median savings of the control houses was 8 therms/year compared to 9.5 therms/year for the audit houses before any adjustments were made. A direct comparison of the audit and control house mean savings (before adjustment) confirms that there is no statistical difference between them. As seen in Fig. 9.7, except for the two control houses excluded for being outliers, little difference in the non-adjusted water-heating energy savings between individual control and audit houses is evident.

In general, the measure selection technique did not accurately predict water-heating energy savings. The average adjusted savings for the water-heating system ECMs was 25 therms/year below the predicted value of 30 therms/year, or about 17% of predicted. It should be noted that the study was not specifically designed to measure small water-heating energy savings (see Sect. 8.3). Decisions regarding water-heating system ECMs should not be made based only on these results.

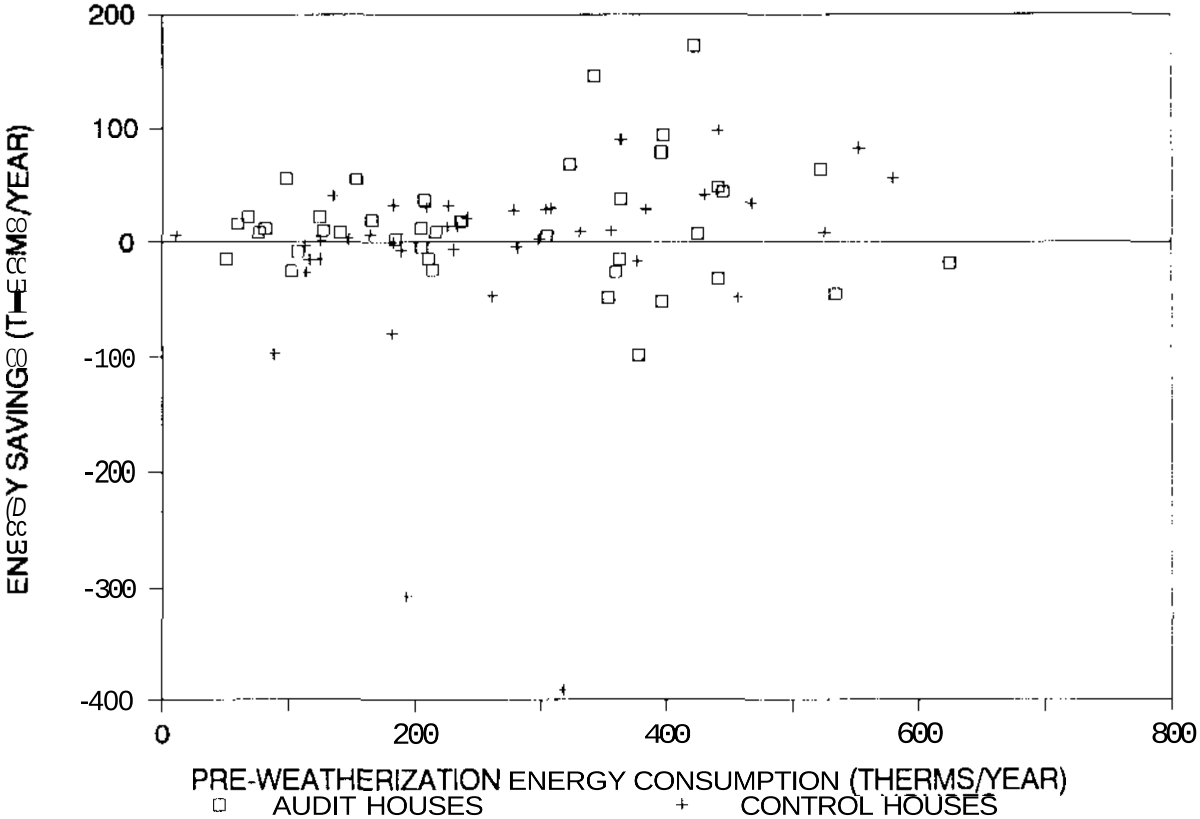

Fig. 9.7. Comparison of the water-heating energy savings of the field test houses to the pre-weatherization water-heating energy consumption.

9.3 TOTAL ENERGY SAVINGS

Adjusted and predicted energy savings are summarized in Table 9.6. Total adjusted energy savings were 257 therms/year compared to a predicted savings of 328 therms/year. The total adjusted savings is 17% of the pre-weatherization house gas consumption and 78% of the predicted value.

9.4 ENERGY SAVINGS ECONOMICS

The economics of the adjusted energy savings can be examined by considering just the ECMs themselves or the weatherization program under which the ECMs were installed. The first analysis is important because the measure selection technique recommends ECMs based on individual house economics and does not consider the cost of conducting the weatherization program. The latter analysis is needed to determine if the total expenditure of funds required to bring about house efficiency improvement is economically justified. In both cases, the economics considered in this report are based only on the energy savings achieved and do not include social benefits.

The economic analyses presented in this report were performed from a consumer viewpoint in that energy savings were valued at the residential cost of gas and discount rates appropriate to a homeowner were used. This approach is justified because the measure selection technique itself was designed and conducted from a consumer viewpoint; the economic criteria used in the selection technique (real discount rate — 0.05 and current residential cost of gas) led to the selection of a set of ECMs estimated to be cost effective from the consumer viewpoint.

Assessing the economics of the measure selection technique results performed from a consumer viewpoint in hindsight from a utility viewpoint can be misleading. Economic criteria used in the selection technique can easily be based on a utility perspective. Had such a utility viewpoint been used, a different set of ECMs would likely have been selected, and

Table 9.6. Summary of audit house energy consumptions and savings

	Annual pre-weatherization energy consumption (therms/year)	Annual Energy Savings				Installation cost ($)
		Adjusted[c] (therms/year)	Predicted (therms/year)	Percent savings	Percent of predicted	
Space heating[a]	1022	252 ± 91	298	25%	85%	1309
Water heating[b]	272	5	30	2%	17%	78
Other gas use	182					
Total	1476	257 ± 91	328	17%	78%	1387

[a]Based on data for 32 audit houses.

[b]Based on data for 36 audit houses.

[c]Includes 95% confidence internal.

the results would likely have been different. Moreover, assessing the economics from a utility viewpoint likely requires a thorough least-cost planning analysis, which is beyond the capabilities of the selection technique and the scope of this project.

In evaluating the economics of the weatherization program, an administration cost of $400/house was assumed. Because of the research orientation of the field test, the cost to administer a full weatherization program is not known. This cost was arrived at by assuming $150/house to audit each house, $50/house to perform an air-leakage test, and $200/house for other administration functions (such as program planning, identifying customers, handling applications, checking program eligibility, inspections and quality control, staffing, and overhead). The costs for conducting the audit and other administration functions are consistent with those assumed by McCold et al. (1988) in a previous evaluation of the measure selection technique ($100 and $200/house, respectively). The $200/house for other administration functions is also consistent with information collected by Berry (1989). These data showed that an administration cost ratio (administration cost divided by cost of ECMs) of 0.20 is a reasonable average figure for residential weatherization programs (conducted by electric utilities). Using this ratio, an administration cost of about $275/house would be estimated for this study. Because this cost includes a cost for auditing, it is consistent with the $200 assumed in this study. Administration costs for weatherization programs are dependent on many factors and vary considerably among programs; thus, the actual administration cost for a given program may be quite different than the $400/house assumed in this analysis. This variation must be kept in mind in applying the analysis results to a specific program.

Results of the economic analyses, based on the total energy savings presented in Sect. 9.3, are presented in Table 9.7. Installation of ECMs costs an average of $1387/house and resulted in an average adjusted savings of 257 therms/year. (The installation cost of $1387/house is the average cost for the 32 audit houses used to estimate the average space-

Table 9.7. Economics of the energy conservation measures and weatherization program

	Conservation Measures	Weatherization Program
Installation cost	$1387[a]	$1787[b]
Annual energy savings	257 therms/year	257 therms/year
Simple payback period[c]	9.3 years	12.0 years
<u>Considering</u> fuel escalation[d]		
Benefit to cost ratio:[c,e]		
discount rate = 0.05	1.44	1.12
discount rate = 0.075	1.17	0.91
discount rate = 0.10	0.98	0.76
Cost of conserved energy:[e]		
discount rate = 0.05	$0.40/therm	$0.52/therm
discount rate = 0.075	$0.49/therm	$0.64/therm
discount rate = 0.10	$0.59/therm	$0.76/therm
<u>Not considering fuel escalation</u>		
Benefit to cost ratio:[c,e]		
discount rate = 0.05	1.24	0.96
discount rate = 0.075	1.02	0.80
discount rate = 0.10	0.86	0.67
Cost of conserved energy:[e]		
discount rate = 0.05	$0.47/therm	$0.60/therm
discount rate = 0.75	$0.57/therm	$0.73/therm
discount rate = 0.10	$0.67/therm	$0.86/therm

[a] Installation cost based on 32 audit houses used to determine average space-heating system energy savings.

[b] Assumes $400/house for administration cost based on estimates discussed in the text.

[c] Assumes current cost of gas = $0.579/therm.

[d] Fuel escalation rates obtained from Lippiatt and Ruegg (1988).

[e] Calculated assuming 81% of space-heating savings due to energy conservation measures with a 20-year lifetime, 7% with 15-year lifetime, 10% with 10-year lifetime, and 2% with 2-year lifetime; and 60% of water-heating savings due to energy conservation measures with a 15-year lifetime, 20% with a 10-year lifetime, and 20% with a 3-year lifetime.

heating energy savings. This cost, rather than the $1453/house reported in Sect, 6.2 for the 36 audit houses unaffected by the error in the measure selection technique, was used because it best represents the costs for ECMs that produced the adjusted savings of 257 therms/year.) Using NF's residential fuel cost at the time the ECMs were installed ($0.579/therm), the simple payback period for the ECMs is 9.3 years. The simple payback period for a weatherization program using the selection technique was estimated to be 12.0 years, assuming a total cost of $1787/house ($1387 for the installation of ECMs and $400/house for administration). Payback periods of this magnitude are not unreasonable because ECMs estimated to produce the greatest annual savings had assumed lifetimes of 20 years.

In Table 9.7, cost effectiveness is presented by the BCR and the cost of conserved energy. To calculate these quantities, the annual adjusted savings had to be divided into savings from envelope and space-heating system ECMs with lifetimes of 2, 10, 15, and 20 years, and from water-heating ECMs with lifetimes of 3, 10, and 15 years based on distributions developed from the predicted savings. BCRs for the installation of the ECMs and the weatherization program are presented for different discount rates, with and without fuel escalation considered, and assuming NF's residential fuel cost at the time the ECMs were installed ($0.579/therm).[2] The ECMs and program are cost effective under the stated assumptions if the BCR is greater than 1.0. Additionally, Che cost of conserved energy is presented for different discount rates with and without fuel escalation considered. If the appropriate cost of gas is greater than the cost of conserved energy, then the ECMs or program are cost effective.

Based on the economic criteria used in the selection technique (discount rate of 0.05, not considering fuel escalation, and NF's residential fuel cost at the time the ECMs were installed at

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[2]Real, rather than nominal, discount and fuel escalation rates were used in the analysis and reported in this document (i.e., these rates are exclusive of general price inflation).

$0.579/therm), the primary goal of the selection technique, to reduce energy consumption cost effectively through the installation of ECMs, was achieved. The installation of the ECMs was cost effective, resulting in an overall BCR of 1.24 and a cost of conserved energy of $0.47/therm. Under these same assumptions, a weatherization program costing $400/house above the cost of ECMs alone would not be quite cost effective (the program would be cost effective at an administration cost less than $335/house).

Assessing the economics of the measure selection technique results using economic criteria different from those used in the selection technique can be misleading. If different criteria were used in the selection technique, a different set of ECMs would likely be selected, and the field test results would likely be different. Nevertheless, the effect of different discount rates and fuel escalation are presented in Table 9.7 (still using the residential cost of gas). By considering fuel escalation, BCRs increase and the costs of conserved energy decrease; the ECMs alone remain cost effective even at discount rates of nearly 0.10, and for a discount rate of 0.05, the weatherization program becomes cost effective. If fuel escalation had been considered in the selection technique, additional ECMs would have been identified as being cost effective and, thus, would have been performed. Higher discount rates decrease the BCRs and increase the costs of conserved energy. Excluding fuel escalation, the ECMs alone remain cost effective at a discount rate of 0.075. If higher discount rates had been used in the technique, ECMs with BCRs near 1.0 using the original criteria would not have been recommended for installation.

The economics of ECMs designed to reduce space-heating energy consumption only (Table 9.8) is of interest because savings of water-heating system ECMs were too small to accurately measure with the approach used in this field test and the small savings that were measured were not achieved cost effectively (a more economical means of implementing water-heating system ECMs will be addressed in Sect. 10.2.2). Compared to results from Table 9.7 for all ECMs, BCRs increased

Table 9.8. Program economics assuming installation of energy conservation measures designed to reduce space-heating energy consumption only

	Conservation Measures	Weatherization Program
Installation cost	$1309[a]	$1709[b]
Annual energy savings	252 therms/year	252 therms/year
Simple payback period[c]	9.0 years	11.7 years
Considering fuel escalation[d]		
Benefit to cost ratio:[c,e]		
discount rate - 0.05	1.51	1.16
discount rate - 0.075	1.23	0.94
discount rate - 0.10	1.02	0.74
Cost of conserved energy:[e]		
discount rate - 0.05	$0.38/therm	$0.50/therm
discount rate - 0.075	$0.47/therm	$0.62/therm
discount rate - 0.10	$0.57/therm	$0.74/therm
Not considering fuel escalation		
Benefit to cost ratio:[c,e]		
discount rate - 0.05	1.30	0.99
discount rate - 0.075	1.07	0.82
discount rate - 0.10	0.90	0.69
Cost of conserved energy:[e]		
discount rate - 0.05	$0.45/therm	$0.58/therm
discount rate - 0.75	$0.54/therm	$0.71/therm
discount rate — 0.10	$0.64/therm	$0.84/therm

[a]Installation cost based on 32 audit houses used to determine average space-heating system energy savings.

[b]Assumes $400/house for administration cost based on estimates discussed in the text.

[c]Assumes current cost of gas - $0.579/therm.

[d]Fuel escalation rates obtained from Lippiatt and Ruegg (1988).

[e]Calculated assuming 81% of space-heating savings due to energy conservation measures with a 20-year lifetime, 7% with 15-year lifetime, 10% with 10-year lifetime, and 2% with 2-year lifetime; and 60% of water-heating savings due to energy conservation measures with a 15-year lifetime, 20% with a 10-year lifetime, and 20% with a 3-year lifetime.

and costs of conserved energy decreased. Because the changes were slight, major observations regarding cost effectiveness remain unchanged.

The economics of ECMs designed to reduce space-heating energy consumption installed in houses with pre-weatherization space-heating consumption greater than 1000 therms/year is provided in Table 9.9. This approach is of interest because targeting high energy users within a weatherization program can be easily accomplished (especially for a utility-run program), and more ECMs were installed and greater energy savings were achieved in houses with high energy consumption. Compared to results in Tables 9.7 and 9.8, this approach results in significantly greater BCRs and lower costs of conserved energy. The ECMs themselves are cost effective at discount rates up to 0.10, even without considering fuel escalation. A weatherization program with $400/house administration cost Is cost effective at discount rates up to 0.075 and, if fuel escalation is considered, up to about 0.10 (the administration cost would have to be less than $100/house for a program to be cost effective at a discount rate of 0.10 and without fuel escalation considered).

9.5 COMPARISON TO PREVIOUS FIELD TESTS

An earlier version of the selection technique was previously field tested in Wisconsin (McCold et al. 1988, Ternes et al. 1988). Results from this previous test are compared to results obtained from the current study in Table 9.10.

Despite differences that existed between the housing characteristics and climate of the two studies, the average pre-weatherization space-heating energy consumptions were about the same.

Adjusted energy savings achieved under this field test were greater than those previously achieved and were obtained from a different set of ECMs. One reason for the difference in energy savings is that water-heating system ECMs were included in the recent test, although they saved only an estimated 5 therms/year. In the current study, attic insulation

Table 9.9. Economics assuming installation of energy conservation measures designed to reduce space-heating energy consumption only and targeting higher energy users (pre-weatherization space-heating energy consumption greater than 1000 therms/year)

	Conservation Measures	Weatherization Program
Installation cost	$1772	$2172[a]
Annual energy savings	399 therms/year	399 therms/year
Simple payback period[b]	7.7 years	9.4 years
Considering fuel escalation[c]		
Benefit to cost ratio:[b,d]		
discount rate - 0.05	1.76	1.44
discount rate = 0.075	1.44	1.17
discount rate - 0.10	1.19	0.97
Cost of conserved energy:[d]		
discount rate = 0.05	$0.33/therm	$0.40/therm
discount rate = 0.075	$0.40/therm	$0.49/therm
discount rate = 0.10	$0.49/therm	$0.60/therm
Not considering fuel escalation		
Benefit to cost ratio:[b,d]		
discount rate - 0.05	1.52	1.24
discount rate - 0.075	1.25	1.02
discount rate - 0.10	1.05	0.86
Cost of conserved energy:[d]		
discount rate - 0.05	$0.38/therm	$0.47/therm
discount rate - 0.75	$0.46/therm	$0.57/therm
discount rate - 0.10	$0.55/therm	$0.67/therm

[a]Assumes $400/house for administration cost based on estimates discussed in the text.

[b]Assumes current cost of gas — $0.579/therm.

[c]Fuel escalation rates obtained from Lippiatt and Ruegg (1988).

[d]Calculated assuming 81% of space-heating savings due to energy conservation measures with a 20-year lifetime, 7% with 15-year lifetime, 10% with 10-year lifetime, and 2% with 2-year lifetime; and 60% of water-heating savings due to energy conservation measures with a 15-year lifetime, 20% with a 10-year lifetime, and 20% with a 3-year lifetime.

Table 9.10. Comparison of current results with those from a previous study of the selection technique

	Current Results (New York)	Previous Results[a] (Wisconsin)
Pre-weatherization space-heating energy consumption	1022 therms	1071 therms
Annual energy savings	257 therms	207 therms
Percent of predicted savings	78%	83%
Expenditures (energy conservation measures only)	$1387/house	$1303/house
Simple payback period	9.3 years	9.5 years
Annual energy savings per dollars expenditure	18.5 therms/year/$100	15.9 therms/year/$100

[a]McCold et al. (1988) and Ternes et al. (1988)

was installed in many houses and was a major contributor to the average energy savings. Additionally, a new space-heating system was installed in only one house. In the previous study, space-heating system replacements were performed in about a third of the houses and attic insulation was less important because most attics were already insulated. In both tests, wall insulation was an ECM installed in many houses that contributed significantly to the average energy savings.

In both studies, the adjusted energy savings were about 80% of predicted. In the previous study, overprediction of wall insulation savings appeared to be a major contributor to this. In the current study, however, the wall insulation savings seems to be estimated correctly. Overprediction of water-heating energy savings contributes to the deviation in the current study.

Expenditures required to install the ECMs and simple payback periods were comparable in both studies. Because of the higher fuel cost in Wisconsin ($0.68/therm compared to $0.579 in this study), the payback periods were about the same despite the increased energy savings achieved in this study.

To the extent that the two studies can be compared, the effectiveness of the selection technique in achieving energy savings for lower expenditures has improved. In this study, 18.5 therms/year were saved for every $100 spent on ECMs as compared to 15.9 therms/year in the previous study. Although this improvement could certainly be due to differences in housing stock and climate, improvements made to the selection technique are also likely contributors. The most significant improvement was that only ECMs with predicted BCRs greater than 1.0 were installed in the current study; in the previous study, ECMs that were not cost effective were installed to maintain a predetermined average expenditure level.

The scatter observed in the predicted versus adjusted energy savings plot for this study (Fig. 9.6) is much less than that observed in similar plots from other studies, especially those that used just billing data as the basis for determining adjusted energy savings. A reduction in this scatter allows the performance of the selection technique and ECMs to be more accurately determined and greater insights to be gained; with large scatter, analysis is limited to average observations. The accuracy of the predictive technique on an individual house is an important factor affecting the nature of this scatter: the better the technique, the less scatter should be observed. Two other important factors are the accuracy of the measured savings and the scatter introduced by the analysis method. Although more study would be required to determine the actual benefit obtained from the analysis method used in this study, it is likely that using submetered space-heating system data to determine space-heating energy savings and normalizing these savings to a constant indoor temperature contributed significantly to the reduced scatter.

10. RECOMMENDATIONS: TECHNIQUE DESIGN AND IMPLEMENTATION

10.1 TECHNIQUE DESIGN

The use of net present value (NPV) instead of BCR as the main selection criterion should be evaluated. BCR allows relative benefits per dollar expenditure to be determined; this is the correct criterion to use if maximizing the BCR for the weatherization program is the primary objective. Because the goal of maximizing the BCR for the program must be balanced against running an equitable program, NPV may be a more useful criterion. The use of NPV would select ECMs that are cost effective (NPV greater than or equal to 0.0) and that provide the greatest net benefits or monetary savings. Using BCR, many inexpensive ECMs that have moderate predicted savings (and thus have high estimated BCRs) are usually selected. However, the actual savings of these ECMs may be quite variable and much smaller than expected. Using NPV, fewer ECMs would likely be selected, but the expected savings of these ECMs (which can be predicted more accurately) are usually large. The use of economic analyses in weatherization programs is further discussed by Zimmerman (1990).

The current method of handling interactions between mechanical-system ECMs could be improved by using the NPV of the ECMs as a selection criterion. The cost effectiveness of the ECM is already assured because it's BCR exceeds 1.0 and the cutoff value. A decision based on NPV selects the ECM that will provide the greatest net benefits or monetary savings. Under the current system, for example, a gas power burner is arbitrarily selected in preference to a vent damper if both have a BCR greater than the value of the cutoff. This is justified because the power burner will save more energy. An alternative is to select the ECM with the highest BCR; however, selecting a vent damper having a BCR of 1.8 at the exclusion of a high-efficiency furnace that has a BCR of 1.7, for instance, does not seem wise, especially if other ECMs with lower BCRs will then also be selected.

To the extent possible, all costs that will be charged by a contractor to install an ECM should be included in the estimated installation costs. For example, the need for an attic access door or increased attic ventilation before adding attic insulation is identified in the field, but the cost for this work is not included in the cost estimates or subsequent economic calculations. Identifying these added costs should not be a major part of the auditing process, however. Rather than identifying all the necessary material and labor needed to perform these supplemental tasks, the auditor could identify the task in a comments section and enter the cost for this work (estimated based on experience) in a column that would be added to the cost of the ECM.

For insulation ECMs, especially attic insulation, different levels of insulation should be considered simultaneously by the measure selection technique. This would allow a more optimum level of insulation to be added within the economic guidelines (BCR cutoff) selected for the program.

The method included in the selection technique to estimate the balance point temperature of the house from previous billing data should be improved. A method that more clearly identifies which balance point temperature is correct (perhaps using regression coefficients rather than visual interpretation), that does not require changing between computer screens, and that would allow most auditors to make the same selection for a given house is needed.

The method of estimating savings and/or costs for foundation insulation needs to be revised to be consistent with recent research results. This ECM may need to be eliminated from the measure selection technique until further research results become available that indicate this is a cost-effective ECM.

A procedure to select the proper size for a new space-heating system would be a useful feature. The data collected under this technique may not be sufficient, though, to perform such a calculation. Depending on the number of houses receiving new systems, sizing may be more easily handled on an individual basis.

Input values to the measure selection technique should be limited to those falling within a pre-selected, reasonable range. Such checking would help eliminate input mistakes such as those that occurred in this study for foundation insulation.

The selection technique should include an easy to use follow-up report to be filed as a permanent record. The ECMs actually installed in each house and their costs should be identified in the report and compared to the recommendations and predictions. The air-leakage rates and reductions achieved from the infiltration work should be documented. A comments section should also be included to explain unusual occurrences or discrepancies. The work order portion of the tested technique includes a follow-up report section meeting most of these requirements, but it was not easily used.

The desire for increased accuracy in measure selection technique predictions should be tempered by the additional input information likely required and the ease with which the selection technique can be implemented. In this technique, reasonable accuracy was obtained using relatively simple estimation techniques and a level of information that could be collected and programmed in 4 hours/house. Although improved accuracy might be obtained through the use of more sophisticated estimation techniques and more detailed descriptive information (building characteristics, system operations, and occupant influences), the resulting benefits may not outweigh the increased effort required to implement the technique.

10.2 IMPLEMENTATION

The measure selection technique was designed to consider all ECMs at one time and, by comparing one to another, to select the most appropriate ECMs for each house. Based on the field test experiences, such an ideal approach has practical limitations. Instead of including all ECMs within the selection technique, the following types of ECMs may be better handled following separate procedures that are performed in parallel to the selection technique: infiltration reduction, low-cost/no-cost ECMs, and occupant education ECMs. Recommendations regarding these three procedures are provided in Sects. 10.2.1-3; other recommendations regarding implementation of the tested technique are presented in Sect. 10.2.4.

10.2.1 Infiltration Reduction

By following the economic based infiltration reduction procedure used in this field test, infiltration reduction work is, in effect, performed independently from the selection technique because the infiltration procedure is applied to every house without the need for a measure selection technique recommendation and the amount and type of work to be performed is determined during the procedure rather than beforehand by the selection technique. A third reason for performing infiltration work separately is the inaccuracy associated with estimating energy savings for infiltration reduction work relative to other ECMs. Accurate estimates of the energy savings for infiltration reduction work cannot be made in the selection technique unless the actual reduction achieved is first known. Estimating the reduction that might be achieved knowing just the current air-leakage rate is like trying to estimate the savings of ceiling insulation if the current insulation level is known but the amount to be added is not. Such an approach also requires additional work by the auditor to make an air-leakage measurement. Estimating the reduction using an estimate of the present air-leakage rate only leads to further inaccuracies. If the BCR selected for the infiltration work is greater than the cutoff value for the selection method, the selection of other ECMs becomes dependent on the savings of the infiltration work because of the interaction of energy savings among ECMs. If the savings for infiltration work are inaccurate or relatively uncertain, then other ECMs can be incorrectly eliminated and/or selected.

In theory, excluding infiltration work from the selection technique may also affect the selection of other ECMs; in practice, though, this should not be the case. The cost-effective guideline for the infiltration reduction work should be determined using a BCR with the same value as the BCR cutoff used in the measure selection technique rather than using a higher value. Consequently, if included in the selection technique, infiltration reduction work should always be the last ECM selected for each house and, thus, would not interact with any other ECM.

There may be a desire to make some estimates regarding the infiltration reduction work in parallel with the measure selection technique to help in the scheduling and tracking of work. This can still be performed as long as it is done outside the mainstream of the selection technique. If such an approach is followed, the equation used in this field test to estimate the reduction needs to be modified to consider the BCR selected for the work. Additionally, minimum air-leakage rates and maximum expenditure levels used in the infiltration procedure should be considered.

Because the reduction obtained from the installation of insulation is on the same order as that obtained from the infiltration work, it may be best to perform infiltration work (still using the cost-effective guideline stipulated by the procedure) at the same time Insulation is installed or after all other ECMs are installed, rather than before as done in this field test. Addition of insulation may seal leakage sites, reducing the need for specific infiltration work. Furthermore, control over the final air-leakage rate of the house can only be obtained by performing specific infiltration work last. Two approaches following these recommendations are outlined by Ternes and Hwang (1989). Use of the auditor to make the initial infiltration measurement as a screening procedure is an individual, programmatic decision. With this approach, houses that do not need infiltration work are identified early, saving the time of infiltration reduction crews; however, the auditor's time at the house is increased slightly. A correct decision may depend on the percentage of houses that typically do not require any work.

The need for thorough training on the infiltration reduction procedure is critical if crews are expected to quickly adapt this new technology. The training provided under this field test was sufficient to know how to use a blower door, make infiltration measurements, and follow the procedure, and was a good introduction to finding and sealing leaks. This training needs to be reinforced by discussing in greater detail sealing methods and materials, having the trainer spend several additional days with individual crews in the field locating and sealing leaks in real houses, and having a follow-up training session several months later to review procedures, refine techniques, and resolve questions or problems. A more complete training program recommended for future studies is outlined by Ternes and Hwang (1989). During the training, application of the guideline to the last increment of work rather than the total work performed must be emphasized. Additionally, setup cost should not be included in evaluating the effectiveness of the latest work. Setup cost should be considered an upfront cost, similar to the cost of collecting the audit information.

10.2.2 Low-Cost Energy Conservation Measures

The following low-cost ECMs considered in the selection technique may be more easily and economically performed under a separate procedure: water heater insulating blankets, water heater pipe insulation, water-heating system thermostat setpoint reduction, energy efficient showerheads, and energy efficient faucets. Basically, the costs and savings of these ECMs do not warrant an extended analysis to decide if they should be installed. Energy savings for these ECMs are difficult to estimate because most depend on factors (such as the amount of hot water consumption) that cannot be measured for input into the technique. Additionally, in the time required to collect and input information regarding these ECMs, many of them could be performed. Because these

ECMs do not interact with other ECMs considered in the selection technique, their removal would not present a problem.

Simple criteria can be used in the field to decide if these ECMs should be installed. For example, showerheads with flows greater than 5 gpm would be replaced and all water heaters with less than 1 in. of insulation would receive an additional blanket. An auditor could quickly make these decisions and either do them at the time of the initial audit or refer them to an insulation crew. As discussed in the next section, reducing the hot water temperature should include the participation of the occupant and, thus, involves more than a simple setpoint adjustment; for this reason, this ECM could be considered an occupant education ECM.

10.2.3 Occupant Education Energy Conservation Measures

Lowering space-heating system thermostat setpoints (either manually or with clock thermostats) may be best performed under an occupant education program. The reasons for this are twofold:

1. energy savings predictions are very uncertain because the occupants current practice is difficult to quantify and the extent to which occupants would maintain reduced temperatures are not known, and

2. costs used in a selection technique usually do not reflect the effort needed to really implement these ECMs.

A thoroughly developed client education program, implemented by well trained educators, is needed to convey the importance of lowering indoor temperatures and methods of doing so in order to achieve and sustain savings from these types of ECMs. Without a separate program, the level of instruction necessary to change behavior would probably not be provided.

Many of these comments also pertain to reducing the hot water temperature. In the field test, there was some evidence that occupants increased the hot water temperatures after the auditors had set them lower. Even if this ECM is performed as a low-cost ECM, the auditor should spend some time with the occupant to discuss the importance of the reduction and to identify an agreeable value. If the current temperature is very high, reducing the temperature in steps (by the auditor and again be a crew member) may be an approach to allow the occupant to adjust to lower settings.

10.2.4 Other Implementation Recommendations

The length of the training courses provided to field personnel on the selection technique need to be supplemented to provide a more complete understanding (additional time than that provided or to be discussed may be required if more inexperienced personnel were being trained). Several additional days are needed in the field training auditors on how to collect the information (especially that peculiar to this technique), to complete audit forms, and to make decisions regarding emergency repairs. The auditors should be trained to collect field information as if they were contractors to increase the accuracy of the installation cost predictions. Under this approach, measurements would be made as contractors would perform them (measuring insulation areas, for example) and all tasks required to install an ECM would be identified (the need for an attic access door, for example). Additional time should also be spent to perform all tasks required for the selection technique on several real houses from start to finish. A floor plan type of drawing used by NF personnel in the field test should be considered in all future applications of the technique to help collect and organize information, especially if several contractors are used to install ECMs.

Space-heating system tune-ups should be performed for efficiency reasons only on units that can benefit from this work, based on efficiency measurements or other system characteristics, to improve the overall BCR of the weatherization program. The approach of tuning-up all units as a standard practice or for liability reasons is costly, probably unnecessary, and likely does not produce energy savings in many units. A tune-up should be performed following a well documented procedure and after receiving adequate training to ensure an efficiency improvement results.

A safety inspection should not be confused with a tune-up, which should be performed in all houses to ensure a safe space-heating system after weatherization. A tune-up performed by an auditor during a safety inspection may be a compromise to the above recommendation regarding tune-ups as a standard practice. Use of a contractor for such a purpose can be expensive because of the cost involved with the site visit.

In an actual program, the consistency of the housing stock and other factors (such as fuel costs and installation costs of ECMs) may be used advantageously to simplify the selection process, so that the selection technique may not need to be applied in every house. Based on these field test results, a decision tree selection procedure (or a simpler, one page calculation form) could likely be developed for a program weatherizing the same types of houses and operating under the same conditions encountered in the field test (fuel costs, costs to install ECMs, etc.) because of the patterns observed in the weatherization work performed. In a program initially using the selection technique, the technique would be applied to every home. After a sufficient number of homes had been weatherized, patterns in the decisions made by the technique would be identified to determine if a simpler approach could be followed. If so, this simpler approach would be used and small samples of homes would be checked yearly using the selection technique to ensure that the simpler approach remains valid. It is likely that different patterns would emerge for different climate regions, fuel types, and possibly by installation agency (if installation costs are different among agencies).

11. SUMMARY: CONCLUSIONS AND RECOMMENDATIONS

The results of this field test lead to conclusions and recommendations about the design and implementation of the improved energy conservation measure selection technique, the ECMs selected, the savings achieved and accuracy of predictions, cost effectiveness, and the field test itself.

Use of a measure selection technique to select unique ECMs for individual houses resulted in a significant cost-effective level of energy savings.

A cost-effective level of energy savings was achieved, on average, in the audit houses by ECMs installed under the guidance of the selection technique. The overall BCR for the ECMs was 1.24 assuming just installation costs, current residential fuel costs, and using a discount rate of 0.05.

Significant savings were achieved, on average, in the audit houses. The average adjusted savings was 257 therms/year: 252 therms/year from space-heating energy savings and 5 therms/year from water-heating energy savings. Adjusted space-heating energy savings was 25% of the average pre-weatherization space-heating energy consumption (1022 therms/year), adjusted water-heating energy savings was 2% of the average pre-weatherization water-heating energy consumption (272 therms/year), and the total adjusted energy savings was 17% of the average pre-weatherization house gas consumption. These savings include an adjustment using normalized control group savings.

The measure selection technique predicted space-heating energy savings and total installation costs with reasonable accuracy, indicating that its recommendations are justified (ECMs were correctly recommended in individual houses and concentration of ECMs in selected houses was justified).

The average adjusted space-heating energy savings achieved in the audit houses was predicted relatively accurately by the selection technique (within 85%). Although not statistically accurate for individual houses, the selection technique's prediction of space-heating energy savings is reasonably accurate for most houses. Differences between predicted and adjusted savings are statistically different in all but six of 38 houses. However, a graphical comparison shows that houses are generally grouped around a line representing equality between predicted and adjusted savings. Changing the balance point temperature used to predict space-heating energy savings of envelope ECMs from 60°F to 57°F eliminates the difference between average predicted and measured savings. Inaccuracies in predicting attic insulation savings may also be a source of the observed differences, but a definitive conclusion is hard to reach.

The selection technique was not very accurate in predicting water-heating energy savings. However, the study was not designed to specifically measure small water-heating energy savings. Additionally, anticipated water-heating energy savings were much less than anticipated space-heating energy savings.

The average cost for performing the ECMs in the houses was estimated quite reliably by the selection technique (within 2%). Comparisons for individual houses varied more widely than this average, though.

ECMs could not always be installed in houses as recommended. This did not have a serious impact on installation costs or other ECMs selected because the ECMs not installed were usually inexpensive and small energy savers. Auditing errors and the manner in which infiltration reduction is included in the selection technique contributed to this problem. These problems can be easily corrected.

Conclusions regarding the benefit of standard, contractor tune-ups and the accuracy of energy savings predictive techniques for this ECM are difficult to make because of the frequent occurrence of negative changes in measured efficiencies.

One need for future research identified during the field test is to develop an accurate method of estimating the energy savings of space-heating system replacements and/or determining whether these savings should be based on steady-state efficiency, seasonal efficiency, or an intermediate value. This need arises because of the infrequent selection of replacements in this study. The accuracy of the savings estimates could not be evaluated in this study because only one new system was installed. Previous tests of the measure selection technique, however, indicated that a simple method using steady-state efficiency was, on average, accurate.

The effectiveness of the selection technique improved from earlier versions and can continue to be improved.

The effectiveness of the selection technique in achieving energy savings for lower expenditures has improved. Under this field test, 18.5 therms/year were saved for every $100 spent on ECMs as compared to 15.9 therms/year measured in a previous study. Although this improvement could certainly be due to differences between the experiments in housing characteristics and climate, improvements made to the technique are also likely contributors (especially limiting recommended ECMs to those with predicted BCRs greater than 1.0).

Through use of the infiltration reduction procedure, significant cost reductions for infiltration reduction work were achieved. Work was not performed in 19% of the houses because their air-leakage rates were already sufficiently low. By requiring infiltration reduction work to be performed at a BCR of 2.0, expenditures were limited to an average of $73/house (excluding a $70/house set up cost). Better trained and more experienced crews may spend more than this to achieve greater reductions. Greater expenditures and reductions would also result if the BCR for the work was lowered.

If envelope and water-heating system ECMs only were to be installed in homes similar to those tested, a simpler selection technique could be devised based on the field test results that could produce near equivalent results. This occurs because the consistency of the housing stock allows patterns to develop regarding correct installations. If space-heating system ECMs are also to be considered, a simpler technique may not be able to be developed; proper decisions regarding the replacement of the space-heating system can be made only after the energy savings of the ECM are interacted with the savings of other ECMs.

Although the selection technique achieved cost-effective energy savings, the technique could be improved to increase accuracy and ease of use. Training on the selection technique should be increased beyond four days to provide a more complete understanding, especially regarding collection and interpretation of data in the field. Interactions between mechanical system ECMs could be improved by using NPV of the ECMs as a selection criterion. All costs that will be charged by a contractor to install an ECM (such as attic accesses or vents) should be included in the estimated installation costs used in the economic analysis. The method used to estimate the balance point temperature of the house from previous billing data should be improved or eliminated (a constant 60°F balance point was used successfully in this study). A procedure to select the proper size for a new space-heating system may need to be included in the technique. ECMs requiring occupant use and control such as thermostat setbacks of the space-heating or water-heating systems should be included in a client education package performed in parallel with the selection technique rather than including them in the technique.

Improved methods of implementing the selection technique should also lead to increased savings and cost effectiveness. Infiltration reduction work should be performed in parallel with the selection technique (following the infiltration reduction procedure used in this study) as well as low-cost ECMs (such as most water-heating system ECMs). Space-heating system tune-ups should be performed for efficiency reasons only on units that can benefit from this work rather than on all units.

Use of the measure selection technique resulted in the installation of a wider variety of ECMs than typically installed under most weatherization programs and produced large variations in energy savings and expenditures among houses.

A wider variety of ECMs than typically installed under most weatherization programs were selected by the technique, although only 11 of 21 ECMs considered by the selection technique were installed. Three water-heating system ECMs (pipe insulation, insulating blanket, and temperature reduction), infiltration reduction, and attic, wall, and sill box insulation were frequently performed. Space-heating system tune-ups were routinely performed to ensure that the systems were operating safely and to avoid liability issues, although energy savings were still expected. Floor insulation, foundation insulation, and space-heating system replacement were ECMs infrequently performed. ECMs that were never performed included storm windows, intermittent ignition devices, and vent dampers. If a clock thermostat with a 5°F setback had been an option considered by the selection technique, it would have been selected in only one house.

The space- and water-heating savings of the individual houses was quite variable. On average, the space-heating energy savings was largest in houses with higher pre-weatherization space-heating energy consumption and that received greater expenditures for ECMs. Adjusted space-heating energy savings ranged from -136 to 1120 therms/year and adjusted water-heating energy savings ranged from -98 to 172 therms/year. The variability of the individual house energy savings and the relation between savings and expenditures can be largely attributed to the selection technique, which was designed to concentrate ECMs in houses that would most benefit from them.

The amount of money spent on each house averaged $1453 for 36 houses ($1387 for 32 houses with energy savings that could be analyzed) but varied over a large range: less than $500/house was spent in five houses and more than $2000/house was spent in 11 houses. Expenditures were predominately for wall and attic insulation: an average of $750 and $400, respectively, was spent in each house for these measures, while less than $75 was spent (on average) on each of the remaining measures.

Average indoor temperature changes following weatherization were small. Indicating that a **significant** take-back effect had not occurred.

Conclusions drawn from previous ORNL experiments, that indoor temperature and its change does not contribute significantly to lower than expected savings observed in weatherization programs but that they do contribute to the variation in measured savings observed in individual houses, were confirmed. The average temperature maintained in the audit houses was about that expected (68-70°F), and the average change in indoor temperature for the audit houses was near zero (+0.5°F) and about equal to that observed, on average, in the control houses (-0.1°F). Indoor temperatures maintained in individual houses and changes in temperature following weatherization are unique for each house, however.

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APPENDIX A. DATA PARAMETER AND FIELD TEST IMPLEMENTATION DETAILS

A.1 DATA PARAMETERS AND MONITORING INSTRUMENTATION

The data collected in this field test can be divided into two classifications: time-independent information and time-dependent measurements. The time-independent information represents data collected before, during, or after the experiment through discussions with the homeowners, visual observations, and some limited measurements. Time-dependent measurements were monitored continuously with instrumentation throughout the experimental period.

A.1.1 Time-Independent Information

The following information were collected:

1. house and occupant descriptive information,
2. house air-leakage measurements,
3. space-heating system steady-state efficiencies, and
4. listing and quality verification of the ECMs performed.

The descriptive information documented the physical characteristics of the house and space-heating equipment as well as the behavioral characteristics of the occupants. Table 3.1 lists the specific information collected. These data were collected in February and March 1988.

The house air-leakage measurements served as descriptive variables characterizing the house air-leakage rate before and after the ECMs were performed. These measurements were in addition to any measurements made under the infiltration reduction procedure used with the measure selection technique. The fan pressurization technique using a blower door was used because repeatable results can be obtained at standard conditions. The flow at 0.04 in. H_2O (10 Pa) to 0.24 in. H_2O (60 Pa) in increments of 0.04 in. H_2O (10 Pa) were measured with the blower door pressuring and depressurizing the house. Measurements were made in both the audit and control houses in July and August 1988, before ECMs were installed in the audit houses, and again in October and November 1988 after the ECMs were installed in the audit houses.

The steady-state efficiencies of the gas-fired space-heating systems were measured by performing a flue gas analysis. These measurements were made in June and July 1988 before ECMs were installed and were repeated in houses receiving mechanical-system ECMs in October and November 1988 after the ECMs were installed.

The ECMs actually installed in the houses and their costs were documented when the installations were completed. The quality of the installations were checked through visual inspections and measurements to ensure that the ECMs had been installed as specified. If an ECM was not installed correctly or completely, additional work was performed until the installation was satisfactory.

A.1.2 Time-Dependent Measurements

Five data parameters were monitored in each of the houses: house gas consumption, house electricity consumption, space-heating system gas consumption, water-heating system gas consumption, and house indoor temperature. In addition, outdoor temperature was measured at three sites. Meters used to monitor the four energy consumptions were read weekly. Hourly indoor and outdoor temperature data were stored internally in the monitoring instrumentation and collected once a month.

A recently calibrated billing meter was installed in each house to measure the house gas consumption to within an accuracy of 3%. Because the gas consumptions were measured in units of ft^3 of gas, information on the heat content of the gas was collected to convert the house consumptions (and other submetered consumptions to be discussed below) into units of energy.

The existing electric billing meter installed in each house was used to monitor the house electricity consumption. Although these meters were not recalibrated, their accuracy should still have been about 3%.

Because the gas consumption rate of the space-heating equipment encountered in the field test was assumed to be steady whenever the unit was operating, the space-heating system gas consumption was monitored by measuring its operating time using elapsed-time (run-time) meters. The meter was installed in the thermostat control circuit, in parallel with the solenoid valve controlling the gas supply valve, so that power was supplied to the meter whenever power was supplied to the valve. A 24 volt DC meter was usually installed because the thermostat operated on a 24 DC circuit. In order to convert the operating time to a gas consumption, the consumption rate of the equipment was measured using the house gas billing meter. These measurements were made in February 1988 and were repeated in December 1988. Measurement of the gas consumption rates is discussed further in Appendix A.3.

The water-heating system gas consumption was measured in each house using elapsed-time meters in a manner similar to that for the space-heating system. In this case, however, the meter was not installed directly into the water-heating system's control circuit because it was different. Instead, the meter was wired in series with a gas pressure switch, with voltage supplied from any continuously available source (usually the space-heating system's 24 volt transformer). The pressure switch was installed to sense the gas pressure in the gas line downstream of the control valve leading to the burner and configured to close when the pressure rose slightly above atmospheric pressure. With this configuration, power was supplied to the meter whenever gas was supplied to the hot water tank. In many water-heating systems, a pressure tap was provided on the control box to connect the pressure switch. In order to convert the operating time to a gas consumption, the consumption rate of the equipment was measured using the house gas billing meter (see further discussion in Appendix A.3). These measurements were made in February 1988 and were repeated in December 1988.

The indoor temperature of each test house was monitored using a single-channel recording device that included a temperature sensor and microprocessor based electronics to calculate and store the average hourly temperature. On average, the temperatures measured by these devices were found to be about 0.75°F lower than actual; the temperatures measured by individual devices were generally within 0.75°F the average. The devices were located in the main living area of the house and placed to minimize their exposure to radiant energy heat sources. The same device was used in each house for both winters.

Hourly outdoor temperature was monitored at three NF field offices using battery powered data loggers, Type T (copper-constantan) thermocouples, and radiation shields. The sites were distributed among the test houses so that the outdoor temperature at each was represented by the data collected from at least one site. The instrumentation measured the outdoor temperature accurately to within 1°F.

A.2 FIELD EXPERIENCES

The amount of effort and time required to select houses for this type of field test can be easily underestimated. A list of 500 to 600 homeowners who were LIHEAP recipients in 1987 and whose houses were located in a targeted area of Buffalo were identified using NF records. Following a telephone screening procedure (Ternes and Hu 1988), 175 of these met the selection criteria and indicated an interest in participating in the field test. The number of eligible homeowners dropped from 500 to 175 for several reasons. Primarily, many of the 500 to 600 homeowners were not interested in participating in the field test and, thus, were removed from further consideration. Other reasons for removing homeowners from consideration (in order of importance) were that they lived in duplex houses, they rented their homes, and their homes had been weatherized under another program within the last 5 years. Site visits were then made to verify compliance with the selection criteria, to further describe the field test to the homeowner, and to have the homeowner sign a participation contract [see Ternes and Hu (1988) for a description of this procedure]. One hundred fifty five houses had to be visited before the 100 field test houses were identified. The need to sign a participation contract caused many homeowners to decide not to participate in the program. Only a few houses were rejected because their previous gas consumption was not weather dependent or because incorrect information was obtained from the telephone questionnaire.

Attrition of houses was considered in the field test design. Of 100 houses initially included in the field test, 89 houses remained to the end of the field test. The reasons for the loss of 11 houses varied: the homeowners of four houses decided to discontinue their participation for personal or medical reasons, three houses were weatherized under a different program, two houses were sold to new owners, insufficient pre-weatherization indoor temperature data were collected in one house, and one homeowner became disgruntled when only a few ECMs were installed in the house. The selection criteria and the careful selection of houses by NF likely contributed to this good performance.

Gas or electric billing meters (or both) were located inside most homes, causing some problems in collecting the weekly data (all elapsed-time meters were installed such that they could be read from the outside). With inside meters, data collection personnel had to establish a regular schedule with each homeowner in order that they could enter the house to collect the data each week, which was contrary to what the homeowners had initially been told. Originally, remote readout devices were to be installed on all inside gas meters; however, gas telemetering equipment was installed on most of these meters as part of another program, making it impossible to install the remote devices. Installation of the telemetering equipment also inconvenienced many homeowners because of the time and number of separate crews required to install the equipment. There were advantages to entering the home each week, though: a personal contact was made with the homeowner each week and the data collection personnel had an opportunity to observe any unusual events (such as seeing that the house was being weatherized).

The instruments used to measure the indoor temperature worked well. Some homeowners accepted their installation reluctantly because they objected to their color and unattractive design. Consequently, the instruments may not have been located in these houses in the most desirable place. Despite repeated explanations and assurances to the contrary, one homeowner felt that the indoor temperature device was a listening device; consequently, the homeowner kept the device in a car.

Several difficulties were encountered in measuring appliance gas consumption using elapsed-time meters. The use of gas meters would likely overcome many of these problems and provide more accurate information. However, this option is unattractive because of cost considerations (equipment, installation, and removal) and the need to enter the house to read the meters (unless remote readouts are installed which further increases costs).

The gas pressure switch used in metering the water-heating system failed in several houses. Additionally, the measured elapsed-time may be greater than actual because, in some cases, a few seconds are required for gas to bleed out of the switch each time the water-heating system turns off. A gas pressure sail switch (as used in many electrically-activated vent dampers) may be a better device. The cost of the sail switch is about the same as the pressure switch, but the installation cost would be greater because the sail switch has to be installed in the gas line. Another option is to use a fiber optic device that closes a switch when the main burner is on.

As will be discussed in Appendix B, subtracting the weekly gas consumptions of the space- and water-heating systems from the house total produced negative results in some houses. Small negative differences (especially in houses without other gas appliances) indicates the inaccuracy associated with measuring appliance gas consumption using elapsed time meters. However, large negative differences indicate a more serious problem. The problem with the pressure switch identified above in measuring water-heating system gas consumption contributed to these inaccuracies. However, in many cases, the space-heating system consumptions rather than the water-heating consumptions were in error. The measured elapsed times were believed to be accurate. Thus, these negative differences may be due to several other factors, including inaccurate gas consumption rates, unsteady gas consumption rates, or inaccurate billing meters. The gas consumption rates of the equipment (measured using the house billing meter) may not be constant because of variations in the pressure of the gas supply line, faulty pressure regulators, and operation of other gas appliances at the same time the space-heating system runs (measurement of the gas consumption rates is further discussed in Appendix A.3). Inaccuracies with the billing meters (although pressure and temperature compensated and recently calibrated) may cause the measured gas consumption rates to be wrong or the house weekly gas consumptions to be incorrect.

NF personnel identified several improvements that could be made to the entrance interview form used to collect the house and occupant descriptive information: the form should be condensed to fewer pages, the infiltration checklist should be deleted, and several redundancies should be eliminated.

A.3 APPLIANCE GAS CONSUMPTION RATES

Gas consumption rates of the space- and water-heating systems (required to convert equipment operating times into actual gas consumption) were measured during the pre- and post-weatherization periods (February 1988 and December 1988, respectively). To measure these rates, all gas appliances in the house were first turned off (while their pilots remained lit). The rate for the space- or water-heating system was measured by turning on one system only and measuring the time required for the lowest dial on the house billing meter (either 1/2, 1, or 2 cubic feet) to complete a pre-selected number of revolutions (usually five or ten so that the elapsed time was approximately five minutes). During this procedure, care was taken to ensure that the system ran constantly (did not short cycle) and that the other appliances remained off. In addition to measuring the rates for the two systems separately, a combined rate (both systems operating at the same time) was also measured.

The gas consumption rates measured following the above procedure include the pilot light consumptions of all the appliances in the house. Although the pilot light consumption of the space- or water-heating system being measured should be included in the measured rate (heat given off by these pilots while the system is running supplies heat to the house), the consumptions of the remaining pilots should not. Therefore, the measured rates of the space- and water-heating systems were modified by knowing what other gas appliances were installed in each house, knowing whether the space-heating system used a pilot light, and assuming the following average gas consumption rates for different appliance pilot lights: water-heating system, 19 ft^3/day; dryer, 6 ft^3/day; range, 12 ft^3/day; and space-heating system, 27 ft^3/day (if a pilot is present).

Comparing the sum of the space- and water-heating system rates to the combined rate in each house further justified the need for the modification described above and confirms the accuracy of the procedure. Without the modification, the sum of the rates should be greater than the combined rate in an individual house because the pilot light consumptions are being accounted for twice. Before adjusting for pilot light use, the sum of the rates was, on average, about 2% greater than the combined rate (statistically significant at a confidence level greater than 0.01); afterwards, the average value of the sum of the rates was equal to the average combined rate. In both instances, statistical tests confirmed that comparisons for individual houses were normally distributed about the average values (2% and 0%, respectively) indicating random differences around the averages.

Comparison of the consumption rates measured in each house before and after weatherization indicated that changes between +/-5% were common (and larger in isolated circumstances) although changes should not have generally occurred. Ideally, the rates for the space-heating systems in the control houses and the water-heating systems in all the houses should be the same before and after weatherization because no work was performed on these systems. Although the space-heating systems in the audit houses were tuned, the specific work performed should not have changed the consumption rate.

Changes in the consumption rates of the space-heating systems measured for the individual control houses were normally distributed about an average value of zero. Because the individual rates should not have changed, this indicates that the changes were likely just random affects (possibly due to measurement errors) and that real changes did not occur. The same average value and distribution was observed for the audit houses, indicating that the tune-ups were not the cause of any observed changes and that real changes also did not occur.

On average, the consumption rates of the water-heating systems increased slightly (1%) for the control houses (statistically significant at a 0.1 confidence level but not at 0.05) but did not change for the audit houses. In both cases, the individual changes were normally distributed about these values. No explanation is offered for the possible increase observed in the control houses. Because no work was performed on the water-heating systems and the observed change in the control houses was small and marginally significant, we conclude that a real change did not likely occur.

A single rate for the space-heating system and a single rate for the water-heating system in each house was used in converting pre- and post-weatherization operating times of the equipment into gas consumptions (unless a specific reason indicated that different rates should be used, such as if a new space-heating system was installed). A single rate is justified because real changes likely did not occur. By using a single rate, changes in space-heating energy consumption before and after weatherization could not be attributed to random changes in the consumption rates. In a majority of the houses, the single rate was calculated by averaging the pre- and post-weatherization measurements.

For the 20 houses listed in Table A.1, either the pre- and/or post-weatherization rate was used because a post-calibration rate was not measured (three houses), the space- or water-heating equipment was replaced as part of the weatherization work (two houses), or the gas consumption of the space- or water-heating systems resulting from the use of the average value was greater than the consumption indicated by the house gas meter (a data inconsistency).

For future experiments, the methods of measuring the gas consumption rates outlined in the experimental plan (Ternes and Hu 1988) should be followed to directly account for pilot light uses. Under this method, all appliances and their pilots are turned off except for the one appliance studied. The time required to relight pilots (in some cases several times) and problems that may occur in trying to relight them are disadvantages of this method; however, the higher quality data obtained justifies the added difficulty. Consumption rates should be measured before and after weatherization and, preferably, more than once per period. Rates measured under this experiment and a similar experiment performed in Wisconsin indicate that the consumption rates fluctuate randomly with time. A more accurate estimate of the average rate over the experiment can be made with more measurements.

Table A.1. Houses not using average consumption rates

3. Used post-rates of the space- and water-heating systems for both periods.
9. Used pre- and post-rates of the space-heating system for the pre- and post-weatherization periods, respectively. Used post-rate of the water-heating system for both periods.
16. Used pre- and post-rates of the water-heating system for the pre- and post-weatherization periods, respectively.
28. Used post-rate of the water-heating system for both periods.
29. Used pre-rates of the space- and water-heating systems for both periods.
31. Used pre-rate of the space-heating system for both periods.
84. Used post-rates of the space- and water-heating systems for both periods.
86. Used pre-rates of the space- and water-heating systems for both periods.
89. Used post-rate of the space-heating system and pre-rate of the water-heating system for both periods.
91. Used pre-rates of the space- and water-heating systems for both periods.
92. Used pre-rate of the space-heating system for both periods.
103. Used pre-rate of the space-heating system and post-rate of the water-heating system for both periods.
120. Used post-rates of the space-heating and water-heating systems for both periods.
140. Used post-rate of the water-heating system for both periods.
146. Used post-rate of the water-heating system for both periods.
148. Used pre-rate of the space-heating system for both periods.
150. Used pre-rates of the space- and water-heating systems for both periods.
155. Used pre- and post-rates of the space-heating system for the pre- and post-weatherization periods, respectively.
156. Used pre-rate of the water-heating systems for both periods.
167. Used pre-rate of the space-heating system for both periods.

APPENDIX B. DATA COLLECTION AND MANAGEMENT

Two classifications of data were collected in this field experiment: time-independent information and time-dependent measurements. After these data were collected in the field, they were sent to ORNL in various formats and on various media for analyses. A data management system was developed to prepare these data for analysis. The system was designed to transfer the field data onto microcomputer databases, check the validity of the data, convert the data into files that can be managed and manipulated by the Statistical Analysis Software (SAS), and merge individual files into one master file for data and statistical analyses.

All data management and analyses were performed in a microcomputer environment. A menu-driven system was developed to facilitate and minimize the data processing effort. The main menu system was invoked by a DOS command and allowed the user to enter either the SAS or the dBASE III Plus software environment, depending on the task and the function to be performed. Previous knowledge of either software was not required.

The field data can be divided into four categories based on the frequency and time at which the data were collected: weekly household energy consumption, hourly indoor and outdoor temperatures, house and occupant descriptive information, and audit related information. Data management and validation procedures, developed for the individual categories, will be discussed in detail, along with how individual files were merged into one master file. Additionally, field experiences and data quality will also be discussed.

B.1 WEEKLY HOUSEHOLD ENERGY CONSUMPTION DATA

Four data parameters were collected weekly from each field test house: house gas consumption, house electricity consumption, space-heating system gas consumption, and water-heating system gas consumption. The raw data for each house were converted into SAS files and the following variables were created for subsequent statistical analyses:

1. household identification (ID) which uniquely identifies individual households,

2. date when the meter data were recorded,

3. space-heating system gas consumption between this and the previous reading,

4. water-heating system gas consumption between this and the previous reading,

5. electricity consumption between this and the previous reading,

6. total house gas consumption between this and the previous reading,

7. elapsed time in hours between this and the previous reading, and

8. seven error check flags.

The field data were recorded by data collection personnel onto data sheets designed by ORNL and forwarded to ORNL for processing. Upon receiving the data, ORNL project staff entered the data into a dBASE III Plus database using a full screen data entry system. The quality of the data was checked as it was entered. Values for the house ID, date, time, and meter readings had to be within a feasible range. Values outside the established ranges could not be accepted by the system.

The dBASE III Plus files were converted to SAS files using a SAS utility program. Then, weekly energy consumptions were determined by concatenating incoming meter readings to readings of the previous week and calculating their difference. All energy consumption data were converted into British thermal units (Btus). For space- and water-heating systems, this was accomplished by multiplying the differences by the house-specific gas consumption rates (one for the space-heating system and one for the water-heating system as discussed in Appendix A.3). Elapsed times between two consecutive readings were calculated in order to standardize the energy consumptions per unit time. During these calculations, the following quality checks were performed:

1. Negative values for the calculated energy consumptions were identified. This occurred most often when the billing meters were replaced (because new meters were initially set at zero) and due to misreading of the meters.

2. Inconsistent data were identified. Inconsistency was defined to be when the weekly house gas consumption was less than the sum of space-heating system gas consumption and water-heating system gas consumption.

3. Space- and water-heating system elapsed times greater than 75% of the recording interval were identified. Such times were considered to be excessive and in need of explanation. In all cases, incorrect meter installation or faulty pressure switches were the cause.

A printout listing all weekly records containing invalid data was generated. ORNL staff corrected all "correctable" errors, recalculated the energy consumptions, and then rechecked the quality of the data. Non-correctable errors were set as being "missing" in order that weekly records with "missing" data could be skipped, if desired, in future analysis. Causes for the non-correctable errors were identified and, to the extent possible, were fixed in the field by NF personnel.

B.2 INDOOR AND OUTDOOR TEMPERATURE DATA

B.2.1 Indoor Temperature

A temperature recorder was installed in every participating house to record and store house-specific hourly indoor temperatures. These data were processed to obtain a database for each house containing the following variables: recorder ID, time and date for each temperature reading, and hourly temperature readings (in units of °F), for the entire winter monitoring period. The recorder ID uniquely identifies the recorder and, with information maintained and updated by NF, the test house in which it was installed.

Field personnel downloaded the data from the recorders to floppy diskettes once a month and forwarded the diskettes to ORNL. Individual house indoor temperature data were stored in separate data files on the diskettes. The data stored on diskette were transferred to the microcomputer using software developed by the manufacturer of the temperature devices. These files were assigned file names identifying their respective recorder ID and the month they were collected. The recorder ID was also a data variable contained within each file.

Special software was developed in SAS to combine the monthly files for each house. This software had to be designed to overcome three complicating factors. First, the indoor temperature files were not formatted in a way that the data could be easily extracted. The SAS software parsed the file in order to retain the recorder ID with the corresponding hourly temperatures. The recorder ID was retained to serve as the identification link between the temperature and energy consumption files. Second, data were redundantly stored because the recorders store the latest 83 days of hourly indoor temperature data, but the data were collected monthly. Additionally, the data for each house extended over different time frames because the data were collected at various dates and times. To avoid processing duplicate data and to increase efficiency, a "benchmark" date was sought for each house. This "benchmark" date was the time and date when the most recent hourly indoor temperature was recorded and processed. When processing the next month's data, only data recorded later than the "benchmark" date would be processed.

The validity of the hourly indoor temperatures were checked. Acceptable values were defined to be within the range of 55°F and 90°F. The data were also checked for repetitiveness by identifying cases where ten consecutive indoor temperatures were identical. Repetitiveness of this order likely indicated that the recorder was not functioning properly. Flags were raised if an invalid range or if constant readings were detected. Output was generated to list all invalid data so that ORNL project staff could manually inspect the list and make appropriate corrective actions.

B.2.2 **Outdoor** Temperature

Outdoor temperature data were collected at three sites to represent the temperature at each test house. The instruments measured the average hourly outdoor temperature and automatically stored the data onto a cassette tape at periodic intervals. Field personnel collected the tapes from the sites once a month and forwarded them to ORNL. These data were further processed to obtain a database for each site containing the following data: weather station ID, time and data for each temperature reading, and hourly outdoor temperature readings (in units of °F) for the entire winter monitoring period.

Data were transferred from cassette to the microcomputer and stored in ASCII format using software developed by the manufacturer of the data logger. These data were then converted to SAS files. In this conversion step, recorded Julian dates were converted to calendar dates and the validity of the data were checked. Outdoor temperature data were considered valid if they were within the range of -20°F and 70°F; year if it was equal to 1988; Julian date if it was within the range of 0 and 366; and time if it was within the range of 0 and 2400. The repetitiveness of the outdoor temperature data were checked in the same manner as the indoor temperature. The instrumentation status and battery voltage were also checked, although these data were not stored. The batteries in the data logger needed to be replaced if the voltage level was below 10 volts. The programming of the data logger had been tampered with if the instrumentation status was not equal to a predetermined constant. Output was generated to list all invalid data so that ORNL project staff could manually inspect the list and make appropriate corrective actions.

B.3 HOUSEHOLD SURVEY DATA

An entry interview conducted at the beginning of the field test established the house and space-heating equipment characteristics of the test houses, and the behavioral characteristics and demographics of the occupants. Field personnel interviewed heads of the test households, visually inspected and measured house structural and physical characteristics, and recorded the information on survey forms designed and provided by ORNL. A full screen interactive data entry system was designed using dBASE III Plus software to facilitate data entry onto computer databases. This data entry system displayed screens which simulated the survey forms, and prompted the user to fill in the blanks. Simple range checks were implemented during data entry so that errors could be corrected immediately. SAS files were created from the dBASE III Plus files for further data analyses.

B.4 MEASURE SELECTION TECHNIQUE RELATED DATA

Based on current structural and physical characteristics of the house, the energy conservation measure selection technique recommended ECMs for each test house. A database was created that listed the recommended ECMs for each house, the estimated cost to install each ECM, and the estimated energy savings for each ECM. A full screen interactive data entry system was designed using dBASE III Plus software to facilitate data entry. After NF completed the installation of the ECMs, the ECMs actually installed were identified in the database, the actual installation cost noted, and the estimated energy savings for each ECM as it was installed (if less area was insulated, for example, the estimated energy savings was lowered).

B.5 MERGING FILES

In order to normalize the energy consumptions and savings, the household energy databases were merged with the indoor and outdoor temperature data files. This required establishing links (such as house ID, recorder ID, and weather station ID) between the different data bases. The survey and audit related data were analyzed separately and, thus, were not merged with the other data sets.

Outdoor temperature was merged rather readily with indoor temperature. For each house, the closest site where outdoor temperature was recorded was identified. The outdoor and indoor temperatures were then merged using the appropriate site (identified by the weather station ID) and the time (to the nearest hour) and date when temperatures were recorded.

While the energy consumption data were merged with the hourly temperature data, a temperature variable was calculated corresponding to the time period represented by the energy consumption data. Two temperature variables were calculated: the average difference between hourly indoor and outdoor temperatures for the period, and the average difference after setting negative hourly differences equal to zero. Using the house and recorder IDs, the temperature and consumption files for each house were merged and temperature variables calculated. Calculating this difference was complicated by the fact that the recording interval for the energy consumption data varied week to week for a given house and also varied between houses. During this process, the energy consumptions were also normalized to time by dividing the consumptions by their respective recording intervals. In this manner, average weekly consumptions for each period were obtained. This normalization was required because the recording intervals varied (especially if a weekly reading for a given house was missed) even though data were collected on primarily a weekly basis. This merged data set was then used in subsequent analysis.

B.6 DATA QUALITY AND FIELD EXPERIENCE

The majority of the errors that were detected in the consumption data were due to the sum of space- and water-heating system gas consumption exceeding the total house gas consumption. This sum consistently exceeded the house gas consumption in 14 houses, six because of metering problems with the water-heating energy consumption and the remaining eight because of unexplained problems with measuring the space-heating gas consumption. In 17 houses, the sum exceeded the house gas consumption in either the pre- or post-weatherization periods by less than 5% and generally for only one to three weeks. Reasons for these observations are further discussed in Appendix A.2.

Some energy data were lost when the meters were being replaced. Because the new meters always had their initial settings at zero, the differences between the old meter reading and the new meter reading were always negative. On a few occasions, the occupants were not home to let the field personnel in to retrieve data. In one house, the occupant began to allow the field personnel in only once a month. For those weeks in which meter readings were lost or not obtainable, the weekly record was set as missing. The house gas or electricity meter reading was estimated on several occasions when it was the only piece of data missing.

The run-time of either the space- or water-heating system was more than 75% of the recording interval in six houses: the pressure switch failed in five and the elapsed-time meter was incorrectly installed on one space-heating system. One pressure switch was replaced and the incorrect installation was modified; corrective actions were not taken due to time constraints in the remaining four houses.

Outdoor temperatures recorded at one site dropped to -6996.80 (an obviously erroneous reading) on several isolated hours. These values were estimated by the average value of the temperatures an hour before and after the invalid reading. Comparisons were made between the temperatures recorded at the three sites to further check the calibration of the monitoring instruments. These temperatures were found to be consistently within a range of 4°F each other. A subsequent recalibration of the equipment reduced this range to half.

APPENDIX C. ENERGY CONSERVATION MEASURE SELECTION TECHNIQUE ERROR

An error found in the selection technique adversely affected the ECMs installed in nine of the 45 audit houses: ECMs that were not cost effective were incorrectly recommended for installation and, conversely, ECMs that were cost effective were not installed.

ECMs were installed in the audit group of houses in the fall of 1988 following the recommendations of the measure selection technique. At this time, a BCR cutoff of 1.25 was used in the technique to limit average expenditures to about $1500/house. After the recommended ECMs had been installed in the houses, a programming error involving a misplaced parenthesis was found in the technique that affected the BCR calculated for wall and attic insulation only. The value of the BCR determined by the incorrect equation in the technique was about 50% higher than the correct value, making attic and wall insulation appear to be more attractive ECMs than they actually were. As a result of this error, attic and wall insulation could be installed in houses when it should not (when the correct BCR was less than 1.0) and cost-effective ECMs that should be installed might not (because of interactions and choosing a BCR cutoff greater than 1.0).

After correcting the programming error, a new list of recommended ECMs was obtained for each house. With a BCR cutoff of 1.0, ECMs recommended by the corrected technique were exactly the same as those previously recommended in 26 houses. In 10 houses, there was no difference between the ECMs recommended by the corrected technique and those installed except that:

1. a vent damper (on two water-heating systems and one space-heating system) recommended by the corrected technique was not installed (three houses),
2. attic insulation with an estimated savings of less than 6 therms/year was installed that was not recommended by the corrected technique (three houses),

3. floor insulation with an estimated energy savings of less than 11 therms/year was not installed but was recommended by the corrected technique (two houses), and

4. wall insulation with a BCR of 0.99 was installed that was not recommended by the corrected measure selection technique (two houses).

As shown in Table C.1, there were significant differences between the ECMs installed and those previously recommended in the remaining nine houses. Thus, despite the error found in the technique, the ECMs installed in 36 houses, based on a BCR cutoff of 1.25, basically conformed to the recommendations of the corrected technique using a BCR cutoff of 1.0.

A BCR cutoff of 1.0 was used with the corrected technique because differences between ECMs recommended by the corrected technique and those installed following the incorrect technique were minimized, an average expenditure of about $1500/house was maintained, and all cost-effective ECMs were performed. In addition to correcting the programming error, two additional changes were also made when the technique was rerun to improve accuracy and to correct other minor mistakes:

1. A balance point temperature of 60°F was used for all houses. Originally, most houses were analyzed using a temperature of 58°F, although values in the low 50's and middle 60's were used in some cases. A temperature of 60°F should have been the default case, with deviations of only several degrees being reasonable in special cases.

2. The R-value of all wall insulation to be installed was set to R-13 and an equation in the technique calculating the savings from wall insulation was modified to reflect this consistency. All wall insulation to be installed under the field test was to be performed using cellulose insulation (which has an R-value of 13 if installed in an average wall). In a few limited cases, the auditor incorrectly entered an R-value of 11. The equation used in the technique to calculate the savings from wall insulation was designed to be applicable whether fiberglass or cellulose insulation was used. To make this equation applicable for both cases, a divisor of 12 was used instead of using a value of 11 specifically for fiberglass and 13 for cellulose.

Table C.1. Energy conservation measures that should or should not have been installed in the nine houses with significant differences

House number	Measures Installed that were not recommended by the **corrected** technique	Measures recommended by the **corrected** technique that were not Installed
9	wall insulation	
29	attic insulation	furnace
73		floor insulation
		attic insulation
		wall insulation
89	wall insulation	attic insulation
		floor insulation
131		wall insulation
141	wall insulation	
153		storm windows
166	wall insulation	
169		wall insulation

Analyses were performed to ensure that the audit group of houses was not biased if the group were limited to 36 houses. First, the 36 houses remaining in the audit group were compared to the control houses:

1. The mean values of the annual space-heating energy consumption for the two groups (calculated using pre-weatherization data and based on pre-weatherization conditions) were compared and no significant difference was found.

2. The mean values of the following house and occupant characteristics were compared: attic UA, attic U, fraction of attic area insulated, attic area, wall UA, wall U, fraction of wall cavity area insulated, wall area, fraction of foundation area insulated, total foundation area insulated, foundation type, presence of sill box insulation, fraction of single-pane windows with and without storm windows, fraction of multi-pane windows with and without storm windows, fraction of exterior door areas with and without storms or thermal insulation, number of floors, house age, basement area, total floor area, heated floor area, non-basement area, fraction of total floor area heated, number of occupants, space-heating system age, type of space-heating system, presence of space-heating system vent damper, and presence of an intermittent ignition device. As discussed in Sect. 4.3, no significant differences were found except for the wall U and fraction of wall cavity area insulated. Because comparisons between the 45 audit houses (the 36 houses plus the nine to be removed) and the control houses revealed the same results, the differences were not caused by the removal of the nine houses.

Second, the 36 houses were compared to the nine to be removed:

1. Of the nine houses to be removed, four had a furnace and were low energy users (annual house gas consumption determined from billing data was in the lower 50th percentile of all the houses used in the field test), four had a furnace and were high energy users, and one had a boiler and was a high energy user. Because about 13% of the audit houses had boilers, only one of the nine houses to be removed should have had a boiler for there to be no bias. With half the houses to be removed being high energy users and the other half being low energy users, no bias existed.

2. The mean values of the annual space-heating energy consumption for the two groups (calculated using pre-weatherization data and based on pre-weatherization conditions) were compared and no significant difference was found.

3. The mean values of the installation costs estimated by the corrected technique for the two groups were compared and no significant difference was found (average of $1507/house estimated for the 36 houses and $1225/house for the nine houses; the average value of the nine houses would have to be less than about $1000/house for there to be a significant difference).

4. The mean values of the annual savings estimated by the corrected technique for the two groups were compared and no significant difference was found (average of $211/house estimated for the 36 houses and $175 for the nine houses).

Information collected on the nine houses remains useful in studying the accuracy of algorithms used in the selection technique to predict energy savings and installation costs. Information from these houses cannot be used, though, to represent the energy savings that would result from use of the corrected technique or the types of ECMs that would be installed, for example.

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