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OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

THE NORTH CAROLINA FIELD TEST: FIELD PERFORMANCE OF THE PRELIMINARY VERSION OF AN ADVANCED WEATHERIZATION AUDIT FOR THE DEPARTMENT OF ENERGY'S WEATHERIZATION ASSISTANCE PROGRAM

T. R. Sharp
Energy Division

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
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ABSTRACT

The field performance of weatherizations based on a newly-developed advanced technique for selecting residential energy conservation measures was tested alongside current Retro-Tech-based weatherizations in North Carolina. The new technique is computer-based and determines measures based on the needs of an individual house. In addition, it recommends only those measures that it determines will have a benefit-to-cost ratio greater than 1 for the house being evaluated. The new technique also considers the interaction of measures in computing the benefit-to-cost ratio of each measure. The two weatherization approaches were compared based on implementation ease, measures installed, labor and cost requirements, and both heating and cooling energy savings achieved.

One-hundred and twenty houses with the following characteristics participated: the occupants were low-income, eligible for North Carolina's current weatherization program, and responsible for their own fuel and electric bills. Houses were detached single-family dwellings, not mobile homes; were heated by kerosene, fuel oil, natural gas, or propane; and had one or two operating window air conditioners. Houses were divided equally into one control group and two weatherization groups. Weekly space heating and cooling energy use, and hourly indoor and outdoor temperatures were monitored between November 1989 and September 1990 (pre-period) and between December 1990 and August 1991 (post-period). House consumption models were used to normalize for annual weather differences and a 68°F indoor temperature. Control group savings were used to adjust the savings determined for the weatherization groups.

The two weatherization approaches involved installing attic and floor insulations in near equivalent quantities, and installing storm windows and wall insulation in drastically different quantities. Substantial differences also were found in average air leakage reductions for the two weatherization groups. Average, weather-normalized heating and cooling energy savings were 33 and 18%, respectively, for weatherizations where the new technique was used, and 23 and 3% for Retro-Tech-based weatherizations. Weatherizations using the new technique achieved 43% more heating energy savings and substantially more cooling energy savings; they cost around 10% less at two agencies and considerably more at the third; and they were nearly equivalent in labor requirements.

The following major conclusions were drawn from the study:

1. The advanced audit significantly increased heating energy savings.

2. Heating energy savings of around 33% were achieved using the advanced audit with blower-door-directed air sealing.

3. The advanced audit appeared to increase cooling energy savings, although wide variances occurred.

4. As tested in North Carolina, the advanced audit overpredicted heating energy consumption and savings for houses with high heating loads.

5. The advanced audit did not increase weatherization costs and actually lowered costs for two of three weatherization agencies.

6. The advanced audit recommended some measures in near identical quantities to Retro-Tech-based weatherizations and others in dramatically different quantities.

7. Blower-door-directed air sealing more than doubled the air leakage reductions achieved from standard air sealing techniques.

8. Low-income houses in North Carolina had much higher average leakage rates than similar New York houses but were sealed as well or better.

EXECUTIVE SUMMARY

The field testing of an advanced weatherization audit was recently completed as part of a development effort by the U.S. Department of Energy (DOE) to produce an improved measure selection technique. Ultimately, this audit will be offered to states to achieve major improvements in the performance of weatherization programs across the nation. The test was conducted in North Carolina and was a cooperative effort by the DOE, the state of North Carolina, the Alliance to Save Energy, Oak Ridge National Laboratory, and three state weatherization agencies.

The primary purpose of the evaluation was to measure and compare the performance of weatherizations based on an advanced audit with the performance of weatherizations done by an existing state weatherization program. The performance evaluation was to assess and compare a wide range of important issues for both weatherization approaches, including heating and cooling savings produced, advantages and disadvantages of each, costs, cost-effectiveness, measures installed, labor requirements, complexity, and implementation ease. The field test was also to provide considerable user feedback that would lead to major improvements in the value, flexibility, and ease of use of the advanced audit for the weatherization auditor. The advanced weatherization audit was developed based on advanced measure selection techniques previously verified in Wisconsin and New York,

At the time of the field test, standard weatherizations in North Carolina were based on "Project Retro-Tech," a manual technique for identifying the best energy conservation measures to install in a house, which was first introduced to weatherization agencies on a national scale in 1978. Retro-Tech-based weatherizations in North Carolina are primarily shell retrofits and are limited to the following measures, presented in order of installation priority (highest to lowest cost-effectiveness):

1. infiltration measures;
2. attic insulation;
3. water heater, pipe, and floor insulation (R-11 and R-19);
4. duct insulation;
5. underpinning (enclosing crawl space); and
6. storm windows and storm doors.

Each measure is installed in order of priority until the allotted funds, up to $1400 per house on average (including administration costs), are expended or the next consecutive measure is unaffordable within the spending limits.

Infiltration (air sealing) measures include caulking, adding new weatherstripping, replacing existing defective weatherstripping around windows and doors, repairing or replacing windows and doors in poor condition, and repairing holes in walls and floors. The identification of infiltration deficiencies and locations is made visually. Attic insulation is installed to a minimum of R-19 and a maximum of R-30. Crawl spaces receive floor insulation or underpinning, depending on the height of the crawl space. Water heaters (electric and fuel-fired), hot water pipes, and heating ducts are also insulated. The remaining measures, storm windows and doors, have the lowest priorities.

The advanced audit, the North Carolina Field Test Audit (FTA), is a computerized measure selection technique that ranks measures by their benefit-to-cost ratio according to the needs of the individual house. This audit addresses a comprehensive list of proven measures, including both shell and mechanical equipment measures, aimed at reducing both space heating and cooling energy consumption. The term "audit" as used here refers specifically to the advanced measure selection technique.

The key to the FTA, in contrast to a set list of priorities, is that its selection technique actually evaluates the expected performance of each potential measure for the individual house. The program ranks the measures in the order that they should be installed based on a computed benefit-to-cost ratio (BCR). Measure ranking is checked and adjusted for measure interactions, a key feature of the FTA, and a final list of recommended measures is provided to the user. A BCR limitation of 1 or greater is used in the audit so that all cost-effective measures can be installed ("cost-effective" meaning that a measure provides a present value savings equal to or greater than its cost). The BCR is calculated for each measure based on local measure costs (labor and materials), measure savings (both heating and cooling), expected lifetime of the measure, current discount rate, and local fuel costs.

Development of the FTA assumed a modular approach to weatherization, in that the selection and installation of measures in a house can be subdivided into categories of activities: air leakage reduction, installation of low-cost measures, building envelope retrofit, and equipment retrofit. The FTA addressed numerous envelope and equipment measures. In addition to these, three measures recommended outside the computerized audit were installed as part of the weatherization package for houses weatherized using the FTA. These were air leakage reduction, the installation of low-cost measures, and heating system tune-ups.

Air sealing was performed using a blower-door-directed procedure based on cost-effective guidelines. A cost-effective guideline of 75 cfm50 [cfm at 50 Pascals (Pa) house depressurization] air leakage reduction per person-hour was used and considered representative for all fuels in the test. A minimum ventilation guideline of 1500 cfm50 per house was used to prevent overtightening. Air sealing was performed in a house until the last hour's work was no longer cost-effective or until the minimum ventilation guideline was reached. This procedure was substantially different from the general infiltration work performed in standard weatherizations, which focused on caulking, glazing, and weatherstripping, and did not use any measurements of leakage or of air leakage reductions to direct the work.

Low-cost, highly effective measures (such as water heater wraps and hot water pipe and heating duct insulation in unconditioned spaces) were recommended outside the FTA by the auditor. Heating system tuneup recommendations were also decided outside the computerized audit based upon the steady state efficiencies resulting from actual flue gas measurements on each system.

The field test was performed at three sites (separate weatherization agencies) in North Carolina. One hundred and twenty houses eligible for North Carolina's low-income weatherization program, 40 at each site, were selected for the test. Houses were detached single-family dwellings, heated by kerosene, fuel oil, natural gas, or propane, and had one or two operating window air conditioners. The houses were selected by identifying individual houses conforming to the selection criteria and accepting them if the owners consented until the 120-house quota was reached. Houses were split into 3 groups of 40 representing an FTA group, a standard weatherization (Retro-Tech) group, and a control group; each site was represented approximately equally (13 or 14 houses per site in each group).

Field testing was conducted over a 2-year period. Weekly space heating and cooling energy use and hourly indoor and outdoor temperatures were monitored between November 1989 and September 1990 (pre-weatherization period) and between December 1990 and August 1991 (post-weatherization period).

Linear heating and cooling energy use models were generated from the measured data. For each house, weekly energy consumption (EC) was modeled as a function of the weekly average indoor-outdoor temperature difference (DT) as:

$$EC = a + (b \cdot DT) ,$$

where a and b represent model intercept and slope coefficients determined by regression. The pre- and post-weatherization measured data were analyzed separately.

Measured consumption rates were weather-normalized to remove the effect of differences in average seasonal temperatures between the before and after seasons. Normalization was carried out by applying each performance model to typical meteorological year (TMY) temperature data for the Raleigh/Durham area. Weekly average temperature differences were calculated using TMY outdoor temperature data, and using 68°F as the indoor temperature for the heating season and 78°F as the indoor temperature for the cooling season. Temperature differences were then used in each performance model to estimate normalized weekly space-heating and cooling energy consumption for the pre- and post-weatherization periods. Weekly consumption rates were summed to provide annual space-heating and cooling energy consumption levels. Differences between pre- and post-weatherization normalized consumption levels were calculated and adjusted for the control group savings to produce adjusted (net) heating and cooling energy savings for the two weatherization approaches.

A total of 24 different measures were considered in the 2 weatherization procedures. Standard weatherizations considered only 10 measures, primarily shell measures, while FTA weatherizations considered 21. Of these 21, the FTA made the installation decision for 17. Three others (duct, pipe, and water heater insulation) were auditor-recommended, and air leakage measurements determined the infiltration reduction work. The FTA evaluated numerous shell and mechanical equipment measures that the standard audit did not.

Except for infiltration reduction, which was performed in all houses, attic, wall, and floor insulation dominated the measures installed in the FTA group; it was installed in 40 to 70% of all houses in this group. Attic and floor insulation measures dominated the standard group in similar quantities. Except for a major difference in average final air leakage rates, the largest contrast between the two weatherization groups is the difference in installed wall insulation and storm windows. The standard audit did not call for installing wall insulation (because it was not an option), compared with an installation rate of nearly 50% for the FTA group. Also, the standard audit called for installing storm windows on more than 80% of all houses, while less than 5% of the FTA group received storm windows (because of poor window condition and not because they were audit-recommended).

The FTA recommended installing attic R-30 in all uninsulated attics and either no additional insulation, R-11, or R-30 in those that had some existing insulation. The standard audit called for filling all attics to an R-30 level independent of the existing attic insulation level. The installation of attic R-30 was much more prevalent in both groups than were other levels of attic insulation. No houses were recommended for R-19 because this level of attic insulation was not considered in the FTA Except for infiltration reduction, attic, wall, and floor insulation, and storm window measures, neither audit recommended installing any other measure in greater than 11% of its houses.

The FTA did not recommend any vent dampers, intermittent ignition devices, flame retention head burners, or heating system replacements, primarily because of the abundance of space heaters (used for primary heating in nearly 70% of all houses), which were not considered compatible with those measures. No heating system replacements, which were limited to central furnaces, were recommended by the FTA A replacement air conditioner was recommended for only one house.

Air leakage measurements were made in all houses before and after weatherization. Measurements were made with a blower door following a multiple-point procedure similar to that specified by the American Society for Testing and Materials. The average pre-weatherization air leakage rate for all groups was 4282 cfm50. Individual group averages were within 5% of this average and not statistically different at a 95% confidence level. The average air leakage reduction was 89 cfm50 for the control group (no treatment), 1710 cfm50 for the FTA group, and 716 cfm50 for the standard group. The average reduction for the standard group was statistically different from the control group at an 85% confidence level. The average FTA group reduction was statistically different from the control and standard group reductions at a 95% confidence level. When average reductions are related to their respective group average pre-weatherization air leakage rates and adjusted for the 2% reduction in the control group, reductions of 37% were achieved in the FTA group and 16% in the standard group.

Sixteen of the original 120 houses in the field test were excluded from the heating energy savings analysis. Fourteen lacked adequate post-consumption data because of their dropping out of the test or other difficulty in obtaining post-consumption data; an unvented heater was replaced by a vented heater in one during the test (a ~ 100% efficient system was replaced by a ~ 75% efficient one for safety reasons only); and one was occupied by two families simultaneously. The exclusions represent six houses from one site, three from another, and seven from the third.

Pre- and post-weatherization models were generated for the remaining 104 houses, and many were found to be highly unreliable based on a technique used by Princeton University researchers. Generally, unreliable models occurred where the consumption data were highly scattered, where nine or fewer data points were available for either period (ten houses), or where the consumption data represented only a small range of expected seasonal temperatures. These problems typically occurred in houses where there was high unmetered energy use (from portable heaters or fireplaces) and where some late weatherizations reduced the number of available data points and the outdoor temperature ranges represented. A screening technique based on model coefficients of determination, R^2s (an indicator of how well the model fits measured data), and on the uncertainty of the normalized pre- and post-weatherization energy consumption levels was used to remove the most unreliable models and create a refined data set for analysis. The screening criteria chosen are those used by Princeton researchers, $R^2 \geq 0.70$ and a relative standard error of normalized consumption ≤ 0.06. Houses that did not meet these criteria were excluded from the analysis, resulting in a refined data set of 65 houses.

Weather-normalized, pre-weatherization space-heating energy consumption ranged from 18 to 106 MBtu. The average pre-weatherization consumption was 50.1 MBtu (around $351 at $7/MBtu) for all 65 houses, and the three group averages were all within 3% of this value. The group averages were not statistically different at a 95% confidence level.

The space-heating savings of all 65 houses ranged from a low of -33 MBtu (the minus indicates an increase in energy use) to a high of 53 MBtu. The average savings for control houses was -2.7 MBtu (-5%), indicating a slight increase in energy use. Average energy savings for the two weatherized groups were much larger, 13.9 MBtu (28%) for the FTA group and 8.9 MBtu (18%) for the standard group. The energy savings of both weatherized groups were found to be statistically different from those of the control group at the 95% confidence level. Even with the refinement to houses with more reliable performance models, the standard deviations of the average savings for the two weatherized groups were still large. As a result, a statistical difference between the two averages could not be detected at the 95% confidence level. When adjusted for the increase in energy use in the control group, net savings were 33% for FTA weatherizations and 23% for standard weatherizations.

Twenty of the original 120 houses in the field test were excluded from the cooling energy savings analysis. Exclusions were due to their dropping out during the testing, air conditioner failure, changes in the way houses were occupied, or other reasons that caused a major loss of data. The exclusions represented seven houses from one test site, eight from a second, and five from a third.

Weather-normalized, pre-weatherization space-cooling energy consumption ranged from 0 to 4867 kWh. The average pre-weatherization cooling energy use for the 100 houses was 781 kWh (around $66 at $0.085/kWh); the three group averages were all within 13% of this value. The group averages were not statistically different at a 95%

confidence level. Most houses in the test were low cooling energy users. Approximately one of every two houses (47%) used less than 500 kWh ($43) before weatherization. Only 14% used more than 1500 kWh ($128).

The average cooling energy savings was 8 kWh (1%) for the control group, 30 kWh (4%) for the standard group, and 165 kWh (19%) for the FTA group. When adjusted for the control group change, the FTA group saved 18% (net savings), which is much higher than the 3% net savings for the standard group. A separate analysis focusing only on the higher cooling energy users produced very similar results. Wide variations in cooling energy savings produced large standard deviations for group average savings. Statistically significant differences between treatment groups could not be detected as a result.

Like the original heating data set, the 100-house cooling energy data set contains every house in the test for which measured pre- and post-weatherization cooling energy data were available. This set includes a number of houses with very poor model fits. Unlike in the heating energy data set, however, the poor model fits resulted from the minimal and random use of air conditioning in many of the houses rather than from bad data or lack of data resulting from data collection problems.

Total weatherization costs for houses in the FTA and standard groups were almost identical, $1056 and $1059, respectively. But although group averages were very similar, individual site averages indicate significant differences between FTA and standard weatherization costs. The average FTA weatherization cost was 14% less than the average standard weatherization cost at one site, 7% less at another, and 38% higher at the third. The much higher cost at the third site balanced the lower costs at the other two, resulting in nearly identical cost averages for the overall group comparison. Standard weatherization costs at the third site were also much less than standard weatherization costs at the other two sites (around 40% less). The lower costs for standard weatherizations at the third site coincided with the installation of many fewer measures in standard group houses at this site than at other sites.

Individual house weatherization costs in the FTA group covered a wider range than costs for standard weatherizations. Approximately 90% of the standard weatherizations cost between $500 and $1500, while only around 70% of the FTA weatherization costs were within this range. Also, no standard weatherization costs exceeded $2000, while more than 10% (four houses) exceeded this expenditure in the FTA group.

The percentage of weatherization dollars spent on labor costs (including labor for repairs and air sealing) was about the same for the two weatherization groups. Thus, total material expenditures were also similar, but the proportions spent on the different measures varied dramatically between the two groups. The percentage of costs spent for insulating materials in the FTA houses was around 34%, compared with only 18% in the standard houses. The other major difference was for storm windows, which accounted for approximately a third of all material costs in the standard houses. Storm windows were almost unrepresented in the FTA material costs (less than 2%). Material costs for repairs and air sealing were similar for the two groups.

The major conclusions drawn from the field test were:

1. Space-heating energy savings achieved in houses weatherized through the use of the FTA were much larger than those achieved using North Carolina's current Retro-Tech-based program.

2. Houses weatherized using the FTA saved a much greater percentage of cooling energy use than those weatherized by North Carolina's standard program; on average, North Carolina low-income households used little cooling energy.

3. Both similarities and wide variances occurred between measures installed using the FTA and Retro-Tech-based weatherizations.

4. FTA weatherizations cost approximately the same as standard weatherizations on average, but may cost less for most North Carolina weatherization agencies.

5. The use of blower-door-directed air sealing achieved air leakage reductions that far exceeded (more than doubled) those resulting from standard air sealing techniques without increasing total weatherization costs.

6. The FTA was used very successfully and affordably by local weatherization programs to improve weatherization performance substantially without increasing total weatherization costs.

1. INTRODUCTION

1.1 BACKGROUND

In 1978, "Project Retro-Tech" was published to provide weatherization agencies a manual means of identifying what energy conservation (weatherization) measures could be installed in low-income homes to maximize the energy savings per dollar spent for weatherizations (DOE 1978). During the 11 years following its publication, weatherization technologies and program changes evolved so that revision or replacement of this audit was needed (Gettings and Kolb 1989). In 1988, the Department of Energy's (DOE's) Weatherization Assistance Program initiated a project with the Oak Ridge National Laboratory (ORNL) to improve the methods of selecting weatherization measures. Based on the assessment of current measure selection techniques and weatherization agency needs, it was recommended that the Weatherization Assistance Program support the development of an upgraded audit (Gettings and Kolb 1989).

Following this recommendation, the Weatherization Assistance Program approved a project in 1989 to support the development of an upgraded audit incorporating new measure selection techniques. The project would be done in three phases: (1) develop an upgraded audit, (2) field test it in North Carolina against the state's current weatherization program (based on Project Retro-Tech), and (3) expand the upgraded audit for use by all weatherization agencies. This report summarizes the results from the field test of the new audit, the second phase of the project.

1.2 PURPOSE

The primary purposes of the North Carolina Field Test were (1) to performance test the new advanced weatherization audit, the Field Test Audit (FTA), which incorporates both heating and cooling measures and advanced air sealing (using a blower-door-directed procedure) in a hot-humid climate; and (2) to compare the results with North Carolina's current weatherization program (NCDOC 1985). In addition, the test was expected to provide substantial experience and recommendations that could be used to enhance the capabilities and the ease of use of the FTA.

13 REPORT ORGANIZATION

This report is divided into several sections describing the details of the FTA and the results of its application in North Carolina. Section 2 describes the design of the 2-year field test. Section 3 describes the two audits (measure selection techniques) that were evaluated in the side-by-side test, the standard North Carolina procedure, based on Project Retro-Tech, and the more-advanced FTA procedure. The total weatherization package built around the FTA and its application in North Carolina is described in Sect. 4. Operation of the FTA is described in Sect. 4, along with specific implementation details. Sections 6 through 11 present the actual field test results. A summary of occupant and house characteristics for all test houses is also provided in this section. Section 7 summarizes the weatherization measures recommended by the FTA. It also compares measures actually installed in the FTA group with those in a second group with measures installed under North Carolina's current weatherization approach (the standard group). Section 8 presents a summary of the air leakage measurements made in all houses and the air sealing results from the blower-door-directed procedure for houses in the FTA group. The analyses of heating and cooling energy consumption and savings are discussed in Sect. 9. Weatherization costs are analyzed in Sect. 10. Section 11 shows the results of FTA consumption and savings predictions compared with measured performance. The final section, Sect. 12, summarizes the results and conclusions of this project.

2. FIELD TEST DESIGN OVERVIEW

The field test was performed in three separate areas of North Carolina (referred to as test sites): a central site including the counties of Johnston and Lee; a northern site including the counties of Franklin, Vance, and Warren; and a southern site including the counties of Robeson, Hoke, Bladen, and Scotland. Test site locations are shown in Fig. 2.1. One hundred and twenty houses, 40 at each site, were identified that satisfied the selection criteria in the experimental plan (Sharp and Ternes 1990).

Houses included in the field test were selected based on certain criteria to limit the sample to those houses that would best represent typical low-income houses served by North Carolina weatherization programs and to keep the groups as homogenous as possible to best ensure the success of the test. These restrictions included limitations on house location and type, heating and cooling system types, weatherization eligibility, and others, described in the experimental plan (Sharp and Ternes 1990). The required house characteristics were identified by a survey of houses at the start of the field test.

Houses were split into three groups of 40 representing an FTA group, a standard weatherization (Retro-Tech) group, and a control group. The number of test houses in each group was selected both to satisfy cost considerations and to allow the estimated sample sizes needed to provide sufficient accuracy for conclusive results. Selection of the houses was performed by identifying individual houses conforming to the selection criteria, determining if the occupants were willing to participate, and accepting them if they consented, until the 120-house quota was reached. This quota sampling approach was used because a more formal statistical sampling technique, such as random sampling, would have required the identification of many more qualified houses, resulting in much greater effort and cost.

The field test was conducted over a 2-year period. Houses were instrumented in the fall and early winter of 1989, and pre-weatherization data collection was initiated in November of that year. Because of some complications in getting fuel suppliers to respond (primarily propane suppliers), some of the houses were not fully instrumented by the November 1 starting date. Pre-weatherization data collection continued through September 1990.

Following pre-weatherization data collection and the completion of pre-weatherization air leakage measurements, the installation of weatherization measures was initiated in October 1990. Weatherizations were completed between October and November 1990.

Post-weatherization monitoring began with 119 houses remaining in the field test and continued through August 1991. The post-weatherization start date was delayed from November 1 to December 1, 1990, to allow for testing associated with indoor air quality. Air quality testing was performed because of indoor air quality concerns resulting from the abundant use of unvented space heaters in the test houses. This testing was performed independently by the state of North Carolina and is not discussed here.

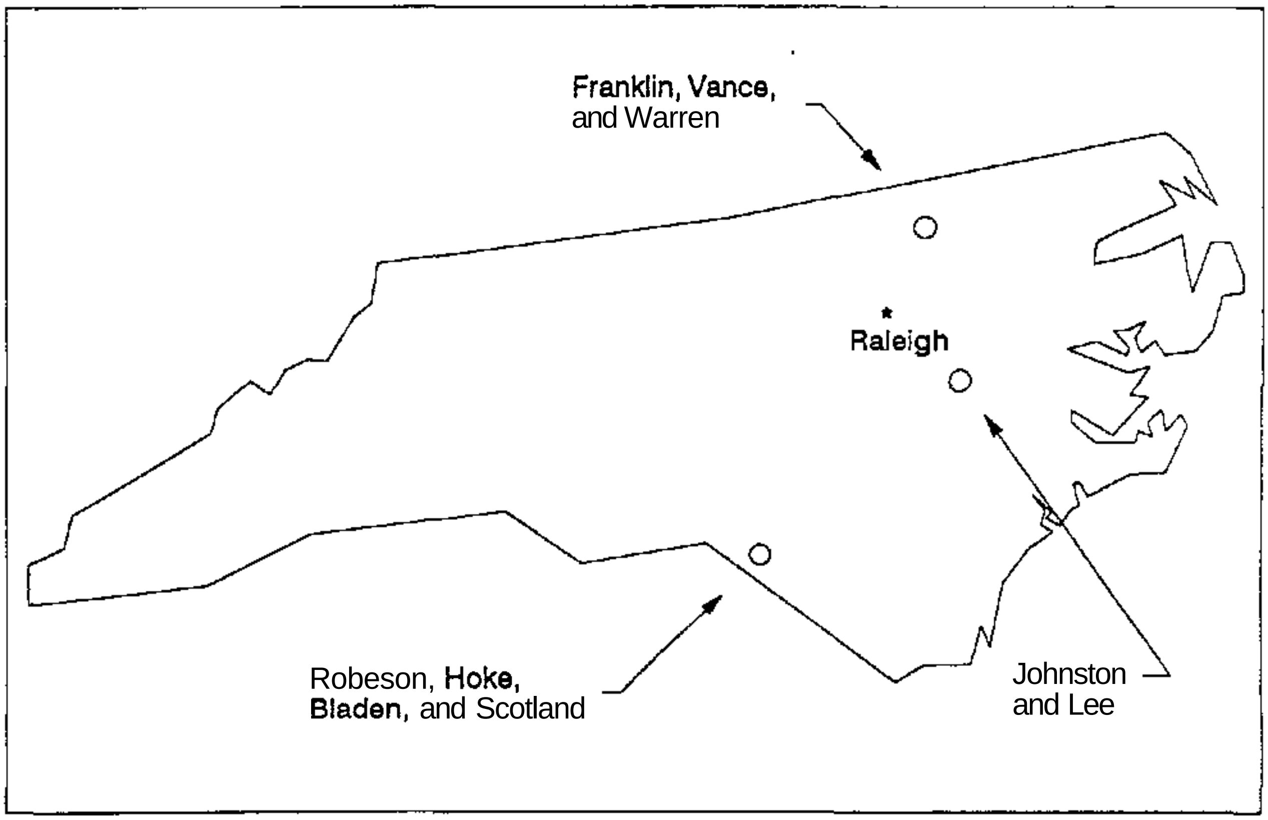

Fig. 2.1. North Carolina test site locations and the counties included in each.

A stratified random assignment procedure was used to assign houses to each test group to help achieve equality between groups. The 40 houses from each agency were grouped by heating fuel, heating system type, and the number of air conditioners (although those houses with 1 air conditioner dominated), and then randomly assigned to each of the three test groups. The unique stratifications that were represented by only one or two houses were grouped together and randomly assigned. To create the equal-size groups of 40 houses each, 13 houses each from two weatherization agencies and 14 houses from the third were assigned to each group.

The assignments were made in June 1990, after the pre-weatherization heating season, to help minimize the possibility that attrition would create unequal groups.

The following time-dependent data were collected weekly for all the houses during the pre- and post-weatherization test periods: house electricity use, space-heating fuel use (natural gas, propane, kerosene, or #2 oil), air conditioner electricity use, and water heating electricity use. Hourly indoor temperatures were monitored in each house and hourly weather conditions were monitored at one location in each test site. The following types of time-independent information were collected or measured:

1. House and occupant descriptive information was collected in the last quarter of 1989.

2. House air leakage rates were measured in all houses in the last quarter of 1989, before weatherization, and again following weatherization.

3. Space-heating system steady state efficiencies were measured in all FTA houses before weatherization (where possible).

4. Blower-door air sealing results in the FTA houses were measured in November 1989. These measurements differ from the pre- and post-weatherization air leakage rate measurements because they were taken specifically to measure the reductions achieved from air sealing only (no other weatherization measures having been installed).

5. Summaries of the installed weatherization measures and their cost and labor requirements for the two groups using the measures were obtained following weatherizations.

The design of the field test is covered extensively in the experimental plan for the North Carolina Field Test (Sharp and Ternes 1990).

3. CONSERVATION APPROACHES

3.1 NORTH CAROLINA'S CURRENT LOW-INCOME WEATHERIZATION ASSISTANCE PROGRAM

North Carolina's current (standard) weatherization program is limited to seven weatherization measures that are installed based on their prioritized ranking. The measures are ordered relative to their perceived cost-effectiveness. The measures, in order of prioritization, are as follows:

1. infiltration measures,
2. attic insulation,
3. water heater, pipe, and floor insulation,
4. duct insulation,
5. underpinning (enclose the crawl space),
6. storm windows, and
7. storm doors.

Each measure is installed in order of priority until the allotted funds, up to $1400 per house on average (including administration costs), are spent or the next consecutive measure is unaffordable within the spending limits. A higher priority measure must be fully installed before the next measure is considered.

Infiltration measures include caulking, adding new weatherstripping and replacing existing defective weatherstripping around windows and doors, repairing or replacing windows and doors in poor condition, and repairing holes in walls and floors. The identification of infiltration deficiencies and locations is made visually. Attic insulation is installed to a minimum of R-19 and a maximum of R-30. It is installed in conjunction with installing appropriate attic vapor barriers and attic ventilation.

All uninsulated electric water heaters receive a water heater insulation wrap. Wrapping of fuel-fired water heaters is permissible. Hot water pipes and heating ducts are also insulated. Houses with a crawl space receive floor insulation or underpinning, depending on the height of the crawl space. The remaining measures, storm windows and doors, generally have a much longer payback and therefore are installed only on a limited basis.

North Carolina's current weatherization program is more fully described in the state's *Weatherization Assistance Guide-Standards and Techniques* (NCDOC 1985).

3.2 THE NORTH CAROLINA FIELD TEST AUDIT

The North Carolina FTA (Gettings 1990) is a computerized measure selection technique that ranks envelope and mechanical equipment weatherization measures by their benefit-to-cost ratio according to the needs of the individual house. Measure selection is based on the principles identified by McCold (1987) and McCold et al. (1986) and is similar to techniques previously tested in Wisconsin and New York (McCold et al. 1988; Ternes et al. 1988; and Ternes and Hu 1988). The audit focuses on reducing both space heating and cooling energy consumption. The term "audit" as used here refers specifically to the measure selection technique.

The key to the FTA, in contrast to a set list of priorities, is that its computerized selection technique actually evaluates the expected performance of each potential measure for an individual house. The program ranks the measures in the order that they should be installed based on their benefit-to-cost ratio (BCR). Information for the audit is collected through house surveys and limited diagnostic measurements. The audit uses these data, combined with estimated measure costs, to determine the BCR of each potential measure. Measure ranking is then checked and adjusted for measure interactions, and a final list of recommended measures is provided to the user.

Development of the FTA assumed a modular approach to weatherization, in that the selection and installation of measures in a house can be subdivided into categories of activities: air leakage reduction, installation of low-cost measures, building envelop retrofit, and equipment retrofit. The computerized FTA developed for North Carolina addressed only envelope and equipment measures. However, the application of the FTA in North Carolina included a separate air leakage reduction procedure and the installation of low-cost measures.

3.2.1 Running the Field Test Audit

The first step in running the computerized FTA is collecting or measuring the following data: building construction and characteristics, heating and cooling system characteristics, heating system steady state efficiencies (optional), and house air leakage rates (optional). The FTA requests from the user, but does not require, measured steady state efficiency of primary heating systems and measured house air leakage rates. The FTA can use default values when measured values are not entered. Occupancy data are not required. The data required to run the FTA are normally collected in one visit.

The second part of performing the audit involves actually running the audit. The program is run on a personal computer and prompts the user to enter the collected field data, using data entry screens identical to the house characteristics data sheets used in the field. The air leakage rate after air sealing is used in the audit so that excessive rates, if they exist initially, will not affect the selection of measures. The audit uses a default value for the air leakage rate after air sealing unless air sealing work is completed before running the audit, in which case the user enters a measured value. The program allows the user to back up within a data screen or back up to previous screens for correcting any data entry errors. Following the last data entry, the program executes automatically.

The selection technique calculates a building load coefficient that consists of the sum of the effective envelope conductances (UA-values) and an effective conductance due to infiltration. Using this and an estimate of internal heat generation and solar gains, the program uses a variable-base degree-hour method (ASHRAE 1989) to calculate annual whole building energy consumption. The technique then applies each measure individually to the house and determines its potential benefits. The selection technique calculates for each potential measure the installation cost, the expected energy and cost savings, and the measure BCR. The installation costs are calculated based on the input building characteristics data and the local labor and materials costs for each measure. Labor and materials costs are retrieved from a computer file that can be changed by the user to reflect local costs. Energy savings for each measure are estimated by assuming that each measure is applied to the house individually. The energy savings of equipment measures are calculated based on assumed efficiency improvements resulting from the particular measure and the whole building energy consumption.

Estimated energy and cost savings are calculated over the life of the measure and projected back to their values in current dollars using a discount rate. Fuel escalation is not considered in this version of the audit. The expected cost savings are then divided by the measure cost to determine the BCR. Then the selection technique reanalyzes the list of measures to account for measure interactions. This is done by ranking the measures by BCR and then applying them to the house collectively from the highest to the lowest BCR. To account for interaction effects, the second highest BCR measure and those following are applied consecutively to the building assuming that all previously recommended measures (with higher BCR ratios) have been installed. All measures with interacted BCRs greater than a pre-selected BCR cutoff (1.0 for North Carolina) are then recommended for installation.

The technique outputs a file listing the measures in a prioritized ranking, their expected savings, costs, interacted BCR, and the material types and quantities to be installed. Table 3.1 represents the program output for one of the FTA houses. The starred "*" measures are not to be installed, either because they have BCRs below 1.0 or because another measure should be installed instead (e.g., both R-30 and R-11 are cost-effective, but R-30 should be installed because it has the highest net present value).

3.2.2. Measures Considered in the Field Test Audit

The North Carolina FTA considers measures to reduce both heating and cooling energy consumption. Specific envelope measures to reduce both heating and cooling loads were attic insulation, wall insulation (including kneewalls), floor insulation, sill insulation, and storm windows. Specific equipment measures to reduce space-heating energy use were vent dampers, intermittent ignition devices, smart thermostats, flame retention head burners, and furnace replacements. Specific measures to reduce cooling energy use included attic radiant barriers, window shading, and replacement air conditioners. The 16 measures evaluated by the FTA are listed in Table 3.2.

Attic insulation measures were limited to the addition of either R-ll or R-30 blown cellulose or fiberglass insulation. Wall insulation was nominally 3.5 inches of blown cellulose and R-ll fiberglass batt for kneewalls. The floor insulation measure was for R-19 fiberglass batt. The FTA was designed to evaluate only the particular heating system equipment measures that were applicable to the specific house and heating system being audited. All heating system equipment measures were evaluated for central, wall, and floor furnaces, except replacement systems, which were considered for central furnaces only.

Table 3.1. Field Test Audit program output for one house

House description:

Auditor:

Audit date:

Measure	Component	Total savings (MBtu/year)	Interacted savings ($/year)	Cost ($)	B/C
* Attic ins. R-11	a1	20.69	213.93	193.04	12.56
Attic ins. R-30	a1	24.28	239.70	495.14	5.49
Wall ins, 3.5"	s1,n1,e1,w1	11.55	96.49	479.75	2.28
Floor ins. R-19	f1	9.25	64.40	380.00	1.92
* Storm windows	wdw4	0.53	4.26	61.90	0.67
* Window shading	wdwl,wdw2,w	−0.01	12.59	165.00	0.57
* Smart thermostat		1.36	10.95	220.00	0.48
* Replace window A/C	ac1	0.65	12.09	512.50	0.23
* Elect. vent dmpr./IID		2.03	17.38	553.00	0.22
* Replace htg. system		3.67	31.47	1800.00	0.17
* Flame retntn. burners		0.93	8.00	540.00	0.11
* Sillbox ins.		0.08	0.46	43.54	0.10
* Radiant barrier	al	0.34	4.86	235.60	0.09
* Electric vent damper		0.23	1.93	328.00	0.04

Material list

Material name	Type	Quantity
Ceiling insulation	Celluls, Blwn—R-30	760 ft^2
Wall insulation	Celluls, Blwn—3.5"	813 ft^2
Floor insulation	Faced Batt—R-19	760 ft^2

User Comments

Table 3.2. The sixteen measures evaluated by the Field Test Audit

Measure
Ceiling insulation:
R-11 blown cellulose
R-30 blown cellulose
R-11 blown fiberglass
R-30 blown fiberglass
Wall insulation, 3.5 in. blown cellulose
Kneewall insulation, R-11 batt fiberglass
Sill insulation, R-19 batt fiberglass
Floor insulation, R-19 batt fiberglass
Vent damper, thermal
Vent damper, electrical
Intermittent ignition device (IID)
Intermittent ignition device and vent damper, electrical
Flame retention head burner
Furnace replacement
Smart thermostat
Radiant barrier, attic
Storm window
Air conditioner replacement:
5000 Btu
15,000 Btu
25,000 Btu
Awnings

The typical room space heater[1] found in many of the North Carolina test houses is pictured in Fig. 3.1. A tuneup was the only measure considered for room space heaters. This approach was followed because of two important considerations. First, many of the space heaters lacked proper safety controls by current standards. Appropriate safety devices were considered a requirement before any modifications would be made to a system. Second, few retrofits were available for space heaters that could be installed without invalidating Underwriter's Laboratories or American Gas Association listings.

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[1] Unless denoted as portable, a space heater is a non-portable, piped-in (from an outdoor fuel source), free-standing room heater furnishing warm air to the room in which it is installed. Combustion products from the space heater are normally vented, although some of the smaller units may be unvented.

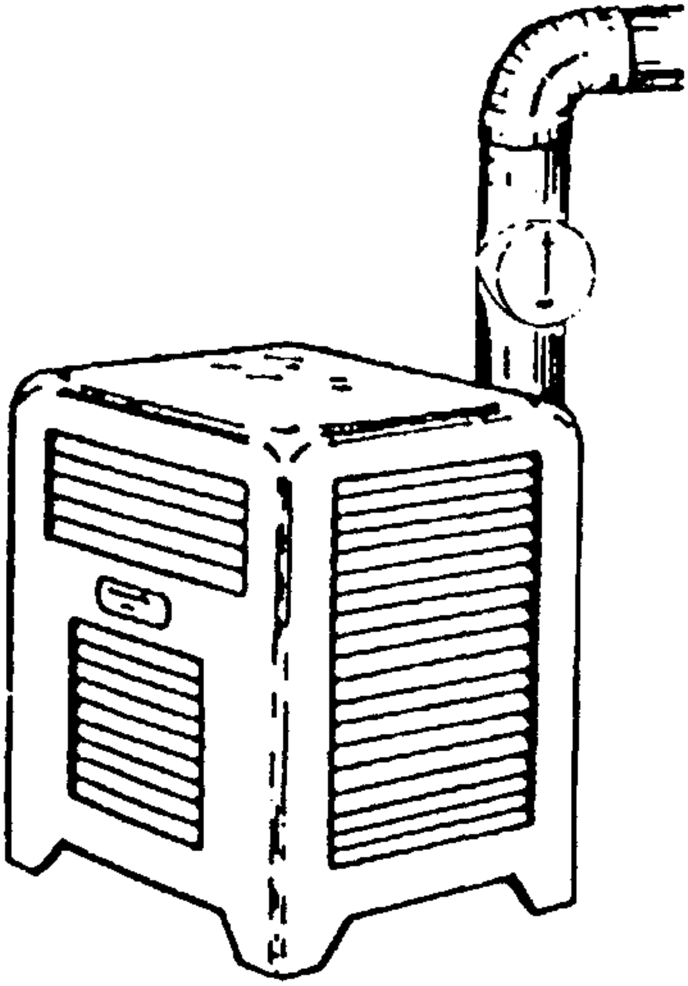

Fig. 3.1. Space heater typical of those found in North Carolina test houses.

A space heater replacement measure was not considered primarily because new space heaters do not have substantially higher efficiencies than existing systems in good operating condition, and tuneups could be used to restore much of the efficiency losses that were found. Tuneups were applicable to all systems but were not considered within the audit; decisions to perform tuneups were made based on measured system efficiencies. This procedure is explained in Sect. 4.4.

4, APPLYING THE HELD TEST AUDIT IN NORTH CAROLINA

The weatherization package applied to houses in the FTA group consisted of four independent activities: (1) installing envelope and equipment measures selected by the computerized FTA, (2) air sealing using a blower-door directed air sealing procedure, (3) installing low-cost measures, and (4) performing tuneups on heating systems.

4.1 APPLICATION OF THE FIELD TEST AUDIT

4.1.1 Audit Implementation and Default Parameters

Use of the FTA required both house characteristics data and some degree of audit operating knowledge. In addition, the audit used measure cost data for the area in North Carolina where the audit was applied. Measure cost data were provided by each weatherization agency. The estimated installation costs (which include material costs) and the lifetimes of the measures addressed in the field test are presented in Table 4.1. A cost range in this table represents the differing costs in different agency areas for the same measure. The large variations in costs for mechanical measures were due to variations in both labor and material costs.

Fuel costs were assumed to be the same for each agency area. The seven fuels considered in the FTA are listed with their corresponding costs in Table 4.2. Test houses were limited to those that used natural gas, propane, kerosene, and #2 fuel oil as primary heating fuels. The use of secondary heating fuels such as wood, coal, and electricity was limited. Fuel prices used were the best estimates that could be made at the time the audit was implemented. The real discount rate used in the economic calculations was 7%.

The FTA uses a house air-leakage rate after air sealing or a default value. A default value of 2500 cfm50[2] was used for every FTA house [the unit cfm50 represents an air flow rate in cubic feet per minute with the house depressurized to 50 Pa below ambient]. This approach was used because the audit was run to select other measures before crews went to the field to perform air sealing. This schedule maximized the amount of measured pre-weatherization energy consumption data that could be collected in support of the field test. The default value was expected to represent the average air leakage obtainable after air sealing, realizing that an average value may not be highly accurate for every individual house. The average measured air-leakage rate after air sealing at two agencies was within 8% of this assumed value. Details of the air sealing procedure are discussed in Sect. 4.2. Air-leakage rates were used to define house tightness for calculating the cost effectiveness of other conservation measures. This procedure prevented a large air-leakage rate in an excessively leaky house from strongly influencing measure selection. This was desirable because air sealing was implemented in every house and was done first (before any other measures were installed).

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[2] For the average test house (around 1150 sq. ft.) this is approximately equal to 0.8 air changes per hour (Meier 1986).

Table 4.1. Installation costs and lifetimes of the energy conservation measures considered in the Field Test Audit (these measures were selected specifically for this test based on a sampling of North Carolina's low-income housing stock)

Measure	Unit	Cost: materials and labor ($)	Life (years)
Ceiling insulation:			
R-11 ceiling, blown cellulose	sq. ft.	.23–.25	20
R-30 ceiling, blown cellulose	sq. ft.	.60–.65	20
R-11 ceiling, blown fiberglass	sq. ft.	.32	20
R-30 ceiling, blown fiberglass	sq. ft.	.48	20
Wall insulation, 3.5-in. blown cellulose	sq. ft.	.59	20
Kneewall insulation, R-11 batt fiberglass	sq. ft.	.29-32	20
Sill insulation, R-19 batt fiberglass	sq. ft.	.48–.51	15
Floor insulation, R-19 batt fiberglass	sq. ft.	.48–.52	20
Vent damper, thermal	each	93-132	10
Vent damper, electrical	each	211-328	10
Intermittent ignition device	each	221-225	10
IID/Vent damper, electrical	each	455-553	9
Flame retention head burner	each	540	10
Furnace replacement	each	1600–1800	15
Smart thermostat	each	65-220	15
Radiant barrier, attic	sq. ft.	.12	15
Storm window	each	51-58	15
Air conditioner replacement:			15
5000 Btu	each	300-499	15
15,000 Btu	each	600-750	15
25,000 Btu	each	910-1100	
Awnings	linear feet	11–20 plus 55 per unit	10

Table 4.2. Estimated North Carolina energy costs used in the Field Test Audit

	Fuel						
	Natural gas	No. 2 fuel oil	Propane	Kerosene	Wood	Coal	Electricity
Cost (S/unit)	5.2635	1.199	1.079	1.299	120	126	0.08543
Unit	ccf	gal	gal	gal	cord	ton	kWh

4.1.2 Benefit-to-Cost Ratio Cutoff Selection

The amount of money spent on weatherizing an individual house in a weatherization program and the overall BCR of a weatherization program can be indirectly controlled by the BCR cutoff used to select measures. Recommended measures for an individual house will be limited to those with a BCR greater than the selected value. Selecting a high BCR cutoff tends to limit the money spent on an individual house and spreads the program funds out over more houses. This approach can help to increase the return on weatherization investment (savings per dollar expended). However, if the BCR cutoff is too high, the number of measures installed in an individual house, on the average, could become very small and the administration costs of the program could tend to overshadow the savings achieved. This could lead to a decrease in the overall BCR for a program. To the other extreme, if a low BCR cutoff is used, on the average, more measures will be installed in individual houses and an individual house will save more energy. However, the cost per unit of energy saved in an individual house will increase and ultimately reduce the overall BCR for the weatherization program.

A BCR cutoff of 1.0 was used for the North Carolina Field Test so that all cost-effective measures would be installed (measures that provide a present value savings equal to or greater than their costs). A BCR cutoff of 1.0 required that a conservation measure have a BCR of 1.0 or greater to be recommended. A BCR greater than 1.0 indicates that the savings from a measure over its life (discounted to present value) is greater than its cost. Additional background on the selection of a BCR cutoff for a weatherization program is provided by Ternes (1991) and Zimmerman (1990).

4.2 AIR LEAKAGE REDUCTION PROCEDURE

The FTA recommends, but does not require, air sealing using a blower-door-directed procedure based on cost-effectiveness guidelines. An air sealing procedure of this type (Schlegel 1990; Schlegel et al. 1986; Gettings et al., 1988) was used in all FTA houses. The procedure was intended to improve air sealing energy savings (by improving air sealing effectiveness) and to reduce air sealing costs. The procedure requires weatherization crews to use a blower door to locate major leaks and to determine the level of sealing work that should be performed. Air sealing was performed independent of the computerized audit because past experience with low-income houses has indicated that most houses in a sample could receive some degree of cost-effective air sealing.

The cost-effectiveness guideline used in North Carolina represents the amount of air leakage reduction that must be accomplished hourly to maintain the cost effectiveness of the air sealing work. The guideline was determined by using appropriate data from North Carolina in the equations provided by Schlegel (1990). The energy savings per 1 cfm50 reduction was calculated based on 3393 heating degree days in Raleigh, North Carolina, and a degree-day correction factor of 0.7 as reported in ASHRAE (1980, 1989). A discount rate of 7% was used, and the life of the air sealing work was assumed to be 10 years. The combined material and labor costs for air-sealing work by participating agencies was estimated to be around $20 per person-hour. Using these values, a cost-effectiveness guideline was determined for each fuel (based on local costs) and the typical efficiency of the associated heating system (65% for space heaters and 70% for natural gas furnaces). From these, a single cost-effectiveness guideline of 75 cfm50 per person-hour was selected as representative for all fuels and heating system efficiencies. A BCR of 1.0 was used in calculating the guideline. The guideline was used to indicate when air sealing work should end. A second criterion, a minimum ventilation limit of 1500 cfm50, was used to indicate when air sealing should be stopped to prevent overtightening.

The air sealing process begins with a crew checking and correcting any moisture problems that exist before starting the actual air sealing. Following this, the air leakage rate of the house is measured at a house depressurization of 50 Pa below ambient. If the air leakage is near the minimum ventilation guideline, so that an hour's worth of work might overtighten the house, the procedure stops. If the air leakage is significantly above the minimum ventilation guideline as in most houses, air sealing begins. The crew identifies major leaks with the blower door operating and begins to seal them. After approximately 1 hour, a second blower door air leakage measurement is made. The reduction between the first and second measurements is calculated and compared with the cost-effectiveness guideline. If that hour's work was cost-effective and the air leakage rate is still significantly above the minimum ventilation guideline, air sealing continues another hour. This process is repeated until the reduction achieved is below or near the cost-effectiveness guideline or the house air leakage rate is near the minimum ventilation guideline. Near the guidelines means that, based on hourly reductions achieved, an additional hour of work would likely not be cost-effective or would likely seal the house tighter than the minimum ventilation limit.

43 INSTALLATION OF LOW-COST MEASURES

Recommended low-cost, highly effective measures (water heater wraps and hot water pipe and heating duct insulation in unconditioned spaces) were identified outside the FTA by the auditor. This was done because their implementation requirements most often do not justify the data collection time required for their inclusion in a computerized selection technique, and their savings are often difficult to predict accurately on an individual house basis. Low-cost measures were installed in conjunction with FTA measures.

4.4 HEATING SYSTEM TUNEUPS

Although heating system tuneups could have been evaluated within the computerized FTA, they were addressed as a separate procedure. This approach was followed because the exact components of a heating system tuneup were not well defined at the time the audit was being developed. The development of a tune-up procedure was hindered because numerous heating system types were encountered (such as kerosene and propane space heaters and natural-gas propane and oil-fired central furnaces) and because the number of systems that could receive tuneups (other than the cleaning of space heaters) was small. The tuneup evaluation was combined with a heating system safety check already being done outside the computerized audit.

Recommendations for heating system tuneups were made based upon the steady-state efficiencies resulting from actual flue gas measurements on each system. The tuneup criteria differed for forced-air and gravity systems and for systems that only supplied part of the heating load (many houses had multiple systems). The criteria for recommending tuneups are summarized in Tables 4.3a and 4.3b. The criteria for houses using one heating system were selected to be around 10% below the steady-state efficiencies that should be obtained after tuneup. This cutoff was used so that the systems that could benefit the most would receive the tuneup. The criteria were considered conservative and were selected with conservatism in mind because the efficiency gains from tuneups can be difficult to predict. Using this conservative approach, if the tuneup brought efficiencies up to those typical of older forced-air furnaces in good operating condition, the improvement would be more than enough to make the tuneup cost-effective. The tuneup criteria for furnaces apply to standard natural-draft furnaces using pilot ignition. Typical steady-state efficiencies for these older forced-air furnaces and many later models in good operating condition range between 75 and 80% (ASHRAE 1979, 1988). Typical steady-state efficiencies for space heaters in good operating condition normally exceed 70% (American Gas Association; Underwriters Laboratories).

The tuneup criteria for heating systems in houses using more than one system were set 5% below those for houses with one system, so that a larger efficiency increase was expected from systems supplying part loads. In addition, the primary system in the house was the only system considered for tuneup.

An across-the-board heating system tuneup program for all systems, without considering present efficiencies, was not used in North Carolina. Although such a program can result in an overall increase in heating system efficiency, the average per-house increase is often insufficient to make the program cost-effective based on economics alone. A program that tunes up all systems will improve efficiency in some systems, cause little change in some, and actually decrease steady-state efficiency for others (Ternes et al. 1991). Measuring actual efficiency to determine the need for tuneups allowed selection of the systems that could benefit the most. Tuneups were recommended only where measurements indicated a substantial increase in efficiency could be expected. If an efficiency measurement could not be made, the system was not recommended for tuneup.

The tuneup for central furnaces consisted of correcting any major system problems, replacing filters, adjusting combustion air, and adjusting fan on/off temperatures as needed. The tuneup of space heaters was limited primarily to repairs and system cleaning.

Table 4.3a. Heating system tuneup recommendation criteria for houses using only one heating system

System	Perform tuneup if the heating system efficiency is less than
Forced-air furnace (central, floor, wall)	65%
Space heater, gravity system (central, floor, or wall), or other system	60%

Table 43b. Heating system tuneup recommendation criteria for houses using two or more heating systems

System	Perform tuneup of the primary heating system if the system efficiency is less than
Forced-air furnace (central, floor, wall)	60%
Space heater, gravity system (central, floor, or wall), or other system	55%

5. HELD TEST IMPLEMENTATION

5.1 TRAINING

Training to implement the field test was provided in three primary areas: blower door air leakage measurements, blower-door-directed air sealing, and audit training. Except for collecting audit data, these procedures were all new experiences for the participating agencies.

5.1.1 Blower Door Measurements and Air Sealing Training

Training for making blower door measurements and performing the blower-door-directed air sealing procedure were done consecutively; they were the most complicated training of this field test. Group training (all agencies represented) was provided to weatherization crew members in the classroom for 2 days and in the field for an additional day. Then training personnel went to the separate service area of each agency for 2 days to provide additional training to the same crew members split into their separate teams. Following training, crews practiced the blower-door-directed air sealing procedure on approximately 10 houses before air sealing work began on actual test houses.

5.1.2 Audit Training

Audit training covered both collecting audit data and executing the computerized audit. Data collection was a mix of classroom and in-the-field training. This mix allowed the requirements of the audit to be experienced as well as taught, and it proved to be an important part of the training effort. With the collected field data in hand, participants were trained in running the computerized audit. The background that weatherization staff already had in collecting characteristics data for Retro-Tech was valuable in reducing training requirements. Training for audit data collection and computer operation was accomplished in 3 days.

5.2 LIMITATIONS ON RECOMMENDED AND INSTALLED MEASURES

The FTA considers four different insulation measures: attic, wall, sill box, and floor insulation. Often field limitations control whether and to what extent a recommended measure can be installed. The auditor can determine that a particular measure cannot be installed and so specify in the audit input data to prevent recommendation of that measure. In cases, this capability can be very important in applying the FTA or another audit because installing one measure can affect the energy savings that result for subsequently installed measures. This is commonly as referred to as "measure interaction"; it is a primary reason why the FTA ranks measures. Measure interactions may reduce the BCR of subsequent measures so that it may no one or more of the lower priority measures may no longer be cost effective to install. This problem can be severe when equipment measures are involved. It is important that the inability to install a measure be identified early enough to allow the auditor to restrict installation of that measure when running the audit.

While the restriction options for attic and wall insulation were used by the auditors, the restriction for floor insulation was not. This omission could have occurred for three reasons: (1) the option was not as clear as for other insulations, (2) the option may have been insufficiently emphasized or clarified during audit training, and (3) it was difficult for the auditor to make a judgement in some cases. Because the auditor often must judge visually whether there is sufficient access to install a measure, the FTA does not make this decision. Because some restrictions were not always specified in the audit when needed, some insulation measures (primarily floor insulation) were sometimes recommended when they could not be installed. This error associated with floor insulation was somewhat forgiving in North Carolina because floor insulation was usually one of the last measures recommended (BCR nearest to 1.0). This fact minimized its interaction with other installed measures.

Sill and floor insulation were treated as independent measures in the FTA (both could be recommended) but were treated as dependent for installation purposes. A separate sill insulation measure was not installed when floor insulation was installed because the floor insulation, when butted to the band joist, provided insulation of the sill area. Insulation measures were partially installed if possible when there were limitations on the complete installation.

Implementation of FTA-recommended heating system equipment measures was substantially limited in the field test. The types of heating systems that normally could benefit from equipment measures represented a small fraction of the heating systems in the test houses. The primary heating system types found in the houses are listed in Table 5.1. Only around 20% of the primary heating systems could benefit from the FTA equipment measures because fixed room space heaters, which could only use the tuneup recommended outside the audit, represented approximately 80% of the primary heating systems (134 space heaters were reported in the 120 test houses).

The installation of heating system measures also may have been reduced because many houses used two or more different heating systems to meet heating loads. If an individual system being considered for retrofit were supplying only part of the heating load, the fuel cost savings (benefit) from its retrofit would be less, leading to a significantly reduced BCR for a heating system measure.

Heating system efficiency measurements were made in 23 of the 40 FTA houses. Efficiency measurements were not made in six houses having unvented primary heating systems. These systems are treated as 100% efficient in the audit. Efficiency measurements were not made in 11 other houses because either the houses were out of fuel or the fuel supply was turned off.

Based on the criteria in Table 3.3, only three systems (13% of those measured) were recommended to receive a tuneup. These were for a central oil-fired furnace in house 4 (having a measured efficiency of around 50% and thought to have some type of major system problem) and kerosene space heaters in houses 22 and 27.

Table 5.1. Primary and secondary heating systems for houses in the Field Test Audit group

House	Primary heating system		Secondary heating system	
	Type	Fuel	Type	Fuel
2	SH	kero	SH	kero
4	F	oil2		
9	F	LPG		
10	F	nGas		
18	SH	kero	SH	kero
21	F	oil2		
22	SH	kero	SH	kero
26	SH	kero		
27	SH	kero		
30	SH	LPG		
36	SH	kero	SH	kero
37	SH	LPG		
40	F	oil2		
46	SH	nGas		
52	SH	LPG		
58	SH	kero	SH	LPG
61	SH	LPG	SH	LPG
62	SH	LPG		
67	SH	LPG		
68	SH	LPG		
72	SH	kero		
73	SH	LPG	SH	kero
79	SH	kero		
85	FF	oil2		
94	SH	LPG	SH	LPG
95	SH	kero		
102	SH	nGas	SH	nGas
103	SH	nGas		

Table 5.1. (continued)

House	Primary heating system		Secodary heating system	
	Type	Fuel	Type	Fuel
107	SH	nGas	SH	nGas
110	WF	oil2		
111	SH	LPG	SH	kero
113	SH	LPG		
118	SH	LPG		
127	SH	LPG	SH	LPG
128	SH	LPG	SH	LPG
137	SH	kero		
138	SH	kero		
140	SH	kero		
145	WF	nGas	SH	nGas

Type: F—central furnace, WF—wall furnace, FF—floor furnace, SH—space heater.
Fuel: Kero—kerosene; oil2—#2 fuel oil; nGas—natural gas; LPG—liquefied petroleum gas.

Note: The primary systems in houses 62, 94, 113, 118, 127, and 128 are unvented.

5.3 DELIVERY OF WEATHERIZATION SERVICES

All weatherization measures, except heating system mechanical measures and wall insulation, were installed by in-house personnel at two agencies and by a contractor at the third. Personnel installing weatherization measures were experienced in weatherization work. All heating system mechanical measures were installed by heating contractors, and all agencies used contractors to install wall insulation.

Air sealing work was performed by both agency and contractor personnel following the procedures taught in the training classes (see Sect. 4.2). Air sealing was the first measure performed on all houses.

5.4 HELD EXPERIENCE

5.4.1 Audit Performance

Agency personnel made the first runs of the FTA for all houses. Copies of the input data and the audit results were provided to ORNL for review. This review indicated exorbitant energy savings for two measures, air conditioners and radiant barriers, and several problems with the audit input data. ORNL traced the problems with energy savings to minor computer program problems, which were corrected. Both minor and major errors were detected in the audit input data for several houses. These errors did not occur for every house; they were sometimes common to only one agency and sometimes to all. Errors were attributable to several causes including weaknesses in the input data format, errors and misunderstandings on the part of the user, user uncertainty as to the exact data to supply, and others. Errors were corrected and the audits were rerun by ORNL to identify the measures to be installed. The following are examples of typical errors:

1. Entering 18000 kBtu instead of 18 kBtu for an air conditioner size (the same type of error occurred for some heating systems).

2. Entering the input rating of a heating system in cubic centimeters per minute or gallons per hour, which were not recognized units in the program (the program did not detect such an entry as an error).

3. Not reporting wall insulation because it was undetected.

4. Entering an R-value where insulation thickness was requested and vice versa.

5. Estimating the percentage of the house cooled.

6. Confusing vent dampers with draft regulators, and identifying intermittent ignition devices.

Most of the errors in the audit input data could be minimized and perhaps eliminated by making minor additions to the part of the computer program that supports the data input routine. These include adding two more heating system rating options, changing rating units to be more in line with the format normally used on actual equipment, and most important, adding range and limit checks on input data. Eliminating the confusion in identifying some heating system components would require additional or more detailed training in those areas, which would be a minor addition to the training program.

Users were very pleased with some parts of the computerized audit and desired changes in others. Eiiminating cumbersome manual calculations as performed under the standard Retro-Tech approach reduced both complications and the amount of time auditors had to spend on computation. Although the audit was found simple to use, it was not always friendly. Users unanimously recommended that the program have the ability to recall previous input data for a rerun. This ability would have saved time and minimized errors in repeated runs. Editing of screens was also sometimes troublesome because the procedure is somewhat different depending on the input screen being used. This problem decreased with experience.

Many if not all of those issues have been addressed through improvements in the FTA since the completion of this test and during the preparation of this report.

The FTA created computer files of the input data and the audit results for each house during its execution. These files were printed to serve as permanent records, which proved to be useful during this test. If the FTA is applied in other locations or on a wide scale, some additional formal recordkeeping procedures are needed to supplement the input and output data files. These records would likely be needed primarily to document items such as installed measures and amounts, installed costs, and the results of a quality-of-work inspection.

5.4.2 Measure Installation

Agency staff at two of the three test sites (sites A and C[3]) normally install weatherization measures. Local contractors are used to install measures at site B. These same practices were used for houses in the field test except for heating system and wall insulation measures, which were all contractor-installed. Air sealing and blower door measurements were performed by the same agency staff at two sites and by the same local contractor at the third. Delivery of services by both agency staff and contractors worked well, although some additional contacts and/or coordination between agency staff and contractors were sometimes required. Except for the specialized measures (wall insulation, heating system, and air sealing), installing FTA measures was no more complicated than standard weatherization installations.

Weatherization measures were installed based on final approval from the homeowner. This approval had an impact on installing two measures: wall insulation and smart thermostats. Installing wall insulation required access to the separate wall cavities created by wall studs, normally by penetrating or removing pieces of siding. Walls with some types of siding, such as aluminum, were not always insulated because of the potential impact on shell appearance. When penetration was needed, the homeowner made the final decision after being shown how the penetrations would be done and how they would be repaired. Wall insulation was not installed in two houses at site B because of homeowner and/or agency concerns. A smart thermostat was not installed in one site B house because of homeowner preference.

5.43 Blower Door Air Leakage Measurements and Air Sealing

During training and practice measurements, weatherization crews became experienced in setting up and making blower door measurements. The training, combined with practice time, was sufficient to become proficient in these tasks. Proficiency in actual sealing of air

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[3] For the purpose of relating measures installed to performance results, test sites are referred to as sites A, B, and C throughout this report. These identifiers are not correlated to the locations shown in Fig. 2.1 intentionally.

leakage areas required considerably more training and practice time. The data received indicate that the time spent on air sealing and the leakage reductions achieved were reasonable. In addition, the average leakage rate in the houses after air sealing was near the rate expected. Based on these data, the extensive training provided for the air sealing procedure appears effective. Uncertainty remains as to which repair costs should be attributed to air sealing and which should be attributed to normal repairs. This is an important issue because normal repair costs would occur independent of the weatherization approach used and therefore should not be attributed to air sealing.

5.5 LABOR REQUIREMENTS: STANDARD VERSUS THE HELD TEST AUDIT

Both auditing techniques involved similar steps and required significant time to collect field data and to complete the audit. Weatherization auditors quickly comprehended the data requirements of the FTA and the procedures for collecting required data. This is no doubt attributable to their experience with Retro-Tech, which had similar data collection requirements.

The current weatherization process used by the participating agencies consisted of five primary activities:

1. collecting data at the site;
2. performing audit computations to specify materials, quantities, costs, and installing locations;
3. installing measures;
4. inspecting installed measures; and
5. summarizing the inspection results and completing audit computations.

The FTA as tested involved all of these activities. Excluding heating system efficiency measurements, however, the primary differences in labor requirements between the two audits were in the collection of field data and the audit computation time. The total time required to complete the two audits was not significantly different. The FTA required more time to collect field data but made up for much of it by requiring less time for audit computation.

The collection of field data was more extensive for the FTA but not necessarily more complicated. The two audits required many similar field data; the most significant additional requirement for the FTA was more detailed information on wall areas, foundation spaces, and heating system characteristics. Excluding heating system efficiency measurements, auditors reported that collecting the additional data required approximately 50% more time at the site than the current procedure (for a crew of two, an average of 35 min compared with 20-25 min). This was not a large increase in labor time considering the travel time to and from the site. Weatherization agency personnel indicated that the average of 35 min required to collect FTA characteristics data decreased as they gained experience.

The time required to complete audit computations was considerably less for the FTA than for the standard (Retro-Tech) audit. The reported manual computation time for the standard audit averaged around 35 min per house. The time required to complete the FTA was essentially equal to the time required to enter the data into the computer program, an average of 10 to 15 min per house.

Measuring heating system efficiency increased the field data collection time. Heating system efficiency testing required approximately 15-20 min, on average, because it was done in late summer/early fall when most systems were not in regular operation. The measurements likely would have required only 5—10 min of extra data collection time if they had been made in winter when heating systems were operating regularly.

6. OCCUPANT AND HOUSE CHARACTERISTICS

Survey data were collected for each house on occupancy, house, and system characteristics before measurement of energy use began. These data were used to confirm that houses met requirements for inclusion in the test, and to determine the types of conservation measures that the FTA would have to address to apply to low-income houses in North Carolina. In addition, these data were used to characterize house construction, occupancy, space heating and cooling systems, and water heating systems. Analysis of the characteristics data is based on information received for 119 of the original 120 houses in the field test.

6.1 OCCUPANT CHARACTERISTICS

The occupancy distribution in the field test houses ranged from one to seven people (Fig. 6.1). Eighty-five percent of all houses had three or less occupants. The average occupancy was two. Houses with single occupants were the most common, representing 42% of the population.

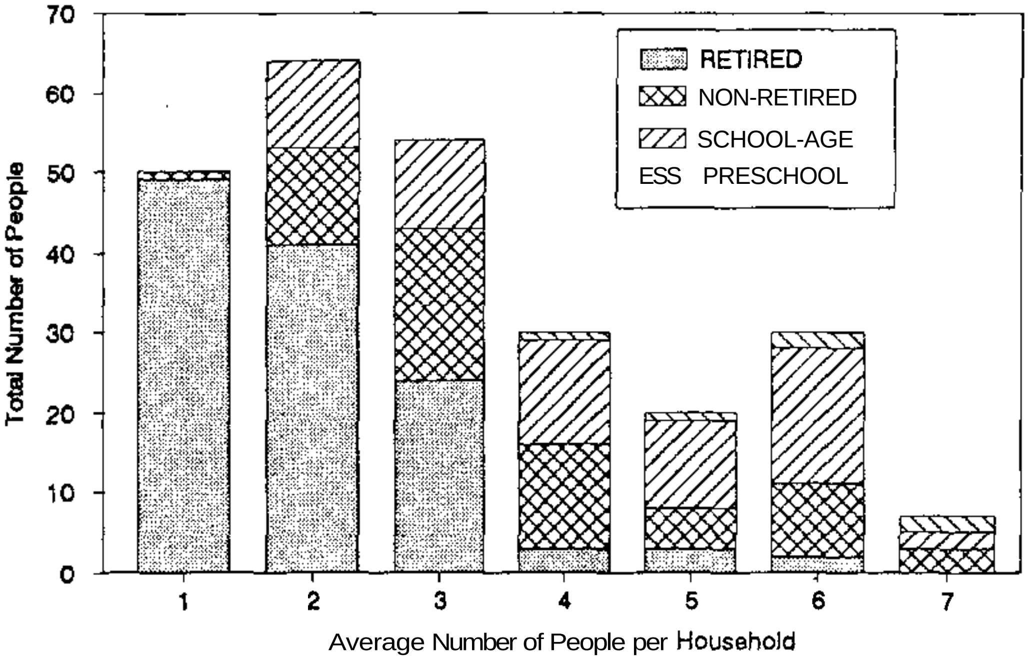
Adults represented 69% of the 242 reported occupants. Retired adults were the most common age category, representing 73% of all adult occupants. On the average, each house had one retired adult and a nonretired adult or a school-age child. Few houses had preschool-age children. The distribution of occupants by age group in each of the seven occupancy levels is shown in Fig. 6.2. Only 2% of all houses reporting one occupant housed a nonretired adult. Among the 32 houses reporting two occupants, at least one retired adult lived in 84% of the houses, and both occupants were retired in 44%. Of the households with more than two occupants, most were headed by nonretired adults and the percentage of school-age children within the household was higher. Many households with a retired adult also had one school-age child. However, 82% of all households with two or more children were headed by nonretired adults. Weekend and weekday occupancies were significantly different. Weekend occupancy averaged just over two people per house, while weekday occupancy averaged only 1.3. Seventy-one percent of all heads of households had lived in their present houses for more than 15 years. Duration of occupancies ranged between 0 and 80 years, with a mean of 23 years. Eighty-five percent of all houses were occupied by owners.

6.2 HOUSE CHARACTERISTICS

An average house participating in the field test was approximately 40 years old and was a single-level house built over a crawlspace. It had approximately 1150 ft^2 of living area and was heated with one or more fixed (nonportable, hard-piped) kerosene- or propane-fueled room space heaters approximately 13 years old. The house was cooled by a 9-year old window air conditioner averaging 13,000 Btu in size. The house had just over 2 in. of attic insulation (around R-7) and no wall, floor, or foundation insulation.

The distribution of house ages is shown in Fig. 6.3. Eighty percent of the houses were built between 1930 and 1980. House ages were reported to range from 5 to 99 years and

Fig. **6.1.** Occupancy histogram for the field test houses.



Hg. **6.2.** The number of people by age group for each occupancy leveL

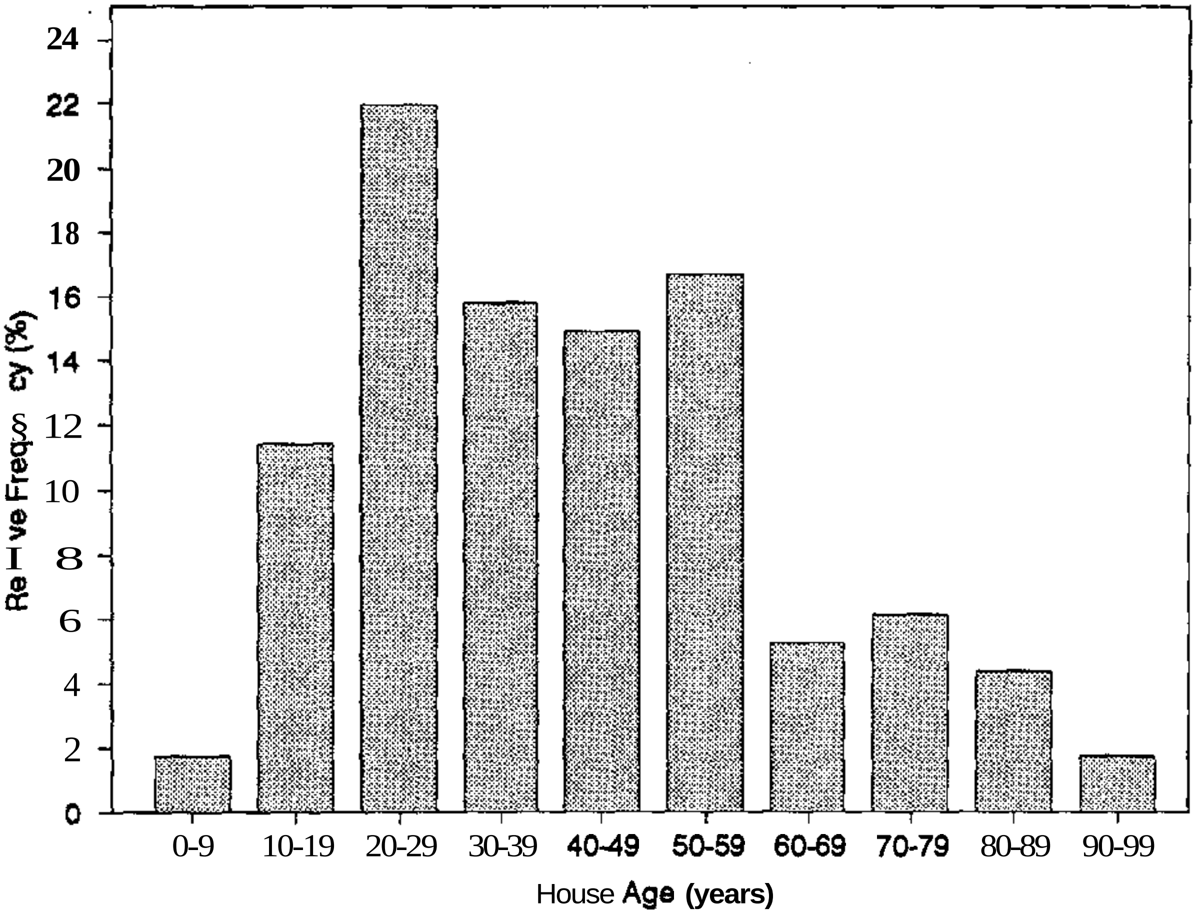


Fig. 6.3. Histogram of the house ages for the field test houses.

averaged 40 years. Ninety-three percent of all the houses were built before the 1973 oil embargo. Twelve percent were 70 or more years old, and only 4% were built within the last 15 years.

Ninety-two percent of the houses were single level (no basement and no finished attic space). Only one house had a basement. Seven percent had a second level of living space; most of these were finished attic spaces rather than separate second stories. No houses had more than two levels of living space. Houses were typically of frame construction built over a crawlspace with masonry walls. Only two houses were built on a concrete slab. The distribution of floor areas of the test houses is shown in Fig. 6.4. Floor areas ranged from around 600 to 2400 ft^2 and averaged 1144 ft^2. Eighty percent of the test houses were between 700 and 1400 ft^2 in size. Only *8%* were larger than 1600 ft^2.

Approximately two-thirds of all occupants closed off rooms during the heating season. Forty-two percent closed off one or more rooms; the number closed off ranged as high as six in one of the larger houses. Fig. 6.5 illustrates the percentages of total floor areas that were heated. The figure shows that approximately a third of all participants heated their entire houses. Only *5%* of the houses larger than 1200 ft^2 had their total floor area heated. Approximately 17% of all participants heated less than one-half of their houses.

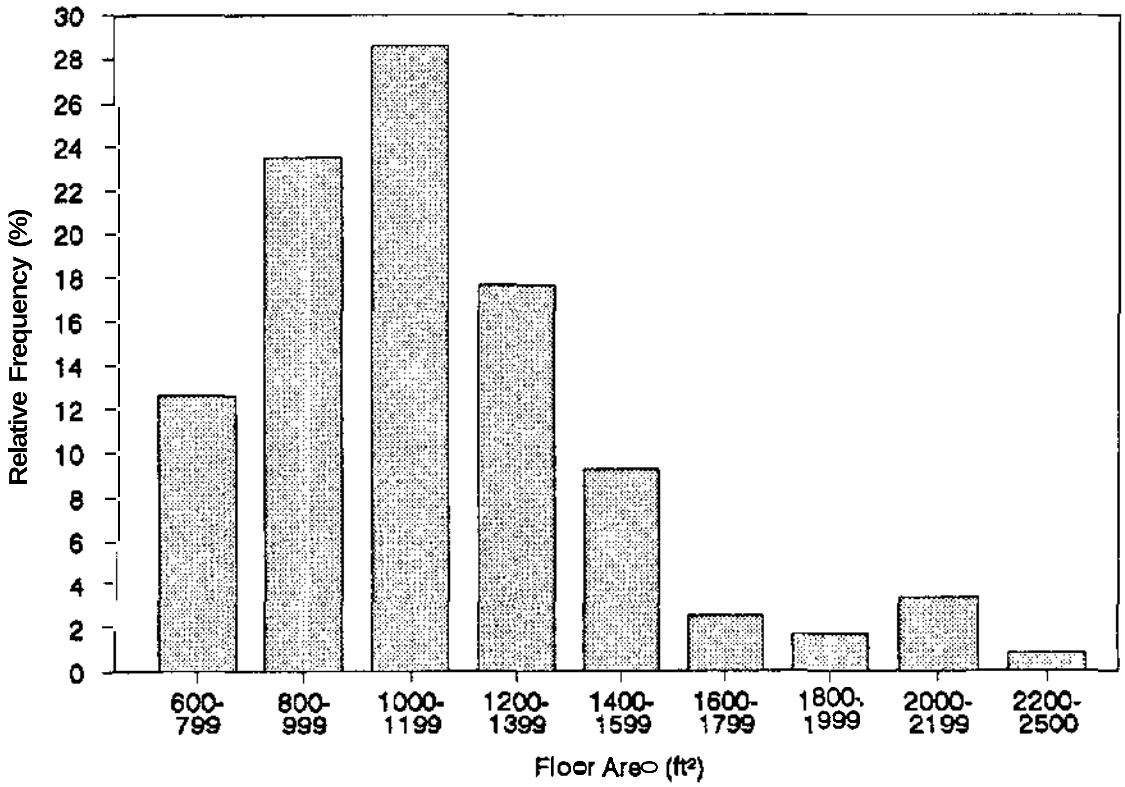


Fig. 6.4. Histogram of the floor areas for the field test houses.

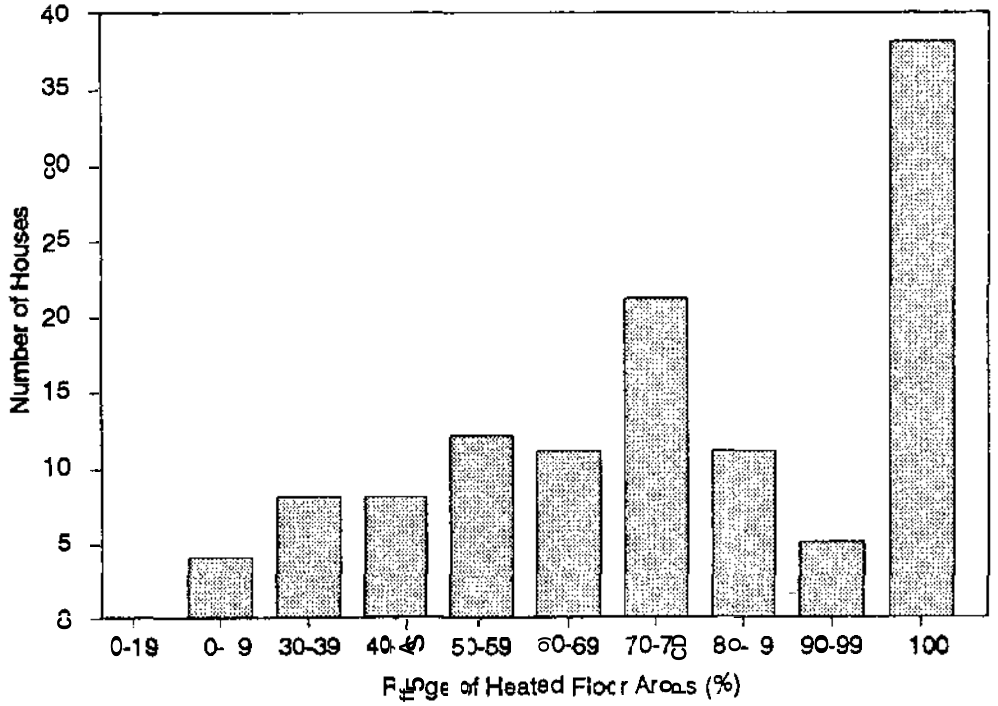


Fig. 6.5. Histogram of the percentage of heated floor area in the field test houses.

Four different fuels were used for primary space-heating systems: propane, natural gas, kerosene, and No. 2 oil. Propane and kerosene were the dominant fuels of primary space-heating systems, accounting for 45 and 42 systems each, respectively. Use of natural gas and No. 2 oil was split approximately evenly between the remaining 33 systems. Fixed space heaters were the main primary heating system used in the test houses, accounting for 76%. The remaining systems consisted of central furnaces (18%) and wall and floor furnaces (6%). Primary heating system capacities averaged 57,000 Btu/h, and total heating capacities averaged 65,500 Btu/h. Because fixed space heaters provided mostly localized heating, several houses had multiple heating systems. Eighty-two houses were reported to have single systems and 30 were reported to have 2 or more. Seven houses had three or more systems, and as many as five were identified in one house. Many of the heating systems were very old, an average age being 13 years. Although around 50% of all participants were reported to use some type of auxiliary heating system during the winter (primarily portable kerosene space heaters), less than 15% reported that those were used more than 20 h per week.

All houses were required to have a window air conditioner, as specified in the house selection criteria. Ninety-eight houses were reported to have one air conditioner and 21 were reported to have two. Air conditioner capacities ranged from 5,000 to 36,000 Btu/h. Of 102 units whose size was reported, 41% were between 8,000 and 10,500 Btu/h. Estimated ages of the air conditioners ranged from 1 to 25 years.

All water-heating systems were electric, as specified in the house selection criteria (except two which were propane fueled), and they typically were either 30- or 40-gal units. Eighty-five percent of these were located within heated living areas.

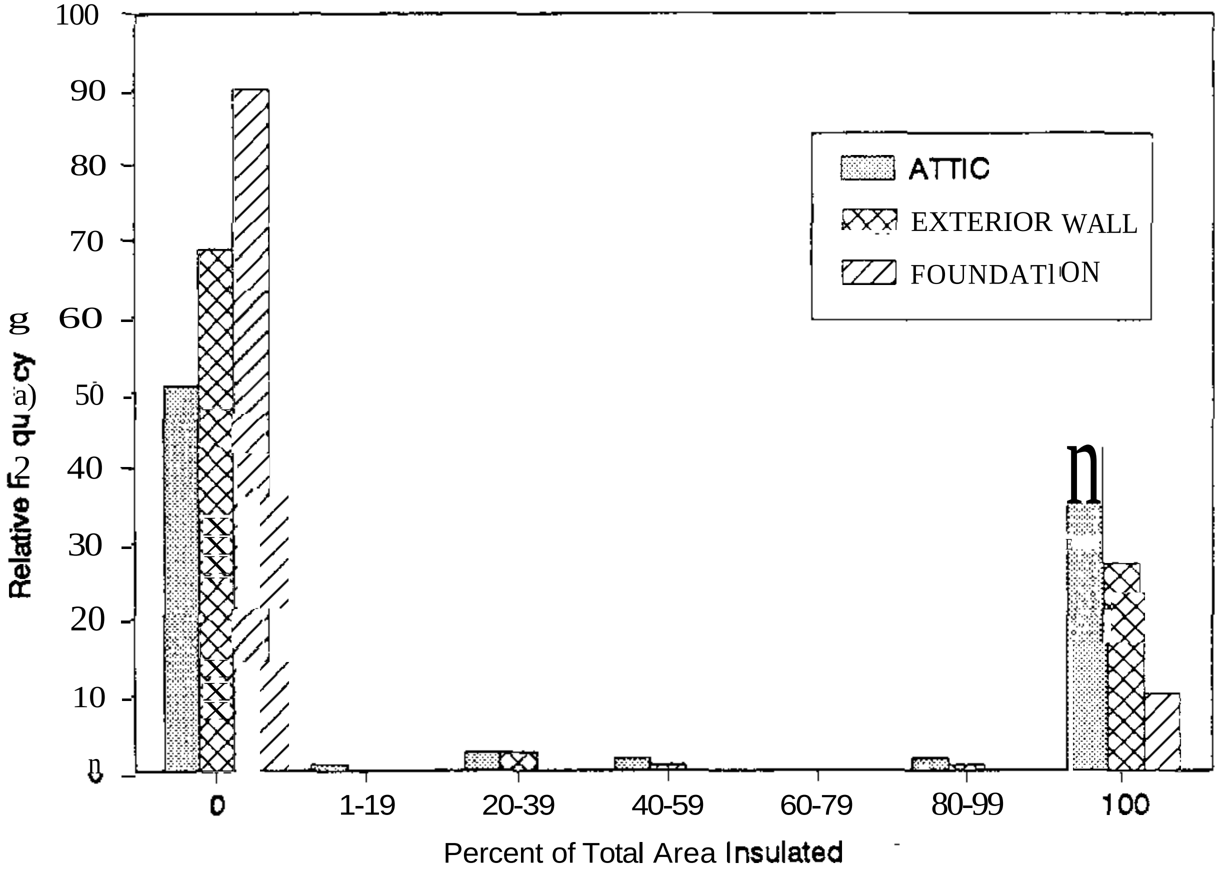
A summary of the appliances in the test houses is presented in Table 6.1. Ninety-four percent of participating houses had electric cooking ranges and ovens, and 6% had gas-fired stoves. Although 87% of the houses were reported as having washing machines, only 34% were reported as having dryers (electric). An unexpectedly large percentage of houses, 82%, were reported as having separate chest or upright freezers (not part of refrigerators). Upon checking, agency staff confirmed this result. Just over half of the houses (70) had microwave ovens; only one was reported as having a dishwasher.

The initial thermal conditions of the test houses are illustrated in Fig. 6.6. Approximately half of the houses had no attic insulation (around 60), 68% were reported as having no wall insulation, and most houses had no floor or crawlspace insulation.

Attic floor areas averaged 1103 ft^2, varying between 612 and 2160 ft^2. Only six attics had finished attic space. All others were typical unfinished constructions (pitched roof trusses with unfloored ceiling joists). Around half of the houses had uninsulated attics and around 45% had between 3 and 6.5 inches of insulation. As shown in Fig. 6.7, these insulation thicknesses provided R-values between R-10 and R-20. Blown cellulose, which was most common, has an R-value of around R-3.5/in., while blown fiberglass is around R-2.2/in. No house had attic insulation greater than R-19. In attics with some insulation, an average 92% of the attic floor space was insulated. Considering all houses with and without insulation, the average attic insulation thickness was only 2.2 in., representing an R-value of around 7 for blown cellulose. The average UA (the rate of heat loss per unit

Table 6.1. **Appliance** use and fuel types

Appliance	Number of houses	Number of houses using natural gas or propane	Number of houses using electricity
Cooking range	118	6	112
Conventional oven	118	6	112
Microwave	70	0	70
Clothes washer	104	0	104
Clothes dryer	41	0	41
Refrigerator/freezer	117	0	117
Separate freezer	97	0	97
Dishwasher	1	0	1



Rg. 6.6. The percentage of field test houses with specific percentages of insulation in attics, walls, and foundations at the start of the experiment.

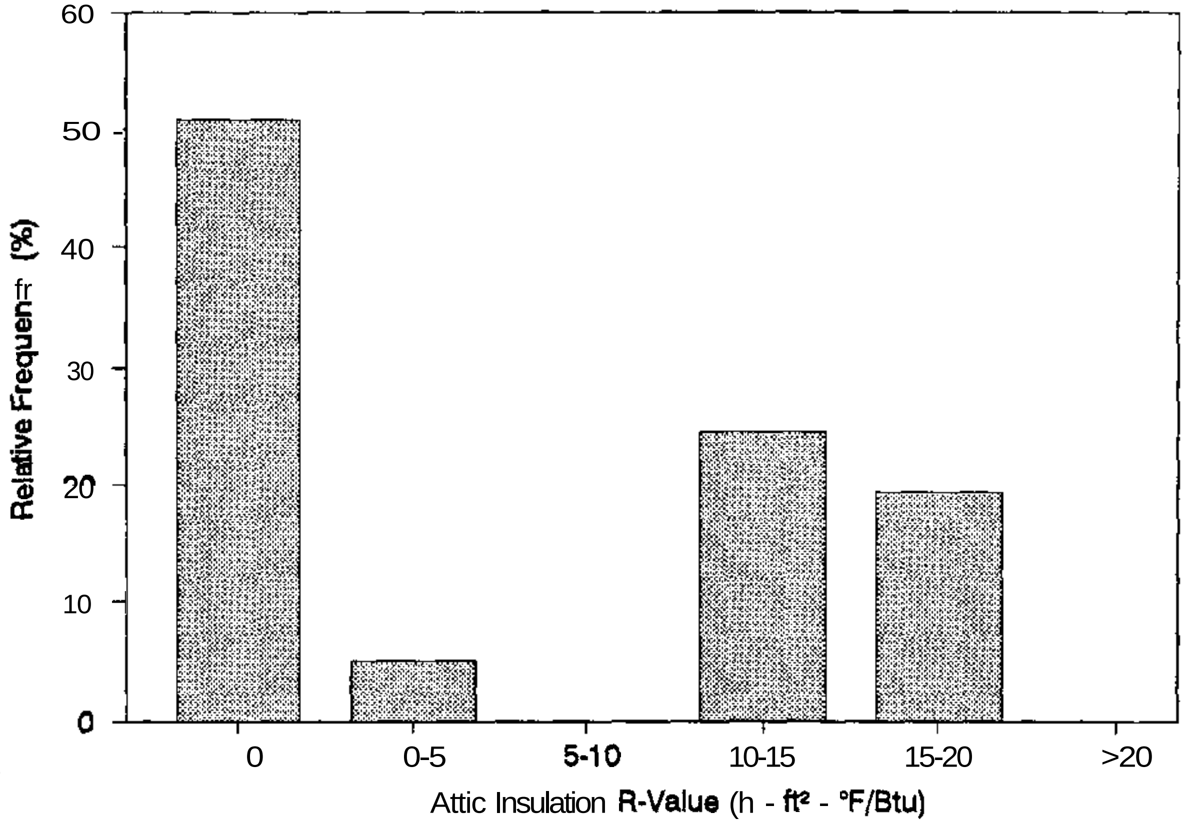


Fig. 6.7. Histogram of the amount of attic insulation (average R-value of the insulation only) present in the field test houses at the start of the experiment

of temperature difference) of the attics for all houses was 260 Btu/h • °F, which was approximately 2.5 times the 97 Btu/h • °F average for attics having some insulation (the UA includes consideration of air film coefficients and building boards).

All houses were of frame construction, except seven that were constructed of concrete blocks. Most frame houses were sided with wood, aluminum, and/or vinyl. Total exterior wall area per house ranged from 696 to 2164 ft^2 and averaged 1173 ft^2. The 37 houses with some reported wall insulation (including insulating building board) represented only 31% of the combined wall area of all houses. Considering only those houses with some wall insulation, 92% of their wall area was insulated. The distribution of wall R-values is shown in Fig. 6.8. The average R-value of the wall cavity insulation in the houses with wall insulation was approximately 9.1 °F • ft^2 • h/Btu. The average wall UA of these was 103 Btu/h • °F, while the average UA was 242 Btu/h • °F for the walls of all 119 houses.

Seven of the eight houses with existing floor insulation used R-11. The insulated floor area totaled only 6.5% of the combined floor area of all houses.

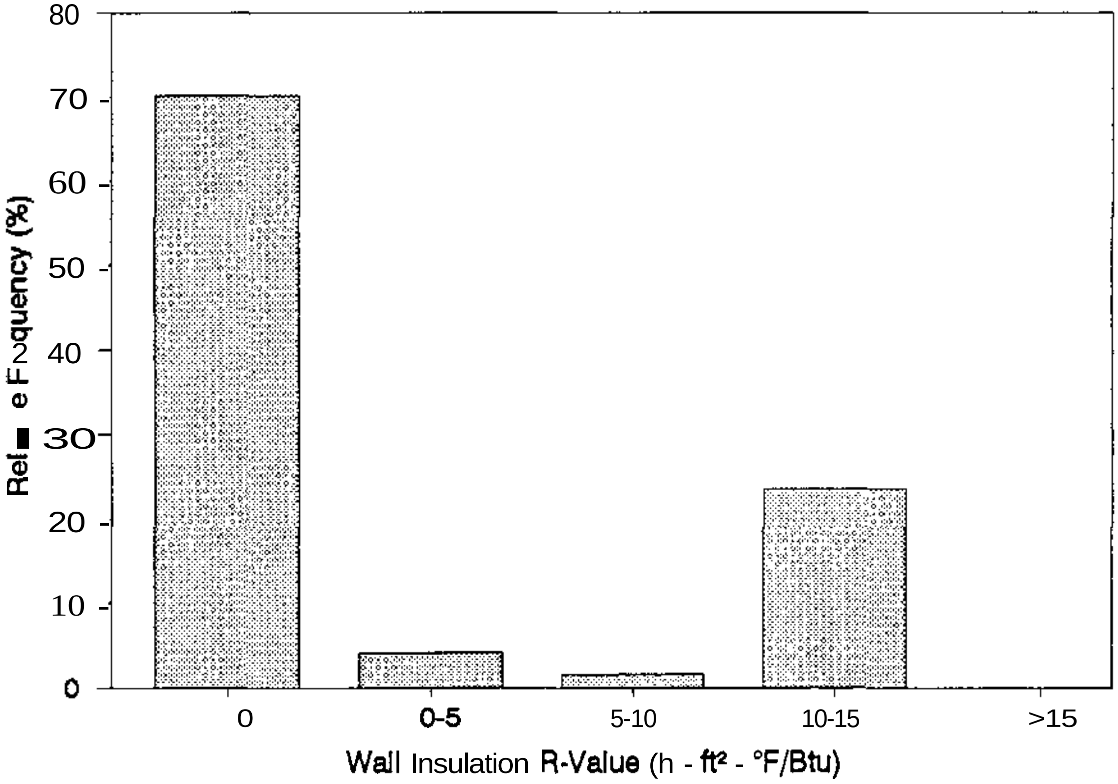


Fig. 6.8. Histogram of the amount of wall cavity insulation (average R-value of the insulation only) present in the field test houses at the start of the experiment.

Total window area for each house averaged 137 ft^2 and varied from 38 to 334 ft^2. The most common type of window system (used in 68% of the houses) was single-pane windows without storm windows. Seventy-four percent of all the windows were single pane without storm windows; 26% were single-pane windows with storm windows; and essentially none were double-pane windows. Approximately 90% of all windows were double-hung systems.

7. ENERGY CONSERVATION MEASURES

7.1 FIELD TEST AUDIT GROUP

Weatherization measures for the FTA group are listed in Table 7.1. The FTA recommended the following 9 of the 17 measures it considered (the two different levels of attic insulation, All and A30, and kneewall insulation are considered as separate measures):

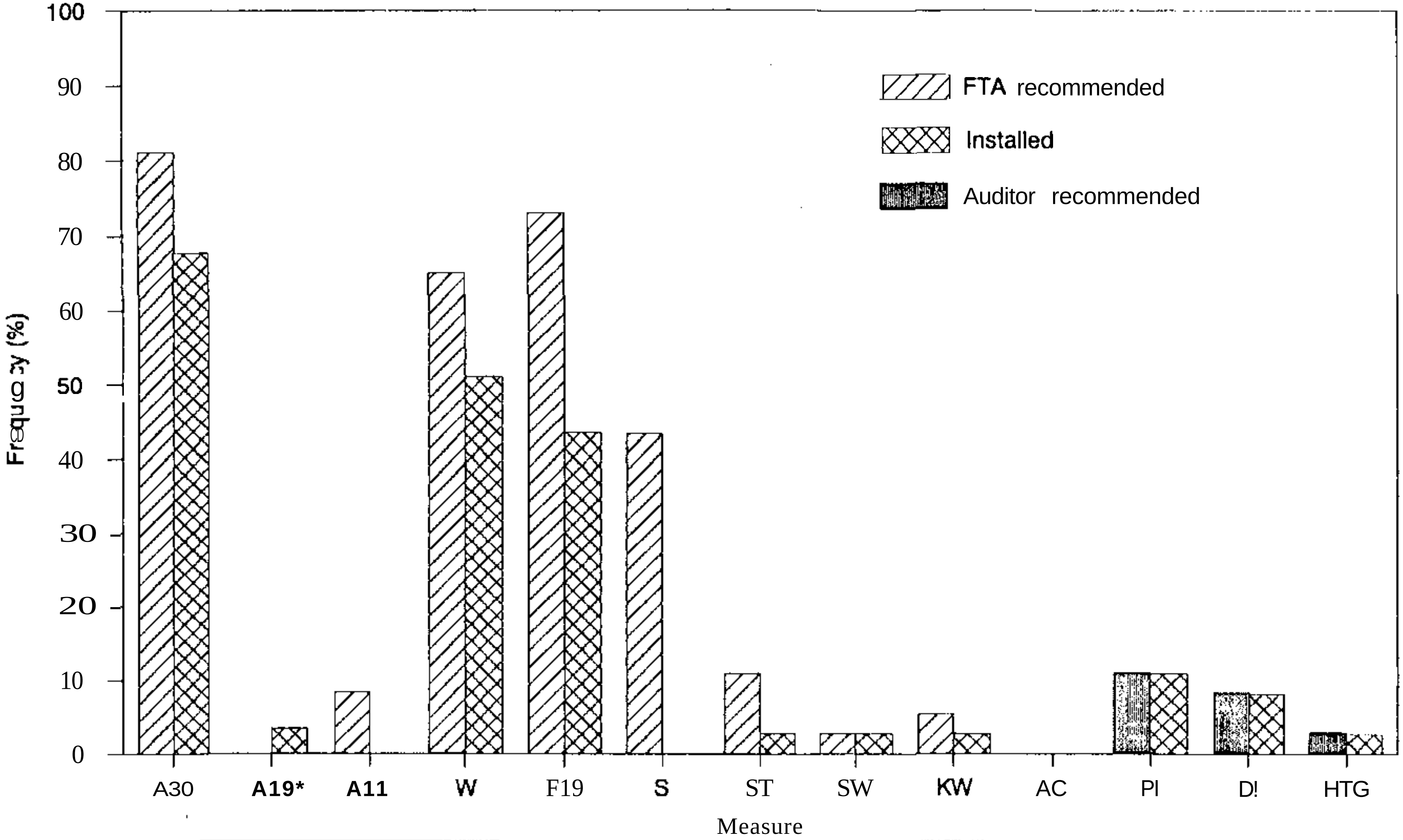
Code	Measure	Code	Measure
A30	R-30 attic insulation	All	R-ll attic insulation
W	Wall insulation	F19	R-19 floor insulation
KW	R-11 kneewall insulation	S	Sill insulation
ST	"Smart" thermostat	AC	Replacement air conditioner
SW	Storm windows		

The frequencies at which measures were recommended and installed in the FTA group are shown in Fig. 7.1. Because three houses in this group dropped out of the test before being weatherized (houses 10, 22, and 69), group statistics are based on 37 weatherized houses.

Attic, wall, and floor insulation dominated the list of recommended measures; they were recommended for between 65 and 89% of the houses. The most prominent measure, R-30 attic insulation, was recommended for 81% of the houses in this group. Of the remaining 19%, or seven houses, four had existing R-19 insulation and three had R-ll. Ninety-one percent of the attic insulation recommendations were for R-30, and only *9%* were for R-ll. All uninsulated attics were recommended for R-30. For six houses that already had R-ll in their attics, an additional R-30 was recommended for three, R-ll for two, and no additional insulation for one. No houses were recommended for R-19 because this level of attic insulation was not considered in the FTA (R-19 was accidentally installed instead of the recommended R-30 in house 62). Attic kneewall insulation was recommended for 10% of the houses.

Floor insulation was the second most recommended measure, recommended for 73% of the houses. Eight percent already had an insulated floor. Wall insulation was also a frequent recommendation, recommended for 65% of the houses. Thirty percent already had wall insulation and the remaining 5% (two houses) had block/masonry walls that the audit did not consider for this measure because of their inaccessibility. The FTA did not recommend any other measures for more than 11% of the houses.

The frequency of recommendation is considerably different from the frequency of installation for many measures in Figure 7.1. The primary reason differences occurred for



Codes Insulation: A11-Attic R11, A19-Attic R19, A30-Attic R30, DI-Duct, F11-Floor R11, F19-Floor R19, KW-Kneewall R11, PI-Pipe/water heater, S-Sill R19, W-Wall (3.5")

Other: AC-Air conditioner, ST-Smart thermostat, SW-Storm windows, HTG-Heating system

***A19 installed for A30 recommendation.**

Fig. 7.1. Measures recommended and installed in the Field Test Audit houses based on all houses in the group (n=37).

attic, wall, floor, and kneewall insulation was inaccessibility to the space. Poor electrical wiring in one house restricted the installation of attic insulation. In another house where R-11 attic insulation was present, the R-30 attic insulation audit recommendation was interpreted to mean that the attic should be filled to an R-30 level. As a result, R-19 was installed rather than R-30.[4] Sill insulation was never installed because floor insulation was also recommended and installed in every house recommended for this measure. Floor insulation normally covers the sill area, except perhaps where trusses are present.[5]

A "smart" thermostat was installed in only one of the four houses where it was recommended. Occupants objected to this measure because it was perceived to be complicated, and agencies had difficulty identifying and installing appropriate units. The pipe/water heater (PI) and duct insulation (DI) measures shown in Fig. 7.1 were installed as part of the total weatherization but were not evaluated in the computerized FTA.

The FTA did not recommend any vent damper, intermittent ignition device, flame retention head burner, or furnace replacement retrofits. Space heaters dominated the heating system types in the test, and they were not considered to be compatible with the first three of these measures. No radiant barriers or awnings (for window shading) were recommended.

A replacement air conditioner was recommended for one house (3%), but the house dropped out of the test before it was weatherized. As a result, no air conditioner replacements are reflected in the results presented in Table 7.1. Storm windows essentially were not recommended by the FTA, even for single-pane windows. A storm window was recommended for only one window on one house. The window did not receive a storm window as part of the weatherization, however, because of its unusually large size. Storm windows were installed on house 40 because of the poor condition of the windows, but not because they were recommended by the audit. One unvented space heater was replaced in this group because it was introducing an unusually large amount of pollutants into the living space.

Installation frequencies based on the number of houses that could actually have the measures installed are quite different from frequencies based on the entire sample. This distribution is shown in Fig. 7.2. The audit resulted in the installation of attic (both R-30 and R-19), wall, and floor insulation for between 84 and 100% of all houses that could receive these measures. Although only one smart thermostat was installed, the audit recommended them for 4 of the 7 houses (57%) that could receive them (only houses with central heating systems were considered compatible with this measure). Kneewall insulation was installed in the only house that could accommodate it. Hot water pipe insulation, water heater wraps, and heating system duct insulation were installed in every house where those systems were located outside the conditioned space. These measures were installed as a general practice and were not evaluated by the FTA.

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[4] It is possible that the audit would have recommended R-19 for this attic had it been an option in the particular audit version available at the time.

[5] The audit has been changed since this test to account for this duplication,

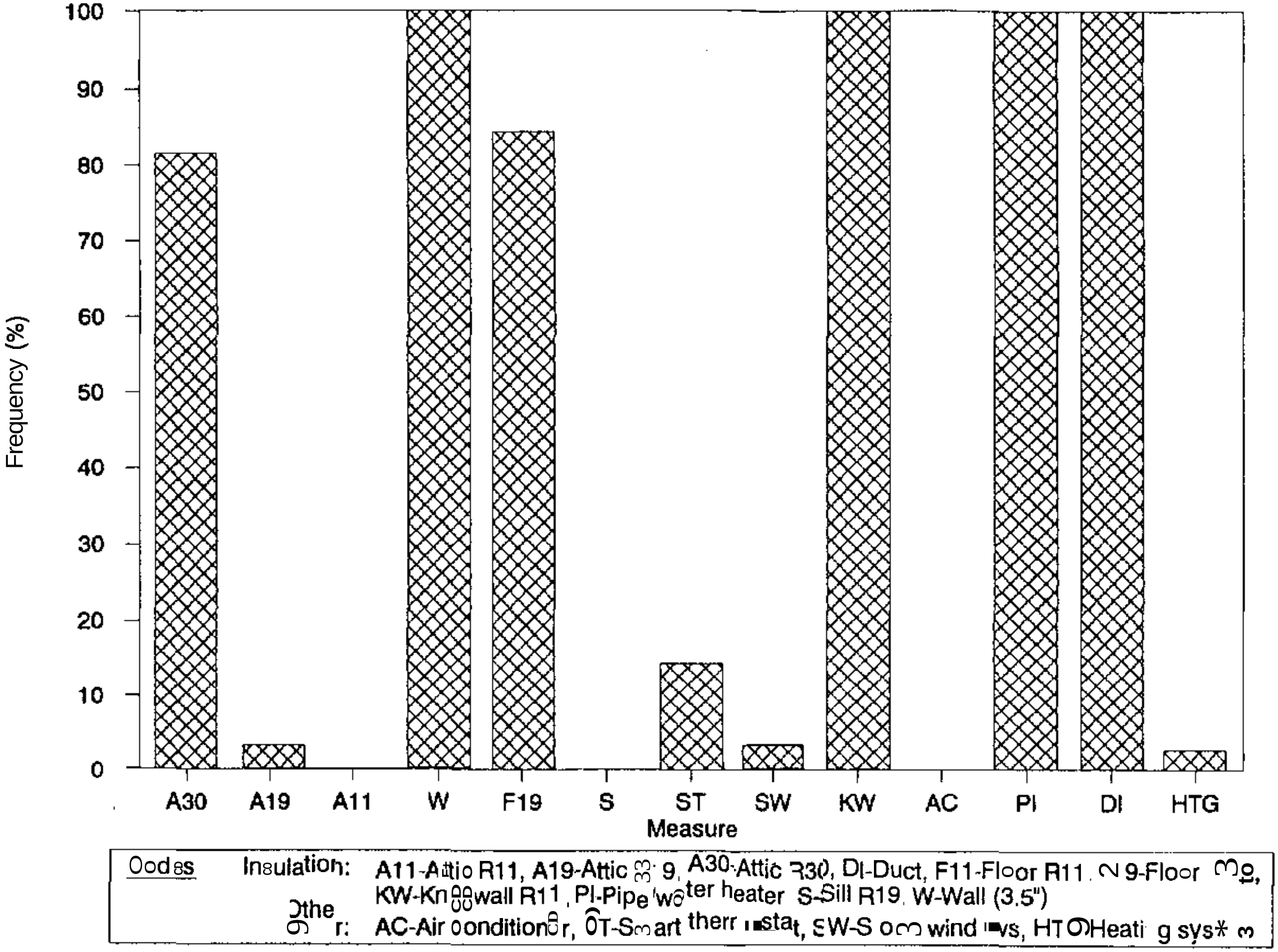


Fig. 7.9. Measures installed in the Field Test Audit houses based on the number of houses that should [illegible] installed.

Table 7.1. **Summary of the energy conservation measures installed in the Field Test Audit (FTA) group**

House	Existing insulation	FTA-recommended measures installed[a]	FTA-recommended measures not installed
2	A11,W,F11		All
4	All	A30,F19,DI	W
9	W	A30,F19	ST
10	Not weatherized		
18		A30,W	F19,S
21		A30,F19,W,DI	
22	Not weatherized		
26	W	A30	S
27	W	F19	A30,KW
30	A11,W,F11		All
36	A19	W,KW	F19,S,SW
37		A30,F19,W	
40		SW	A30,W,F19
46		F19,W,PI	A30
52		A30,F19,PI	W
58	W	A30,F19,S,PI	
61		A30,W	F19,S
62	A11,W	A19	A30,F19
67		A30	F19
68		A30,F19,W	
69	Not weatherized		
72	A19,W	F19,S	
73		A30,W	F19,S
79		A30	
85		A30,F19,W,PI,DI	S,ST
94		A30,W	F19,S
95	Bad attic wiring		A30,W,F19,S
102		A30,W	S
103		A30,W	S
107	A19,F11	W	
110	A19,W	All	F19,S,ST
111	All	A30,F19,W	
113	W	A30,F19	
118	W	A30,F19	

Table 7.1. (continued)

House	Existing insulation	FTA-recommended measures installed	FTA-recommended measures not installed
127		A30,F19,W	
128		A30,W	S
137		A30,F19,W	S
138		A30,W	
140		A30,W	F19,S
145	All		W,S,ST

Insulation codes:	A11=Attic R-11	A19=Attic R-19	A30=Attic R-30
	DI=Duct	F11=Floor R-11	F19=Floor R-19
	KW=Kneewall R-11	PI=Pipe/water heater	S=Sill R-19
	W-Wall (3.5 in.)		

Other codes:
AC=air conditioner
ST=Smart thermostat
SW=Storm window

[a]PI and DI recommended outside FTA. A19 installed in place of A30 in house 62.

Note: All houses received blower-door directed air sealing except 10, 22, and 69, which dropped out of the test early.

7.2 STANDARD WEATHERIZATION "RETRO-TECH" GROUP

Seven measures were installed in the standard weatherization group: attic insulation (All, A19, and A30), floor insulation (F11 and F19), storm windows, hot water pipe/water heater insulation, heating system duct insulation, underpinning, and air sealing and caulking. The measures installed in this group are summarized in Table 7.2 by house.

The frequencies at which measures were installed in the standard houses are illustrated in Fig. 7.3. Attic insulation was added to 27 of the 40 houses (68%) in the test group to bring insulation levels to approximately R-30. Of that 27 houses, R-30 was added to 24, R-19 to 1, and R-11 to 2 houses. Thirteen houses, or 33%, received floor insulation; R-19 was installed in seven of those and R-11 in six. Storm windows were installed on 34 houses (85%), and one house had them when the test started. Four houses (10%) received pipe/water heater insulation, one received duct insulation, and two received underpinning. Air sealing and caulking, not reflected in Fig. 7.3, was performed on all houses.

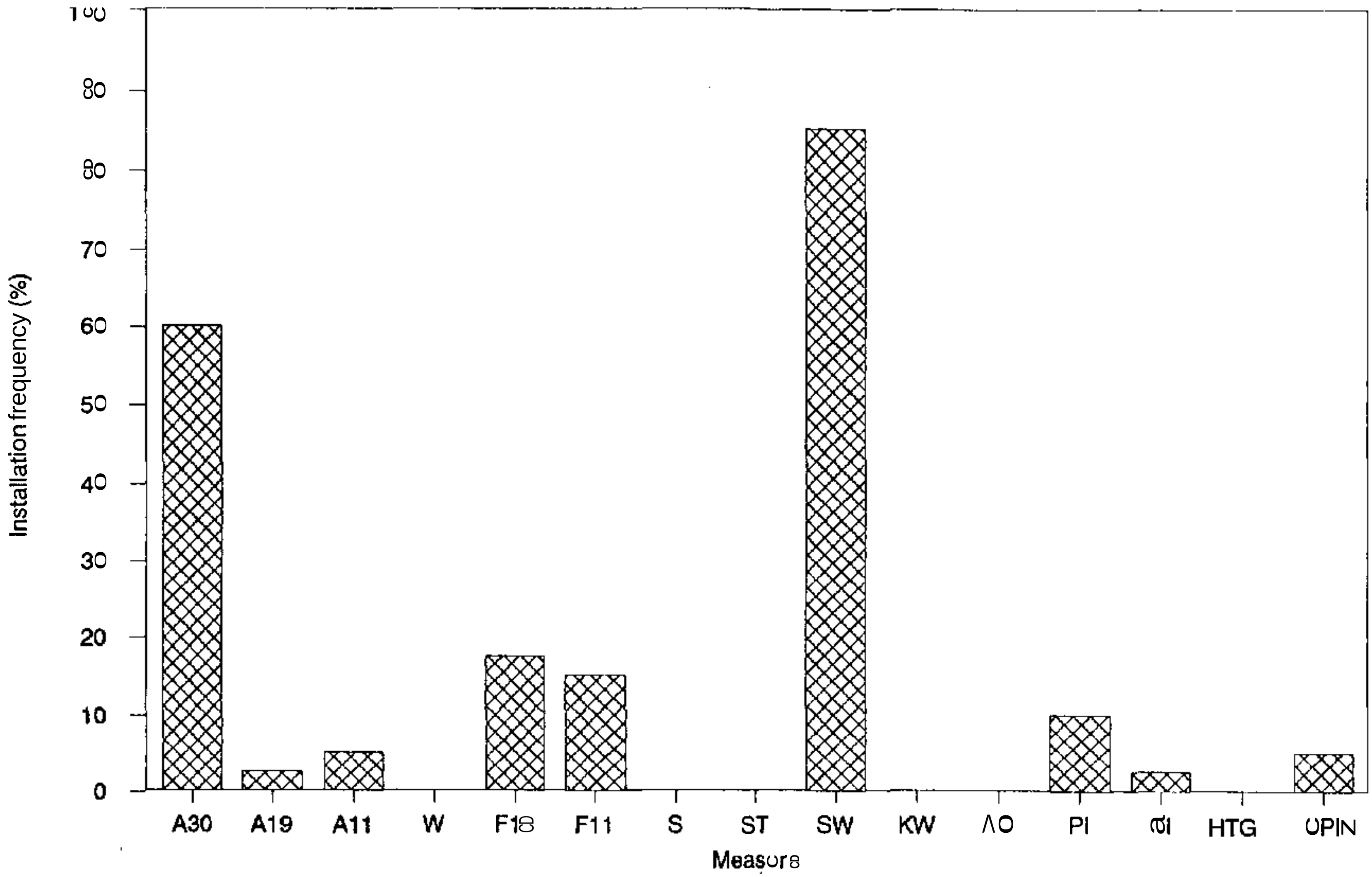
Table **7.2.** Summary of the energy conservation measures installed in the standard group

House	Measures installed	House	Measures installed
3	A30,F19,SW	88	A30,F11,SW,PI
5	A30,SW	90	A30,F11,SW
6	SW	91	A30,SW
7	F19,SW	93	A30,SW
8	A30,F19	96	SW
13	A30,SW	97	A19,F11,SW,PI
15	A30,F19,SW	99	A30,F11,SW,PI
20	A30,F19,SW	109	A30,SW
28	A30	112	
29	A30,SW	114	SW
31	A30,SW	115	A30,SW
32	F19,SW	116	A30,UPIN,SW
33	F19,SW	117	SW
59	A11,F11,SW	120	
65	A30,SW	122	UPIN,SW
77	A11,SW	129	SW
78	A30,SW	135	SW
81	A30,F11,PI,DI	141	A30,SW
82	A30,SW	143	SW
87	A30,SW	144	A30

Insulation codes:
A11-Attic R-11
A19-Attic R-19
A30-Attic R-30
DI-Duct
F11-Floor R-11
F19-Floor R-19
KW-Kneewall R-11
PI-Pipe/water heater
S-Sill R-19
W-Wall (3.5 in.)

Other codes:
AC-Air conditioner
SW-Stormwindow
ST-Smart thermostat
UPIN-Underpinning

Note: All houses received standard air sealing, weatherstripping, and caulking.



Codes Insulation: A11-Attic R11, A19-Attic R19, A30 Attic R30, DI-Duct, F11-Floor R11, F19-Floor R19, KW-Kneewall R11, PI-Pipe/water heater, S-Sill R19, W-Wall (3.5"

Other: AC-Air conditioner, ST-Smart thermostat, SW-Storm windows, HTG-Heating system UPIN-Underpinning

Fig. 7.3. Measures installed in the study group.

There was considerable difference between the measures installed by standard weatherizations at site C and those installed at the other two sites. The difference is most significant for floor insulation, which was not installed in any house at site C but which went into 7 houses and 6 houses at the other two test sites (representing at least 42% of the houses at those sites). In addition, approximately half as many standard group houses received R-30 attic insulation at site C as at the other two sites. The numbers of storm windows installed at all test sites were comparable. The major differences in attic and floor insulation installations that occurred could easily result in much lower energy savings and weatherization costs for standard weatherizations at site C compared with other sites and with FTA weatherizations.

73 COMPARISONS OF MEASURES INSTALLED BY THE FIELD TEST AUDIT AND BY THE STANDARD "RETRO-TECH" AUDIT

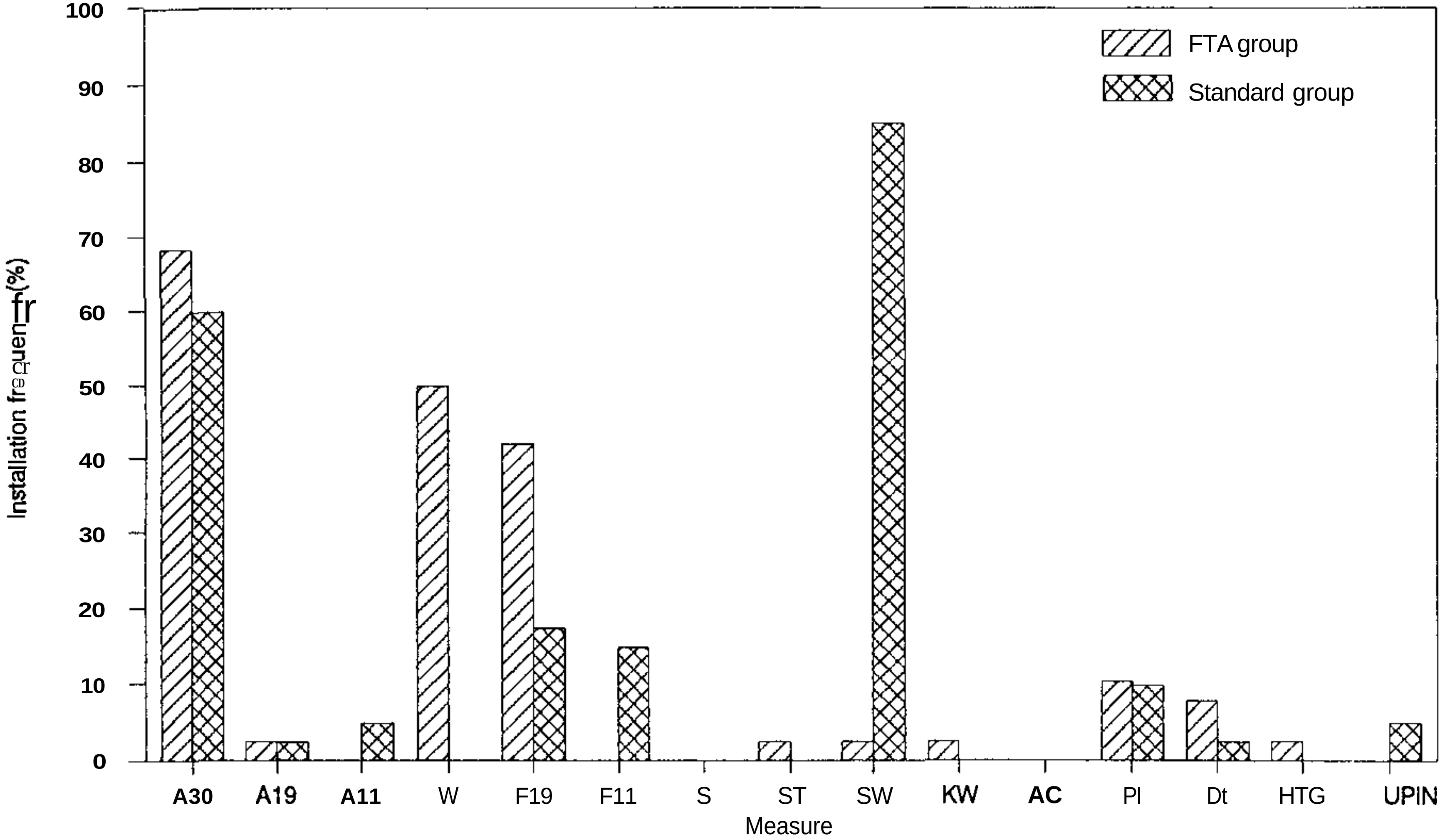
The two audits resulted in similar installation frequencies for some measures and significantly different frequencies for others. Measure installations in the two audit groups are compared in Fig. 7.4.

Although the two audits recommended attic insulation using two completely different approaches (the FTA evaluated two distinct attic insulation levels, while the standard audit generally added attic insulation until an R-30 level was achieved in every house), the installation frequency of this measure was similar, based on all houses in each test group. The installation frequency also was similar for floor insulation, although standard weatherizations installed both R-11 and R-19 floor insulation rather than just R-19 as in the FTA houses.

The major differences between measures installed were due primarily to two factors: (1) the FTA often installed wall insulation, which was not an option in the standard audit; and (2) the FTA almost never installed storm windows (rarely found to be cost-effective). Wall insulation went into 65% of the FTA houses and none of the standard houses. The audits installed storm windows for 85% of the houses in the standard group and only 3% (one house) for the FTA group. Two other FTA measures were not available in the standard audit: the FTA installed kneewall insulation in the only house that had accessible attic kneewalls, and one programmable thermostat.

Sill insulation and replacement air conditioners were not installed in either weatherization group. They were not installed in the standard group because those measures were not options; they were not installed in the FTA group because they were not cost-effective. The high first cost of replacing air conditioners produced low BCRs for that measure. For sill insulation, a cost-effective payback was always negated by the higher-priority floor insulation measure. Pipe insulation and water heater wraps were installed in similar quantities in both weatherization groups. Duct insulation was installed more often in FTA houses than in the standard group.

Underpinning was installed for two houses in the standard group and for none in the FTA group because it was not an option. For safety reasons, one heating system replacement occurred in the FTA group.



Codes Insulation: A11-Attic R11, A19-Attic R19, A30-Attic R30, Dl-Duct, F11-Floor R11, F19-Floor R19, KW-Kneewall R11, Pl-Pipe/water heater, S-Sill R19, W-Wall (3.5")

Other: AC-Air conditioner, ST-Smart thermostat, SW-Storm windows, HTG-Heating system UPIN-Underpinning

Fig. 7.4. Comparison of measures installed in the Field Test audit and standard groups.

& AIR SEALING RESULTS

8.1 PRE- AND POST-WEATHERIZATION AIR LEAKAGE RATES

Pre- and post-weatherization air leakage measurements are reported in Table 8.1, along with air leakage changes for each test house by group. Associated statistics for each group are included at the bottom of this table. Post-weatherization measurements were not completed in the control group at two sites. As a result, statistics associated with the control group represent only one of the three test sites (Site B). Data are not reported for eight additional houses (one in the control group, four in the FTA group, and three in the standard group) because both pre- and post-weatherization air leakage measurements were not available. Those data are unavailable because the participants dropped out of the test. The analyzed data set represents 12 houses in the control group (where no air sealing was performed), 36 in the FTA group, and 37 in the standard group.

Air leakage rate corresponds to the rate of air flow into the house when it is depressurized to 50 Pa (0.20 in. H_2O) below the ambient pressure. Measurements were made by depressurizing the house with a blower door and following a procedure similar to that specified by the American Society for Testing and Materials (ASTM 1981). Six air leakage measurements were made in most houses at depressurizations between 15 and 70 Pa. Data from these measurements were fit to a power curve and, from this, the air leakage rate at 50 Pa depressurization was determined. The leakage in some houses was so large at the start that it was not always possible to achieve depressurizations as high as 50 Pa and obtain the six measurements with the blower door.

Pre-weatherization air leakage rates ranged from 1419 cfm50 to 11475 cfm50. Average leakage rates for each group were similar, ranging from 4091 to 4400 cfm50, a maximum difference of less than 8%. Group averages were not statistically different at a 95% confidence level. The distributions of pre-weatherization leakage rates by group are shown in Fig. 8.1. Eighty-six percent of all houses had pre-weatherization air leakage rates between 1500 and 6000 cfm50; 13% (14 houses) had rates greater than 6000 cfm50; and only 1% (1 house) had a pre-weatherization leakage rate less than 1500cfm50. The control group had five of these higher-leakage houses, the FTA group had two, and the standard group had seven.

Average reductions for each group were considerably different. The average reduction was 89 cfm50 for the control group (based on one test site only), 1710 cfm50 for the FTA group, and 716 cfm50 for the standard group. The air leakage rate of most houses in the control group changed very little between the pre- and post-weatherization measurements. Approximately two-thirds of the houses measured in this group (six) had air leakage rate changes less than 350 cfm50; 17% (two) had changes between 900 and 1150 cfm50; and the remaining 17% (two) had large changes between −3468 and 2300 cfm50. The causes of the large changes are unknown. It is likely that either a major leakage problem with the shell occurred between these measurements, or a major leakage path that was sealed during one measurement was overlooked during the other (such as a chimney damper). The average reduction of only 89 cfm50 for the control group represents a 2% decrease in the average air leakage rate for these houses over a 1-year period. This suggests that

Table 8.1. Pre- and post-weatherization (wx) air leakage measurements and air leakage reductions by group

Control group				Field Test Audit group				Standard group			
Air leakage rate (cfm50)				Air leakage rate (cfm50)				Air leakage rate (cfm50)			
House	Pre-wx[a]	Post-wx	Change	House	Pre-wx	Post-wx	Change	House	Pre-wx	Post-wx	Change
12	3264			2	4736	1871	2865	3	3714	3535	179
14	3571			4	3764	2767	997	5	2428	1835	593
16	3849			9	3944	2659	1285	6	7418	2046	5372
19	3471			18	4085	2808	1277	7	3234	3204	30
23	2980			21	4053	3745	308	8	6027	1573	4454
24	4544			26	4792	1921	2871	13	7066	5477	1589
35	2707			27	5201	4511	690	15	3840	3733	107
38	3788			30	5045	4005	1040	20	4129	3678	451
39	5557			36	4585	2776	1809	28	3454	1874	1580
41	3502			37	4539	2909	1630	29	2615	3017	-402
42	3076			40	4572	1548	3024	31	2545	1605	940
43	2575			46	4737	3080	1657	32	3684	3202	482
45	2944			52	4343	2066	2277	33	2944	3135	-191
51	2475	2481	-6	58	5245	1803	3442	59	1815	1453	362
57	2404	2201	203	61	5257	4197	1060	65	2410	2074	336
60	2246	2053	193	62	1556	1501	55	77	2708	2191	517
64	5453	5779	-326	67	4235	2997	1238	78	4211	3829	382
66	4019	4200	-181	68	3650	2426	1224	82	3527	2808	719
70	3341	3416	-75	72	3526	2025	1501	87	3029	2115	914
74	11475	9148	2327	73	3665	3049	616	88	2116	2059	57
80	4901	4828	73	79	3524	2060	1464	90	4713	4133	580
84	6581	10049	-3468	85	4188	2385	1803	91	8762	5702	3060
86	3456	2536	920	94	5053	2889	2164	93	4327	4057	270
92	5529	5242	287	95	8791	4981	3810	96	2785	2349	436
98	6282	5160	1122	102	3961	2330	1631	97	4609	4296	313
101	4139			103	4808	2773	2035	99	2475	1933	542
104	10451			107	3223	2562	661	109	5129	3148	1981
105	4913			110	2396	2449	-53	112	5309	4829	480
106	4518			111	4606	2562	2044	114	2538	2562	276
119	3667			113	2064	1765	299	115	3443	2502	941
123	4085			118	5382	3235	2147	116	8863	6817	2046
124	1871			128	4988	2330	2658	117	1830	1924	-94
126	1971			137	5244	2562	2682	120	3029	2069	960
130	4774			138	2469	1765	704	122	6848	9790	-2942
131	3326			140	10457	3849	6608	129	6797	6817	-20
132	10594			145	1419	1381	38	135	4382	4246	136

Table 8.1. (continued)

Control group				Field Test audit group				Standard group			
Air leakage rate (cfm 50)				Air leakage rate (cfm 50)				Air leakage rate (cfm 50)			
House	Pre-wx	Post-wx	Change	House	Pre-wx	Post-wx	Change	House	Pre-wx	Post-wx	Change
134	4692							143	2297	3235	-938
136	2508										
Average	4355	4758	89[b]		4400	2690	1710		4091	3374	716
Observations	38	12	12		36	36	36		37	37	37
Median	3728		133		4441		1566		3527		451

[a]wx = weatherization.

[b]Change based on difference between pre- and post-weatherization averages for houses 51 through 98 only.

average air leakage rates associated with changes not related to weatherization were near constant between the pre- and post-weatherization air leakage measurements. As a result, almost all of the change measured in the treatment groups should be associated with weatherization-related work. The small average air leakage reduction of the control group is not statistically different from zero at a 95% confidence level.

The average reduction of the FTA group is statistically different from both other groups at a 95% confidence level. The average standard group reduction is statistically different from the control group average at an 85% confidence level. The distributions of air leakage reductions for all groups are shown in Fig. 8.2. Air leakage reductions ranged from -3468 cfm50 in the control group to 6608 cfm50 in the FTA group. Fifty-one percent of the houses in the standard group had air leakage reductions between −500 and 500 cfm50, indicating that standard air sealing techniques were providing only minimal benefits in one of every two houses sealed. Fifty-seven percent (21 houses) had reductions less than 500 cfm50. In contrast, most houses in the FTA group had air leakage reductions between 500 and 2500 cfm50. Only 14% of this group (5 houses) had reductions less than 500 cfm50. This indicates that air sealing using standard sealing techniques was less effective in many more houses than the blower-door directed air sealing procedure. The air leakage reductions achieved in the treatment groups are shown side-by-side in ascending order in Fig. 8.3. This figure shows the clear distinction between the reductions accomplished in these groups.

When average reductions are related to their respective group average pre-weatherization air leakage rates and adjusted for the 2% reduction in the control group, reductions of 37% for the FTA group and 18% for the standard group result. Comparison based on medians also indicates that the FTA group reductions were more than double the reductions achieved in the standard group.

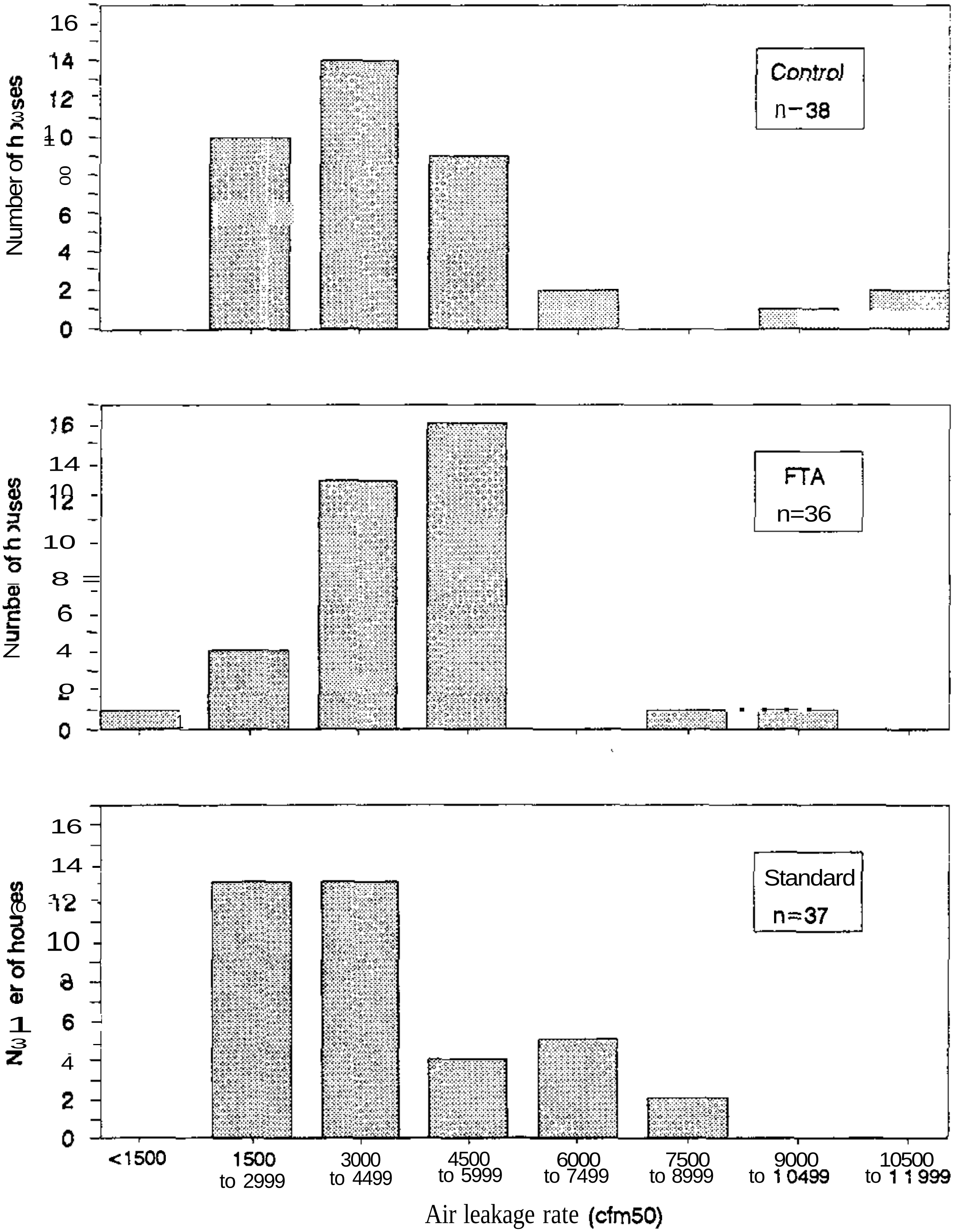


Fig. 8.1. Distribution of pre-weatherization air leakage rates by group

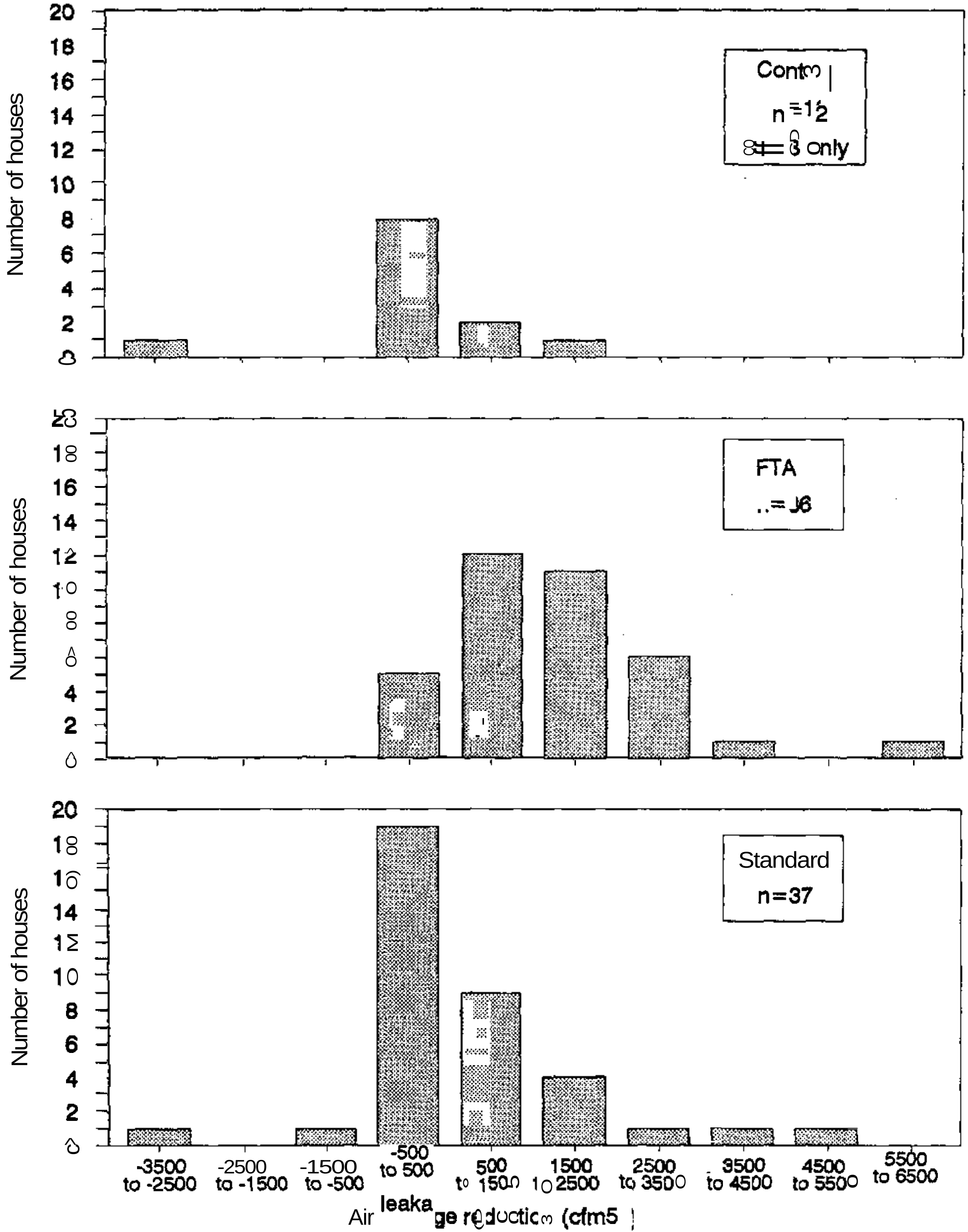


Fig. 8.2. Distribution of air leakage reductions based on pre- and post-weatherization measurements by group.

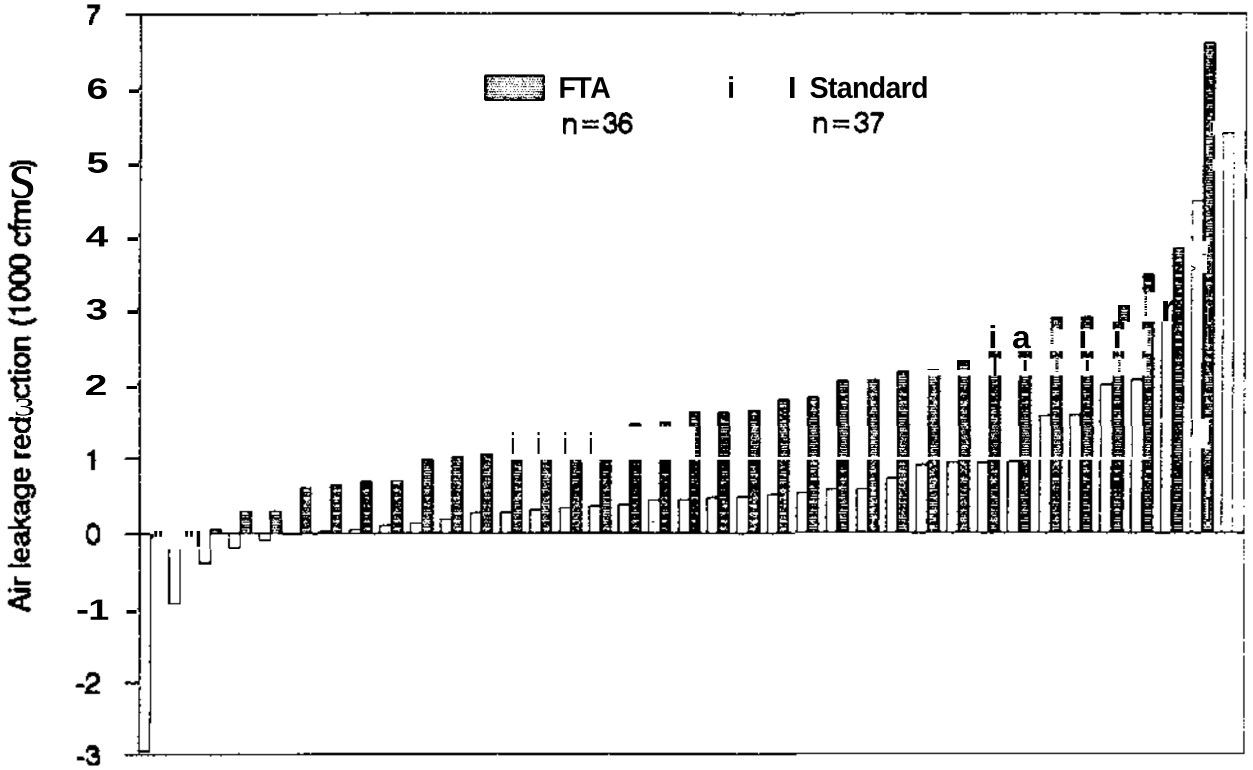


Fig. 83. Comparison of the air leakage reductions achieved in the standard and Field Test Audit groups.

Average post-weatherization leakage rates were 3374 cfm50 in the standard group and 2690 cfm50 in the FTA group. The FTA group average of 2690 cfm50 is very near the 2500 cfm50 default value assumed when the FTA was run for each house.

8.2 BLOWER-DOOR-DIRECTED AIR SEALING RESULTS

The use of a blower-door-directed air sealing procedure in FTA houses offered the opportunity to make additional house air leakage measurements beyond the pre- and post-weatherization measurements for this group. By making leakage measurements at the start and end of air sealing, the first measure installed, the impact of the blower-door-directed air sealing procedure alone could be determined.

Blower-door-directed air sealing was performed between November 1990 and January 1991, following the procedure outlined in Sect. 3.2. Blower-door measurements made during the air sealing procedure were single-point measurements (made at only one pressure). Single-point measurements generally give reliable results but are not as accurate as the multiple-point procedure used to make pre- and post-weatherization measurements (see Sect. 8.1).

The pattern of change in house air leakage rate associated with the four leakage measurements made in each FTA house is reflected in Fig. 8.4. Because no changes to test houses were expected to occur before the beginning of air sealing, the starting leakage when air sealing began should be nearly equivalent to the pre-weatherization air leakage as illustrated in the figure. The averages would not be expected to match exactly because of measurements being made at different times, differing weather conditions, and measurement error. Close agreement also assumes that no significant changes occur to the houses during the time between measurements. The measurement after air sealing is considerably less than the starting leakage because of the major impact of air sealing. The final measurement, post-weatherization leakage, shows a leakage rate somewhat lower than the rate after air sealing (see Fig. 8.4). This decrease is expected because the weatherization measures installed after air sealing can have a significant impact on house air leakage.

In a comparison of the four air leakage measurements made in each FTA house, the trends in Fig. 8.4 are generally supported except in the case of measurements during air sealing at site A (houses 2 through 46). A number of indicators suggest that there are some major problems with the final air leakage measurements in these houses. The series of four air leakage measurements for houses 2 through 46 are summarized in Table 8.2.

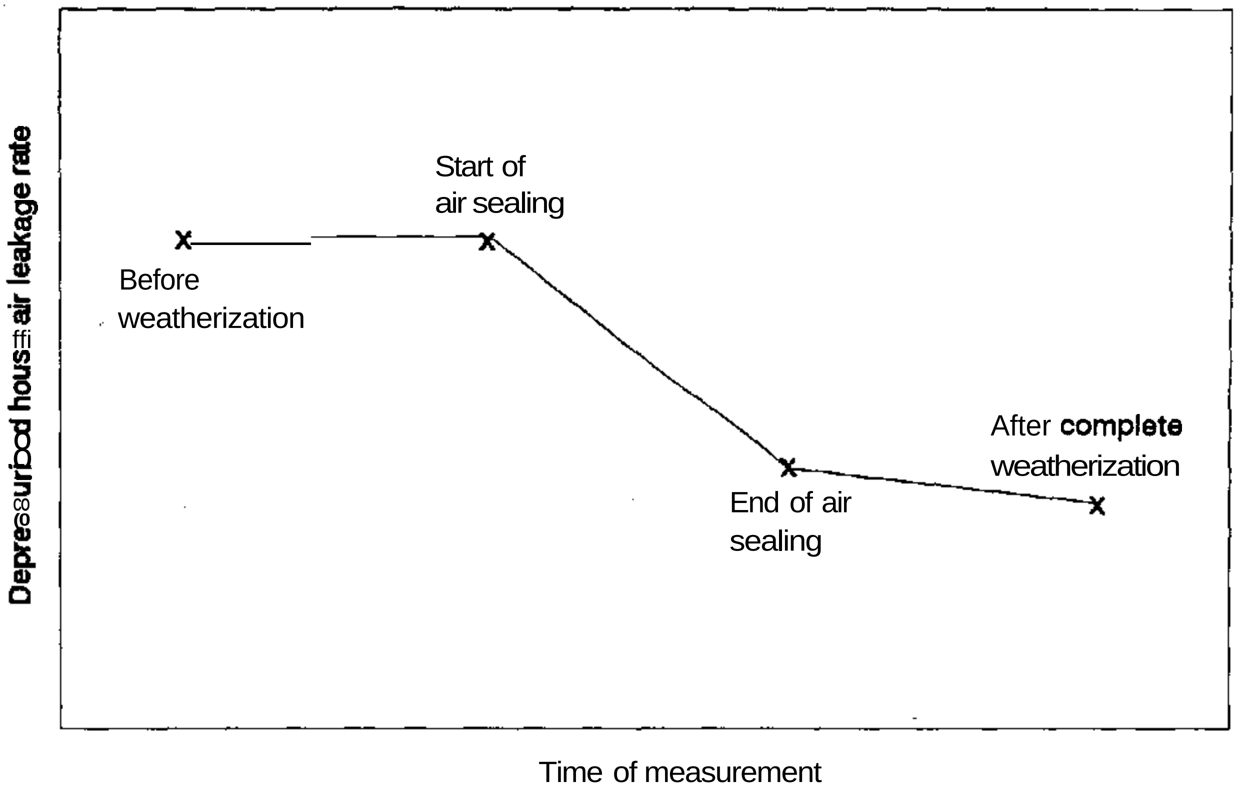


Fig. 8.4. The expected pattern of change between the four blower-door air leakage measurements made in each Field Test Audit house.

Table 8.2. Pre-weatherization, air sealing starting and final, and post-weatherization air leakage measurements in the Field Test Audit group for site A

House	Pre-wx[a] air leakage (cfm50)	Air sealing start leakage (cfm50)	Air sealing final leakage (cfm50)	Post-wx air leakage (cfm50)
2	4736	5244	1588	1871
4	3764	4119	1588	2767
9	3944	4246	1407	2659
18	4085	5244	1388	2808
21	4053	4829	2307	3745
26	4792	5244	1588	1921
27	5201	2670	2069	4511
30	5045	1857	676	4005
36	4585	5041	1765	2776
37	4539	5041	1765	2909
40	4872	5244	1588	1848
46	4737	5041	1765	3080
Average	4529	4485	1625	2908

[a] wx = weatherization

For these houses, most air leakage measurements after air sealing were at least 1000 cfm50 below the more reliable, post-weatherization air leakage measurements made at this site at a later date. This figure contradicts the expected results described in Fig. 8.4. This contradiction did not occur at the other two sites. In addition, final measurements after air sealing in 10 of the 12 houses for this site were below 1800 cfm50, compared with only 1 of 23 houses at the other two sites combined. Also, three houses at this site had final measurements below the minimum ventilation cutoff, which should not have occurred. A blower door operational or operator problem is suspected, although neither could be confirmed. Because these indicators suggest major problems with these data, these houses are not included in the following discussion of air leakage rates and reductions measured during the air sealing process. For comparison purposes, however, their results are included in Table 8.3 alongside the air sealing results of all other FTA houses. Averages without these houses are provided at the bottom of Table 8.3.

Based on the 23 houses, 52 through 140, air sealing starting leakage rates ranged from near the 1500 cfm50 cutoff (1588 cfm50) to 10372 cfm50. As expected, most of the starting leakage rates in Table 8.3 are only slightly different from the pre-weatherization leakage measurements made earlier (refer to Table 8.1). For these houses, the average pre-weatherization air leakage rate of 4462 cfm50 was very comparable to the average air leakage rate of 4550 cfm50 when air sealing began. Most houses (17 of the 23) had initial air leakage rates between 3000 and 6000 cfm50. Final leakage rates ranged between 1400 and 4200 cfm50, except for one house with a final leakage rate of 4829 cfm50. Seventy-four percent had final leakage rates less than 3000 cfm50.

Table 83. Starting and final air leakage measurements and associated results from the **blower-door-directed** air sealing work in the **Field** Test Audit bouses

House	Starting air leakage (cfm50)	Final air leakage (cfm50)	Leakage reduction (cfm50)	Labor (person-h)	Reduction per person-hour labor (cfm50)	Air sealing benefit-to-cost ratio[a]
2	5244	1588	3656	6	609	8.1
4	4119	1588	2531	9	281	3.7
9	4246	1407	2839	4	710	9.5
18	5244	1388	3856	12	321	4,3
21	4829	2307	2522	10	252	3.4
26	5244	1588	3656	9	406	5,4
27	2670	2069	601	6	100	1.3
30	1857	676	1181	4	295	3.9
36	5041	1765	3276	12	273	3.6
37	5041	1765	3276	15	218	2.9
40	5244	1588	3656	6	609	8.1
46	5041	1765	3276	15	218	2.9
52	4370	2204	2166	8	271	3.6
58	5245	2449	2796	8	350	4.7
61	4370	2069	2301	8	288	3.8
62	1588	1411	177	2	89	1.2
67	4490	3400	1090	4	273	3.6
68	3849	2449	1400	8	175	23
72	3479	2069	1410	8	176	2.4
73	3706	2670	1036	6	173	2.3
79	5244	3235	2009	8	251	3.3
85	4370	2330	2040	8	255	3.4
94	5194	3059	2135	4	534	7.1
95	8791	4829	3962	6	660	8.8
102	3986	2449	1537	12	128	1.7
103	5041	2562	2479	18	138	1.8
107	3148	2449	699	6	117	1.6
110	2449	2069	380	9	42	0.6
111	4606	2670	1936	15	129	1.7
113	2069	1924	145	3	48	0.6
118	5342	2967	2375	12	198	2.6
128	5144	4119	1025	6	171	*23*
137	5244	2449	2795	15	186	2.5
138	2562	2449	113	3	38	0.5
140	10372	3399	6973	21	332	4.4
Average for **all** 36 **houses**[b]	4528	2319	2209	9	266	3.5
Average for houses **52-140**[b]	4550	2682	1869	9	218	2.9

[a] **Based** on **cost-effectiveness** guideline of 75 **cfm50/person-h** = **benefit-cost** ratio of 1.

[fe] An unidentified **problem** apparently occurred during final measurements in houses 2 through 46. Final measurements were much too low, even below the minimum allowed, and much below the **post-weatherization** air leakage measurements in these houses, which were much more reliable multi-point measurements (refer to Table 8.1).

Leakage reductions ranged from 113 cfm50 for a house where three person-hours of work was performed to 6973 cfm50 where 21 person-hours of work was performed. An average leakage reduction of 1869 cfm50 (41%) was achieved. This average reduction is in line with the 39% (1710/4440) reduction for the entire FTA group indicated by the averages for the pre- and post-weatherization measurements in Table 8.1. This supports the accuracy of the post-weatherization air leakage measurements for houses 52 through 140.

The average air leakage reductions per person-hour alongside the average BCRs for air sealing are also presented in Table 8.3 (the BCR calculation procedure is described in Section 4.2). The average leakage reduction per person-hour in each house ranged from 38 cfm50 (BCR = 0.5) to 660 cfm50 (BCR = 8.8). The average leakage reduction per person-hour for houses 52 through 140 was 218 cfm50, corresponding to an average BCR of 2.9. Sixty-five percent of the air sealing BCRs were 2.3 or greater, and 39% were 3.3 or more.

The BCRs for air sealing work in houses 52 through 95 (site B) range from 1.2 to 8.8 and from 0.5 to 4.4 for houses 102 through 140 (site C). The BCRs for air sealing work at site C are generally somewhat lower than those at site B. Three houses at site C had air sealing BCRs below 1.0. These houses had the lowest starting air leakage rates of all houses at site C (between 2069 and 2562 cfm50), and minimal reductions were achieved in two of the three where only one crew-hour (three-person hours) of time was expended. The slightly lower BCRs at site C could be related to a larger crew size at site C and to the fact that air sealing occurred over multiple visits for some of these houses. This delay was apparently associated with acquiring materials to complete the weatherization work. This situation did not occur at site B; it could easily have increased the labor requirements necessary to complete air sealing.

The average time spent air sealing houses was 9 person-hours. The average time spent air sealing by site was 9, 6.5, and 11 person-hours. Only one house (62) was near enough the minimum ventilation guideline (1500 cfm50) that performing air sealing was questionable.

9. ENERGY CONSUMPTION ANALYSIS

9.1 SPACE-HEATING MODELS AND ANALYSIS APPROACH

For each house, weekly space-heating energy consumption was modeled as a linear function of the weekly average indoor-outdoor temperature difference. This model is represented as

$$EC = A + (B \cdot DT) ,$$

where

EC = weekly space-heating system energy consumption,
DT = average weekly indoor minus outdoor temperature difference,
A = model intercept coefficient (determined by regression),
B = model slope coefficient (determined by regression).

The pre- and post-weatherization measured data were analyzed separately using linear regression techniques to estimate the slope and intercept coefficients for each model. Hourly temperature differences were created by combining hourly indoor temperature files for each house with hourly outdoor temperature files from each test site. The time periods between the space-heating energy use measurements were used to determine the weekly periods over which the average indoor-outdoor temperature differences were calculated (to the nearest hour). The energy use and temperature difference files were then combined and used to create models of space-heating energy consumption. Energy consumption levels were normalized to 168-h weeks before models were created because some weekly periods were longer than others (depending on when energy use meter readings were taken).

When energy use data from one heating season are compared to those from another to determine energy savings, weather-normalizing the consumption is necessary to remove the effect of differences in average seasonal temperatures. An extremely cold winter following weatherization could result in higher heating energy use than in the pre-weatherization period, masking weatherization performance. Normalization was carried out by applying each performance model to typical meteorological year (TMY) weather data for the Raleigh/Durham area (National Climatic Center). Weekly average temperature differences were calculated using these outdoor temperature data and using 68°F as the indoor temperature for all houses. A common 68°F indoor temperature was used to remove occupant behavior impacts from energy predictions (different occupants often maintain different indoor temperatures, even for identical houses). Because positive temperature differences can result even during summer months for this indoor temperature, only temperature differences from September 17 to May 13 (representing a 34-week winter period during which space heating was required) were used. These weekly temperature differences, the DT terms, were then used in each performance model to estimate normalized weekly space-heating energy consumption for the pre- and post-weatherization periods. Weekly consumption was summed to calculate annual consumption. The difference between the normalized pre- and post-weatherization consumption was the space-heating energy savings.

9.2 SPACE HEATING: MODELING RESULTS AND ENERGY SAVINGS

Post-weatherization consumption could not be modeled for 14 of the test houses. These houses (10, 22, 26, 28, 29, 30, 56, 69, 105, 118, 131, 137, 138, 140) either dropped out of the test, switched to unmetered fuel, or had some other difficulty that resulted in no post-weatherization data. Two additional houses were excluded. House 92 was excluded because an unvented space heater (efficiency around 100%) was replaced by a vented unit (efficiency around 75%) during the test for safety reasons; the change would have significantly increased energy use. House 116 was excluded because it was found to be a multi-family unit during the test, with two families living separately within the same building. These 16 houses represented 6 houses from site A, 3 from site B, and 7 from site C. Remaining were 104 houses for the heating energy savings analysis (36 in the control group, 31 in the FTA group, and 37 in the standard group).

Normalized pre- and post-weatherization space-heating energy consumption (measured annual consumption that has been weather-normalized), corresponding space-heating energy savings, the number of data points available for each model, consumption model coefficients of determination (R^2s—also referred to as the squares of the correlation coefficients), and associated group statistics are summarized in Tables 9.1 through 9.3.

For the 104 houses, pre-weatherization space-heating energy consumption ranged from 14 to 121 MBtu. The average pre-weatherization consumption was 51.1 MBtu (around $358 at $7/MBtu), and the three group averages were within 4% of this value. The group averages were not statistically different at a 95% confidence level. Average post-weatherization consumption was 53.5 MBtu for the control group (almost no change), and near equal rates for the FTA and standard groups at 37.3 and 38.6 MBtu, respectively. Average post-weatherization consumption of the two treatment groups was not statistically different at the 95% confidence level, although both were statistically different from the control group at this confidence level. The distributions of savers and nonsavers (energy use increase) are shown in Fig. 9.1 for each group. Fifty percent of the control group, 84% of the FTA group, and 86% of the standard group showed energy use reductions. Average heating energy savings were near zero for the control group, while average savings for the FTA and standard groups were 24% of the pre-weatherization average consumption rates (11.7 MBtu for the FTA group and 12.3 MBtu for the standard group).

These results, indicating like performance of the two treatment groups, may be influenced by predictions from highly unreliable performance models. The accuracy of performance models based on linear regression analysis is influenced by the amount of data used and the amount of correlation present between the modeled parameters. Although the number of measured weekly data points on which house models were developed was high on average (18), several post-weatherization models and some pre-weatherization models were based on a small number of weekly data points (fewer than 10). This problem can lead to unreliable results when normalized predictions for an entire winter are based upon models developed from limited measured data. Ninety-five percent of the 208 models (2 for each house) had 10 or more heating data points. The collection of fewer than ten data points for some houses (8, 21, 27, 104, 109, 113, 114, 126, 132, and 133) was primarily attributable to problems with data collection at site C and to completion of weatherizations late in the post-weatherization heating season at site A

Table 9.1. Space heating energy consumption, savings, and associated statistics for the control group

Control group							
House	Pre-wx[a] space heating energy use (MBtu)	Post-wx space heating energy use (MBtu)	Space heating energy savings (MBtu)	Number of data points		Model R^2	
				Pre-wx	Post-wx	Pre-wx	Post-wx
12[b]	57.5	48.7	8.8	24	11	0.91	0.46
14	24.4	38.1	-13.7	18	13	0.91	0.80
16	84.0	80.6	3.5	32	19	0.95	0.97
19[b]	52.8	25.9	26.9	14	17	0.89	0.32
23[b]	58.0	60.0	-2.0	21	13	0.94	0.16
24	25.1	26.8	-1.7	20	20	0.89	0.89
35[b]	61.8	65.6	-3.8	21	12	0.92	0.63
38	26.6	26.0	0.6	21	20	0.95	0.94
39[b]	61.6	30.6	31.0	20	17	0.85	0.31
41	69.6	70.3	-0.7	18	20	0.95	0.73
42?	37.6	30.0	7.7	18	15	0.86	0.01
43	43.2	46.4	-3.1	18	16	0.95	0.84
45	58.1	76.7	-18.6	24	13	0.95	0.89
51	47.6	55.6	-8.0	25	20	0.95	0.72
57*	58.3	66.6	-8.3	17	13	0.56	0.32
60	25.6	22.9	2.7	18	21	0.97	0.95
64	70.7	68.5	2.2	25	20	0.92	0.91
66	47.9	44.2	3.7	24	20	0.85	0.85
70	28.1	26.6	1.5	18	18	0.96	0.86
74	79.9	86.7	-6.9	21	18	0.95	0.92
SO	76.4	67.8	8.6	21	19	0.97	0.98
84	56.5	79.6	-23.1	19	18	0.88	0.87
86	32.7	29.5	3.2	21	16	0.97	0.98
98	50.8	50.4	0.4	25	21	0.96	0.96
101	60.0	64.6	-4.6	23	19	0.97	0.97
104[b]	64.5	79.9	-15.4	11	6	0.83	0.16
106	47.5	49.1	-1.6	23	19	0.98	0.98
119	52.9	52.1	0.9	20	16	0.93	0.96
123	57.9	50.2	7.8	23	15	0.96	0.88
124	52.4	66.3	-13.9	22	19	0.91	0.73
126*	5Z6	24.7	28.0	8	19	0.77	0.70
130	44.5	56.1	-11.6	23	14	0.96	0.88
132[b]	70.9	128.2	-57.3	20	3	0.87	0.01
133*	25.1	28.2	-3.1	13	9	0.71	0.67
134	73.1	66.3	6.8	21	15	0.88	0.94
136[b]	71.1	35.4	35.7	14	15	0.92	0.18

Table 9.1 (continued)

Control group							
				Number of data points		Model R^2	
Statistic	Pre-wx space heating energy use (MBtu)	Post-wx space heating energy use (MBtu)	Space heating energy savings (MBtu)	Pre-wx	Post-wx	Pre-wx	Post-wx
Based on 104-house data set							
Average	53.0	53.5	-0.5	20	16	0.90	0.70
Standard deviation	16.4	22.8	16.0	4	4	0.08	0.30
Observations	36	36	36	36	36	36	36
Minimum	24.4	22.9	-57.3	8	3	0.56	0.01
Maximum	84.0	128.2	35.7	32	21	0.98	0.98
Median	54.7	51.2	-0.1				
Based on 65-house refined data set							
Average	51.5	54.2	-2.7	22	18	0.94	0.89
Standard deviation	17.8	18.6	8.2	3	2	0.03	0.08
Observations	24	24	24	24	24	24	24
Minimum	24.4	22.9	-23.1	18	13	0.85	0.72
Maximum	84.0	86.7	8,6	32	21	0.98	0.98
Median	51.6	53.9	-0.1				

[a] wx = weatherization.
[b] Excluded from the refined data set by the screening criteria.

Table 9.2. Space heating energy consumption, savings, and associated statistics for the Field Test Audit group

Field Test Audit group							
House	Pre-wx[a] space heating energy use (MBtu)	Post-wx space heating energy use (MBtu)	Space heating energy savings (MBtu)	Number of data points		Model R^2	
				Pre-wx	Post-wx	Pre-wx	Post-wx
2[b]	25.6	20.8	4.8	15	13	0.90	0.32
4[b]	45.0	25.0	20.0	20	14	0.59	0.57
9	67.4	62.2	5.2	17	17	0.85	0.95
18*	62.4	55.9	6.5	16	19	0.91	0.58
21*	73.5	110.4	-36.8	17	5	0.93	0.41
27[b]	67.1	31.4	35.7	16	7	0.91	0.51
36*	88.5	59.0	29.5	18	13	0.69	0.84
37	44.7	44.4	0.3	22	16	0.98	0,96
40[b]	53.2	33.0	20.2	14	13	0.31	0.57
46	44.4	23.0	21.4	19	14	0.77	0.93
52	29.3	16.5	12.7	17	19	0.98	0.91
58*	24.3	13.4	10.9	25	13	0.70	0.85
61	37.5	26.8	10.7	16	23	0.98	0.96
62	25.3	21.2	4.1	19	16	0.98	0.95
67[b]	22.5	41.7	-19.1	22	15	0.66	0.88
68	40.5	12.2	283	14	14	0.92	0.84
72*	60.8	33.6	27,2	16	16	0.81	0.65
73	60.8	50.0	10.8	22	15	0.83	0.96
79	64.2	45.7	18.5	26	18	0.81	0.76
85	69.2	32.5	36.7	25	20	0.91	0.88
94	65.3	32.0	33.3	20	23	0.97	0.97
95	51.1	49.4	1.6	25	19	0.93	0.88
102	61.7	25.0	36.8	23	18	0.97	0.94
103	81.1	28.1	53.0	24	20	0.93	0.98
107	18.2	15.5	2.7	20	16	0.96	0.91
110	34.0	45.6	– 11.6	18	14	0.92	0.77
111	49.9	36.6	13.3	17	21	0.90	0.96
113*	14.0	8.9	5.1	15	6	0.79	0.17
127[b]	60.7	65.0	-4.3	36	20	0.66	0.83
128*	24.0	11.4	12.6	25	15	0.45	0.28
145	52.0	793	-273	22	19	0.86	0.87

Table 9.2. (continued)

Statistic	Pre-wx space heating energy use (MBtu)	Post-wx space heating energy use (MBtu)	Space heating energy savings (MBtu)	Number of data points		Model R^2	
				Pre-wx	Post-wx	Pre-wx	Post-wx
Field Test Audit group							
Average	49.0	37.3	11.7	20	16	0.83	0.77
Standard Deviation	19.4	21.8	19.1	5	4	0.16	0.23
Observations	31	31	31	31	31	31	31
Minimum	14.0	8.9	-36.8	14	5	0.31	0.17
Maximum	88.5	110.4	53.0	20	16	0.83	0.77
Median	51.1	32.5	10.9				
Based on **65-house refined** data set							
Average	49.8	35.9	13.9	20	18	0.91	0.91
Standard deviation	16.6	17.1	18.6	3	3	0.06	0.06
Observations	18	18	18	18	18	18	18
Minimum	18.2	12.2	-27.3	14	14	0.77	0.76
Maximum	81.1	79.3	53.0	26	23	0.98	0.98
Median	50.5	32.3	11.8				

[a] wx = weatherization.

[b] Excluded from the refined data set by the screening criteria.

Table 93. Space heating energy consumption, savings, and associated statistics for the standard group

Standard group							
House	Pre-wx[a] space heating energy use (MBtu)	Post-wx space heating energy use (MBtu)	Space heating energy savings (MBtu)	Number of data points		Model R^2	
				Pre-wx	Post-wx	Pre-wx	Post-wx
3[b]	100.3	50.7	49.6	17	20	0.83	0.04
5[b]	86.8	62.2	24.6	16	18	0.92	0.58
6[b]	120.1	107.2	12.9	18	14	0.68	0.87
7	24.0	19.2	4.8	16	17	0.97	0.83
8*	61.0	34.5	26.5	18	4	0.89	0.75
13	54.8	50.1	4.7	33	20	0.98	0.89
15	24.5	23.5	1.0	27	20	0.95	0.92
20	64.9	34.3	30.5	18	19	0.90	0.79
31*	52.8	47.3	5.6	24	16	0.96	0.01
32[b]	34.4	32.6	1.8	17	15	0.93	0.20
33*	21.1	21.6	-0.5	13	14	0.47	0.22
59	29.0	20.4	8.6	18	19	0.99	0.97
65*	21.4	15.0	6.4	20	16	0.99	0.56
77	34.8	32.1	2.7	22	21	0.89	0.94
78	54.9	43.8	11.0	21	16	0.96	0.95
81	106.3	87.8	18.5	19	16	0.97	0.96
82	59.7	30.2	29.5	18	21	0.98	0.95
87*	60.0	35.6	24.3	32	10	0.90	0.19
88	59.2	38.2	21.0	23	16	0.97	0.74
90	58.7	60.4	-1.6	18	21	1.00	0.95
91	100.6	78.4	22.1	20	19	0.95	0.95
93	46.4	42.5	3.9	20	19	0.99	0.99
96*	40.8	10.7	30.1	25	15	0.93	0.89
97	37.1	32.8	4.4	22	18	0.94	0.84
99	40.6	21.9	18.6	19	19	0.98	0.96
109[b]	70.5	18.3	52.1	5	12	0.02	0.25
112	67.5	47.7	19.7	23	22	0.96	0.99
114	39.0	45.2	-6.3	9	9	0.82	0.85
115	35.3	21.3	14.0	17	16	0.83	0.77
117	27.6	24.2	3.4	17	17	0.95	0.87
120	36.0	33.0	3.0	25	21	0.98	0.95
122*	37.8	27.7	10.0	15	12	0.35	0.79
129	34.2	67.3	-33.1	20	16	0.93	0.88
135	56.6	39.9	16.6	17	22	0.85	0.84
141	32.9	25.4	7.5	21	18	0.94	0.92
143[b]	23.8	24.2	-0.4	17	16	0.80	0.45
144*	28.5	21.8	6.7	16	13	0.61	0.20

Table 93. (continued)

Statistic	Pre-wx space heating energy use (MBtu)	Post-wx space heating energy use (MBtu)	Space heating energy savings (MBtu)	Number of data points		Model R^2	
				Pre-wx	Post-wx	Pre-wx	Post-wx
Based on **104-house** data set							
Average	50.9	38.6	12.3	19	17	0.86	0.72
Standard Deviation	25.0	20.7	15.2	5	4	0.20	0.30
Observations	37	37	37	37	37	37	37
Minimum	21.1	10.7	-33.1	5	4	0.02	0.01
Maximum	120.1	107.2	52.1	33	22	1.00	0.99
Median	40.8	33.0	8.6				
Based on **65-house refined** data set							
Average	48.9	40.0	8.9	20	18	0.94	0.90
Standard deviation	21.3	18.2	13.1	4	3	0.05	0.07
Observations	23.0	23.0	23.0	23	23	23	23
Minimum	24.0	19.2	-33.1	9	9	0.82	0.74
Maximum	106.3	87.8	30.5	33	22	1.00	0.99
Median	40.6	38.2	7.5				

[a]Wx = weatherization

[b]Excluded from the refined data set by screening criteria.

The amount of correlation between two parameters, another indicator of model reliability, is related to the ability of one parameter, the indoor-outdoor temperature difference in this case, to explain variations in the other (space-heating energy use). When there is variability around a linear model, the coefficient of determination (R^2) that results from regression analysis can in many cases be used to judge the adequacy of the model (Hines and Montgomery 1980). R^2s near 1 (perfect correlation) indicate strong correlations, while those near 0 (no correlation) indicate very weak correlations. R^2s in Tables 9.1 through 9.3 indicate that strong model correlations resulted for most houses. Over 50% of the models had R^2s greater than or equal to 0.90, and 80% had R^2s of 0.70 or larger. For illustration, the approximately linear relationships between space-heating energy consumption and indoor-outdoor temperature differences for houses 51 and 66 are shown in Figs. 9.2 and 9.3, respectively. The R^2 for house 51 is 0.94 and the R^2 for house 66 is 0.85. In contrast, a number of houses had very low correlations (less than 0.20) for post-weatherization measured data. These generally were houses with a small number of measured data points, where the consumption data represented only a small range of expected seasonal temperatures, or where the consumption data were highly scattered. High data scatter normally occurred in houses where there was significant unmetered energy use (from portable heaters or fireplaces).

The lack of measured data points and the poor models resulting for several houses suggest that some major prediction errors could be present in the averages obtained for

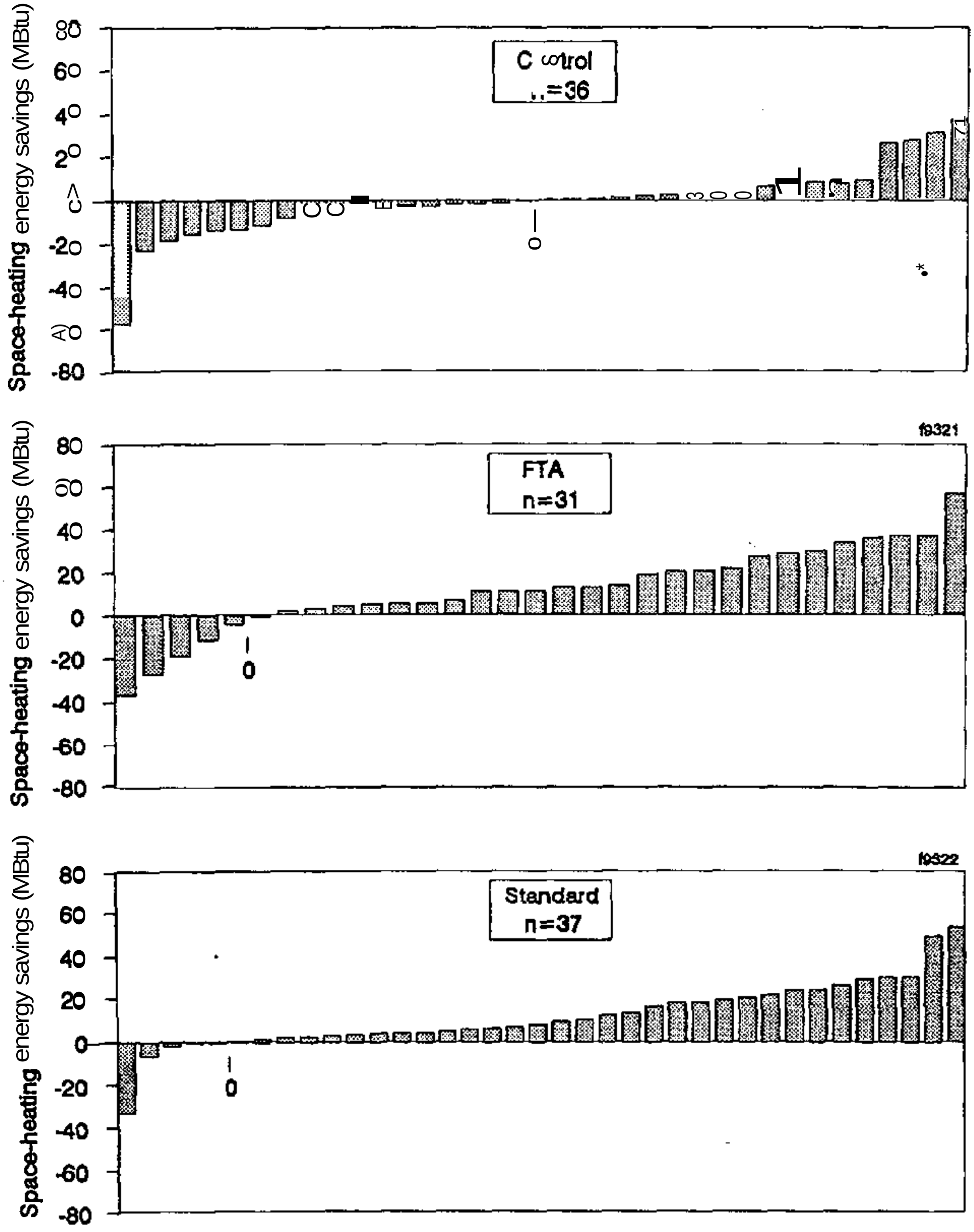


Fig. 9.1 Distribution of heating energy savers vs. nonsavers by group.

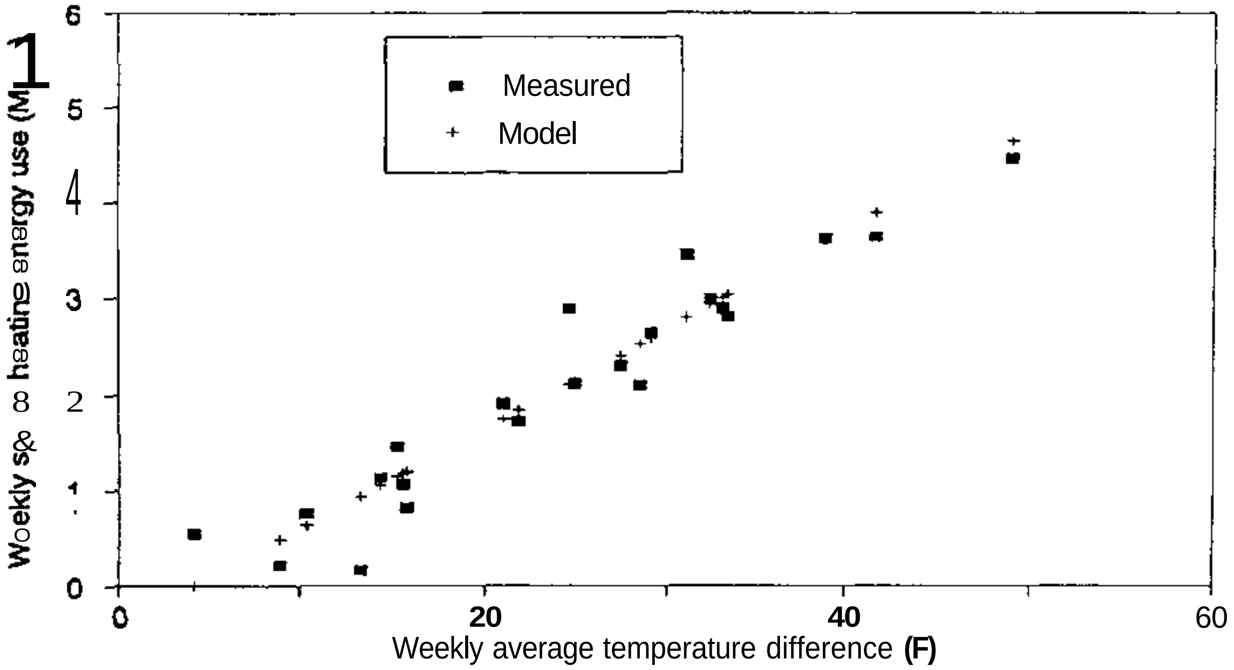


Fig. 9.2. Pre-weatherization space heating energy consumption data and the model fit for house 51.

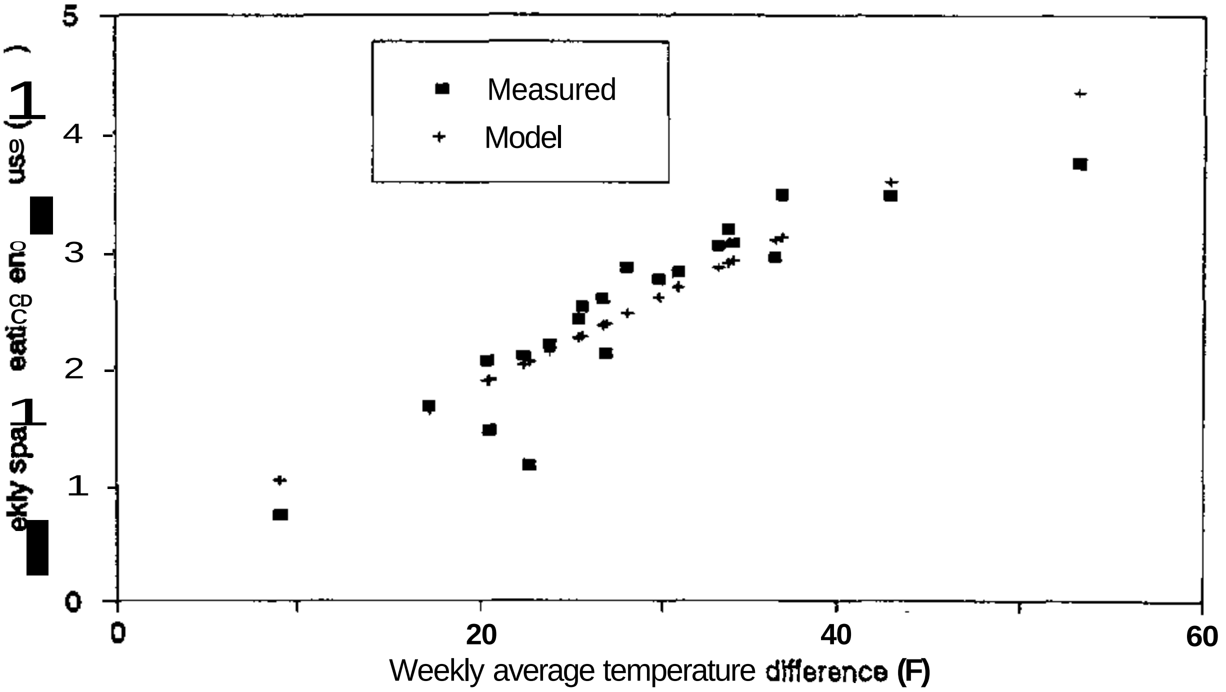


Fig. 93. Pre-weatherization space heating energy consumption data and the model fit for house 66.

the three test groups from the entire 104-house data set. Some prominent examples of this in Tables 9.1 through 9.3 are houses 132 and 136 in the control group, house 21 in the FTA group, and houses 3 and 109 in the standard group. Many of these are extreme savers or nonsavers (increased energy use) and have a low number of data points and/or very low R^2s for at least one model. If these types of houses have major impacts on group averages or are not equally distributed among groups, the true average energy savings for weatherization groups could be masked by results from a small number of houses with models that could be classified as highly inaccurate and unreliable.

A method used by Princeton Scorekeeping Method developers (Fels 1984) was applied to the 104-house data set as an impartial algorithm for screening out unreliable models (Fels and Reynolds 1990). The technique is based on model R^2s (an indicator of how well the model fits measured data) and the uncertainty of the normalized energy consumption levels (an indicator of the reliability of predictions). Results from a refined data set based on these criteria should be more reliable and accurate. In addition, the exclusion of houses with unreliable results could produce smaller standard deviations for group averages, which could improve the potential for detecting statistical differences. Houses are plotted as a function of the two screening criteria in Figs. 9.4 and 9.5 for the pre- and post-weatherization periods. The houses in the upper left corners of these figures (low R^2 and large relative standard errors) are the most unreliable. Those in the bottom right corner are the most reliable. The criteria chosen for screening were the same suggested by Fels and Reynolds, $R^2 \geq 0.70$ and a relative standard error of normalized consumption ≤ 0.06. Applying these criteria resulted in a refined data set of 65 houses.

The distributions of savings for the refined 65-house analysis are shown in Fig. 9.6. The control group is centered somewhere between 0 and -10 MBtu savings, while the two treatment groups are centered well to the right of 0, indicating a net energy savings for both weatherized groups. Space-heating energy use decreased for 50% of the control group houses, 88% of the FTA group houses, and 87% of the standard group houses. Twenty-two percent (four houses) of the FTA houses had savings exceeding 30 MBtu, compared with only 4% (one house) of the standard group.

Group statistics for the refined data set are presented at the ends of Tables 9.1 through 9.3. Almost all statistical parameters experienced some degree of change from the refinement. The range of savings estimates was reduced for all groups, indicating that a number of the highest and lowest savers in these groups were houses with poor model results. Average savings for the control and standard groups decreased, and the average savings for the FTA group increased. Standard deviations of energy use and savings averages were reduced in almost all cases, a direct result of the refinement to more reliable data. The standard deviation of the savings average for the control group decreased around 50% from the refinement. The refinement produced variability reductions of around 3% and 14% for the two weatherization groups.

Control group results in Table 9.1 indicate a small increase in average energy use of 2.7 MBtu (savings of -2.7 MBtu) for this group, around 5% of the pre-weatherization average heating energy use. This increase is larger than the 1% increase indicated by the original data set. The standard deviation of space heating energy savings decreased substantially from the refinement. The range of savings represented by houses in the

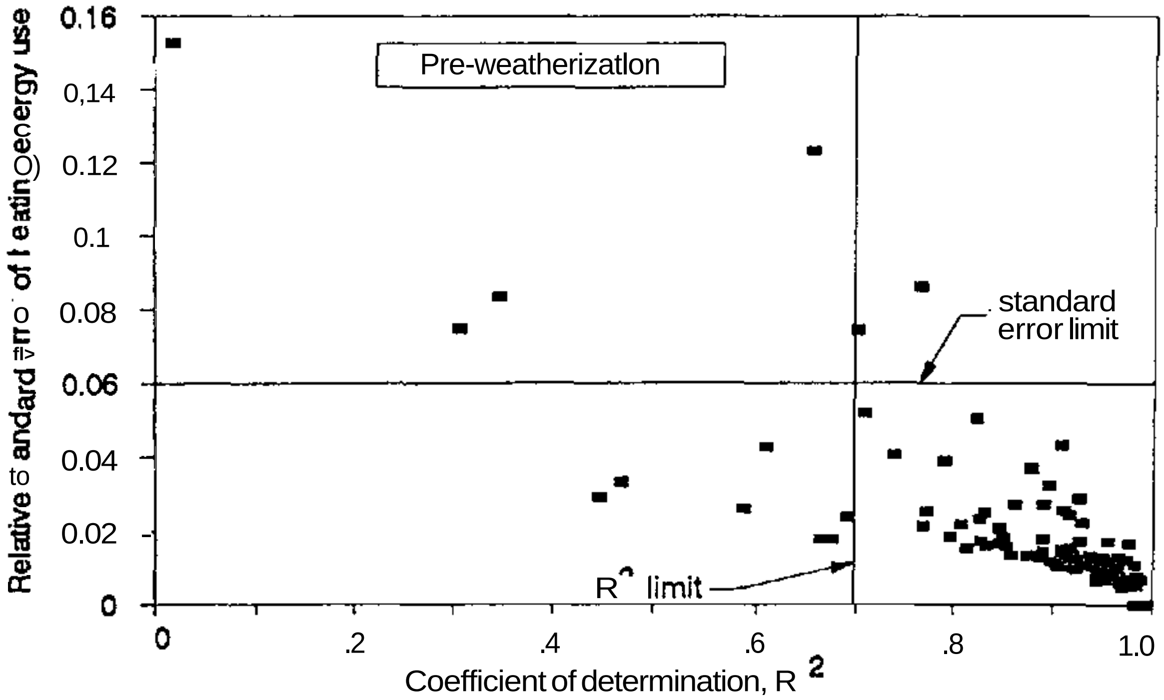


Fig. 9.4. Normalized pre-weatherization heating energy consumption as a function of reliability screening criteria.

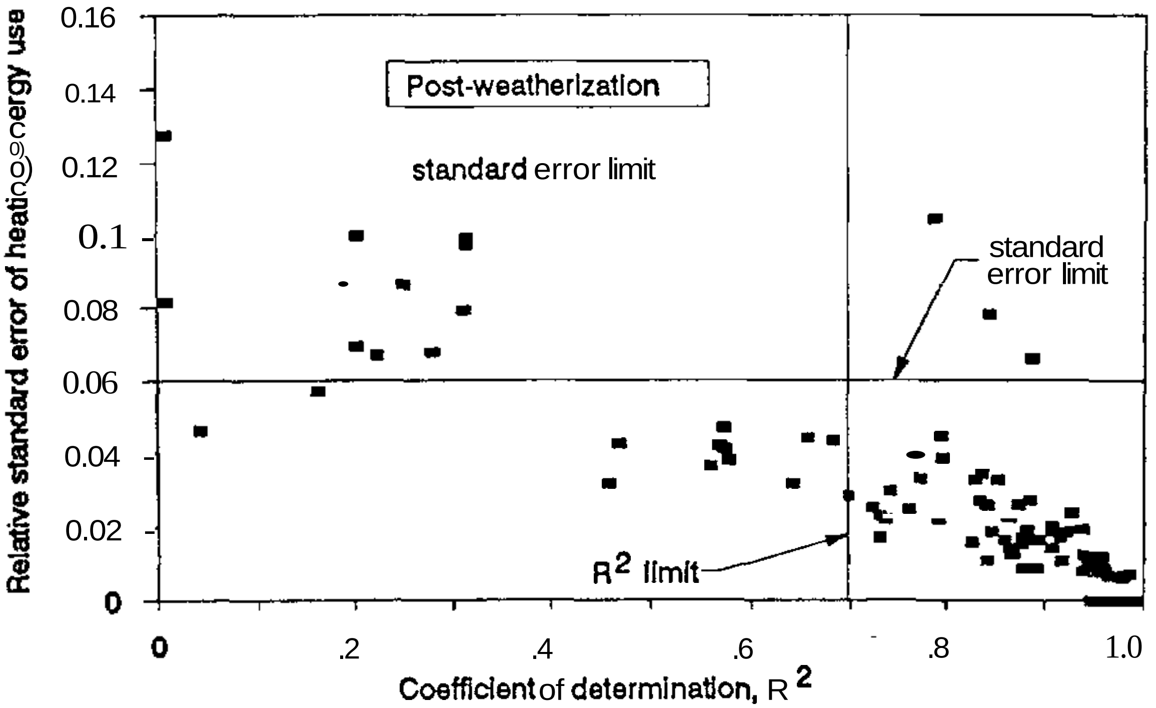


Fig. 9.5. Normalized post-weatherization heating energy consumption as a function of reliability screening criteria.

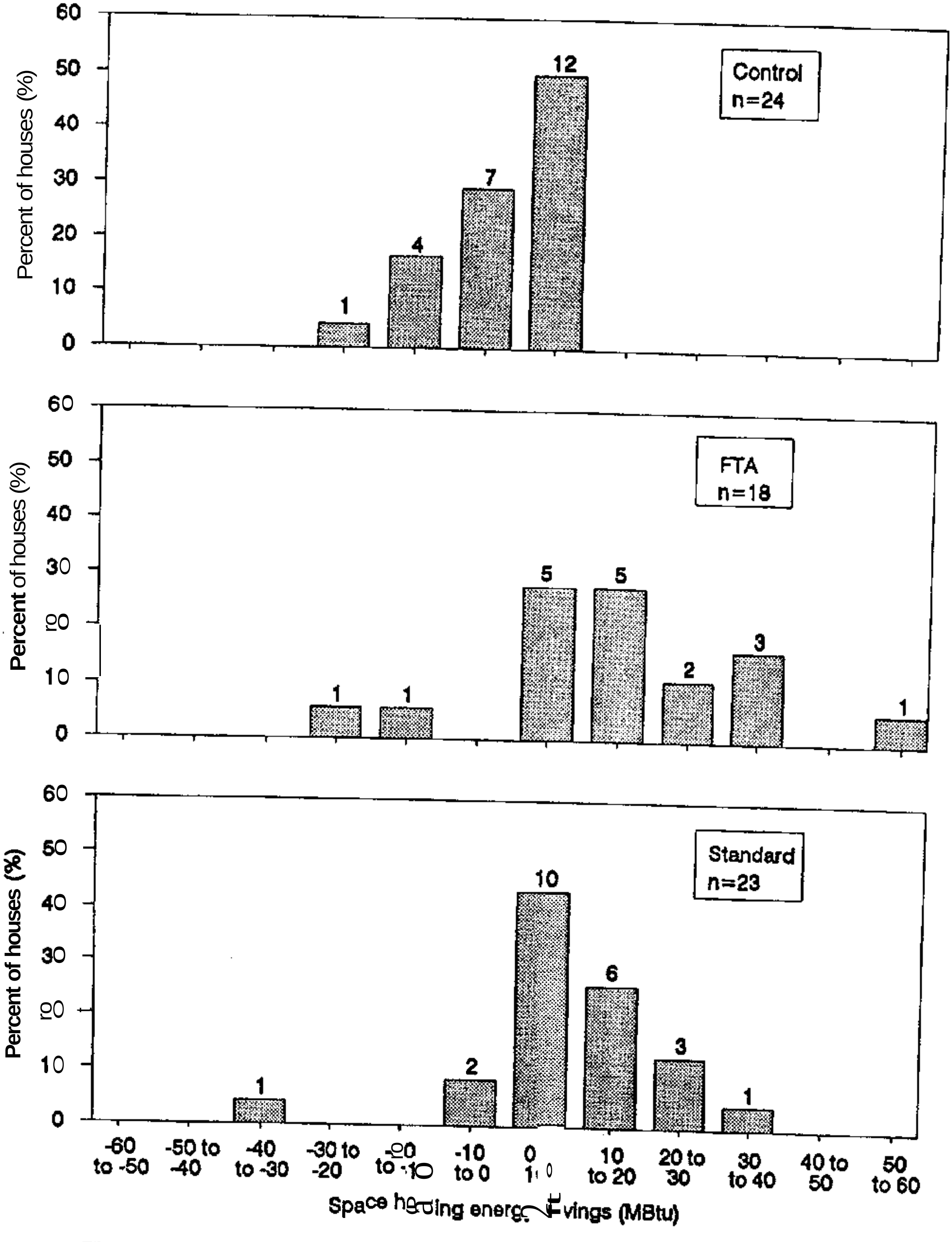


Fig. 9.6. Space heating energy savings distributions by group for the refined 65-house data set.

refined control group, -23.1 MBtu to 8.6 MBtu, is much less than that for the original data set. Twelve houses in this group failed the model reliability screening criteria.

FTA group results for the refined data set are presented at the end of Table 9.2. FTA group average heating energy savings are 13.9 MBtu, around 28%. This figure is slightly higher than the 24% indicated by the original data set. Slight reductions occurred in the standard deviations of group heating energy use and savings. Thirteen houses in this group could not meet the reliability screening criteria.

Standard group results for the refined data set are presented at the end of Table 9.3. Standard group average heating energy savings are 8.9 MBtu, around 18%. This figure is less than the 24% savings indicated by the original data set, indicating a higher influence on the original average from extreme savers than from extreme nonsavers for those houses with models that could not meet the reliability criteria. Slight reductions occurred in the standard deviation of group savings and in the range of savings represented by houses in this group. Thirteen houses in this group could not meet the model reliability screening criteria.

Differences between group average savings were examined by analysis of variance to check for statistical differences between groups. A statistical difference was found and Duncan's multiple range test (Hines and Montgomery 1980) was then applied to identify which groups were statistically different. The energy savings of both weatherized groups were found to be statistically different from the control group at the 95% confidence level. The standard deviations of savings for the two weatherized groups remained large, however, resulting in no statistically significant difference between these averages at 95% confidence.

Group space-heating energy savings statistics for the refined 65-house data set are listed in Table 9.4. The *5%* average heating energy use increase of the control group was used to adjust the savings of the two treatment groups to determine adjusted (net) heating energy savings. The adjustment resulted in an average 33% savings for the FTA group and 23% for the standard group. Average FTA group heating energy savings are 43% greater than those from the standard group. These results are more reliable since estimates from highly unreliable models have been removed.

Table 9.4. Space-heating energy savings statistics for the refined 65-house data set

Group	Range (MBtu)	Average savings (MBtu)	Std. dev. of average (MBtu)	Percent based on averages (%)	Number of houses	Median savings (MBtu)	Percent based on medians (%)
Control	-23 to 9	-2.7	8.2	-5.3	24	-0.2	-0.3
FTA[a]	-27 to 53	13.9	18.6	27.9	18	11.8	23.3
Standard	-33 to 31	8.9	13.1	18.2	23	7.5	18.5

[a] FTA = Field Test Audit

93 SPACE-COOLING MODELS AND ANALYSIS APPROACH

Space-cooling energy consumptions were modeled as a linear function of indoor-outdoor temperature difference for primary air conditioners and as a linear function of outdoor temperature for secondary air conditioners. Primary air conditioners were those located in the same room as the indoor temperature recorder (living rooms, in most cases). Secondary air conditioners, the second air conditioner in the house if two were present, were located in rooms where individual room temperatures were not monitored. The energy use of the primary air conditioner in each house was modeled as a linear function of the average weekly difference between house indoor and outdoor temperatures. This model is represented as

$$EC = A + (B \cdot DT) ,$$

where

EC = weekly energy consumption of the primary air conditioner,
DT = average weekly indoor minus outdoor temperature difference,
A = model intercept coefficient (determined by regression),
B = model slope coefficient (determined by regression).

The pre- and post-weatherization measured data were analyzed separately using linear regression techniques to estimate the slope and intercept coefficients for each model. Hourly temperature differences were created by combining hourly indoor temperature files for each house with hourly outdoor temperature files from weather stations at each test site. The time periods between the space-cooling energy use measurements were used to determine the weekly periods over which the average indoor-outdoor temperature differences were calculated (to the nearest hour). The energy use and temperature difference files were then combined and used to create models of space-cooling energy consumption. Energy consumption levels were normalized to 168-h weeks before models were created because some weekly periods were longer than others.

Secondary air conditioners were modeled as a function of outdoor temperature only, because indoor temperatures near these units were not measured. This model is similar to that for primary units except that the temperature difference term, DT, is replaced by a term representing the weekly average outdoor temperature.

When energy use data from one cooling season are compared to those from another to determine energy savings, weather-normalizing the consumption is necessary to remove the effect of differences in average seasonal temperatures. An extremely warm summer following weatherization could result in much higher cooling energy use than in the pre-weatherization period, masking weatherization performance. Normalization was carried out by applying each performance model to TMY weather data for the Raleigh/Durham area. Weekly average temperature differences were calculated using TMY outdoor temperature data and using 78°F as the indoor temperature for all houses. Using a common indoor temperature of 78°F normalized the energy use of each house to a common setpoint, which removes the impact of differing indoor temperatures (an occupant behavior) from energy use predictions. Because positive temperature differences can result even during noncooling months for this indoor temperature, only temperature data between April 30 and October 14 (representing a 24-week summer period during which space cooling was required) were used. These weekly temperature differences, the DT terms, were then used in each performance model to estimate normalized weekly space-cooling energy consumption for the pre- and post-weatherization periods. Reported cooling energy savings are the differences between weather-normalized cooling energy consumption levels of the pre- and post-weatherization periods.

9.4 SPACE COOLING: MODELING RESULTS AND ENERGY SAVINGS

Twenty of the original 120 houses in the field test were excluded from the cooling energy savings analysis. Sixteen of these lacked post-weatherization cooling energy data because of dropping out during the testing, air conditioner failure, or some other reason that caused a major loss of data. Four others were excluded because of a major change in the way each house was occupied. All problems resulting in the exclusion of houses were discovered or verified by field personnel. The exclusions represented seven houses from test site A, eight from site B, and five from site C. Remaining were 100 houses for the cooling energy savings analysis (34 in the control group, 33 in the FTA group, and 33 in the standard group). Fourteen of these 100 houses had secondary air conditioners.

Normalized pre- and post-weatherization space-cooling energy consumption (measured annual consumption normalized for weather differences and indoor temperature setpoint differences), corresponding space-cooling energy savings, and consumption model R^2s are summarized in Tables 9.5 through 9.7 for each test group. Modeled pre-weatherization space-cooling energy consumption ranged from 0 to 4867 kWh for all 100 houses. The average pre-weatherization consumption was 781 kWh (around \$66 at \$0.085/kWh). The distribution of pre-weatherization cooling energy consumption for all 100 houses is shown in Fig. 9.7. This distribution shows that most houses in the test were low cooling energy users. Approximately two of every five houses (38%) in the test used less than 250 kWh (\$21 at \$0.085/kWh). Approximately one of every two houses (47%) used less than 500 kWh (\$43) prior to weatherization. Only 14% used more than 1500 kWh (\$128 per year). The average pre-weatherization cooling energy consumption for the control and standard groups was 753 and 713 kWh, respectively, while the average for the FTA group was higher at 877 kWh. These group averages are not statistically different at a 95% confidence level.

Model R^2s ranged from 0.00 to 0.99. The R^2s around 0.00 typically occurred when cooling energy was used for only a small number of weeks. Small, random weekly consumption levels with no clear relation to outdoor temperature occurred for these houses. The higher R^2s generally occurred for the houses using more cooling energy. These houses usually had numerous weekly consumption levels greater than zero representing consumption during low, moderate, and high outdoor temperatures. Although occupant behavior influenced consumption in many of these houses also, it did not overwhelm the temperature-dependent energy use as in houses using little cooling energy. The R^2s could not be calculated for the 13 pre- and post-weatherization periods where no air conditioning use occurred (11 for primary and 2 for secondary air conditioners—refer to Tables 9.5 through 9.7). Only 43% of the 228 models (92 of 200 primary and 7 of 28 secondary air conditioner models) had R^2s > 0.70.

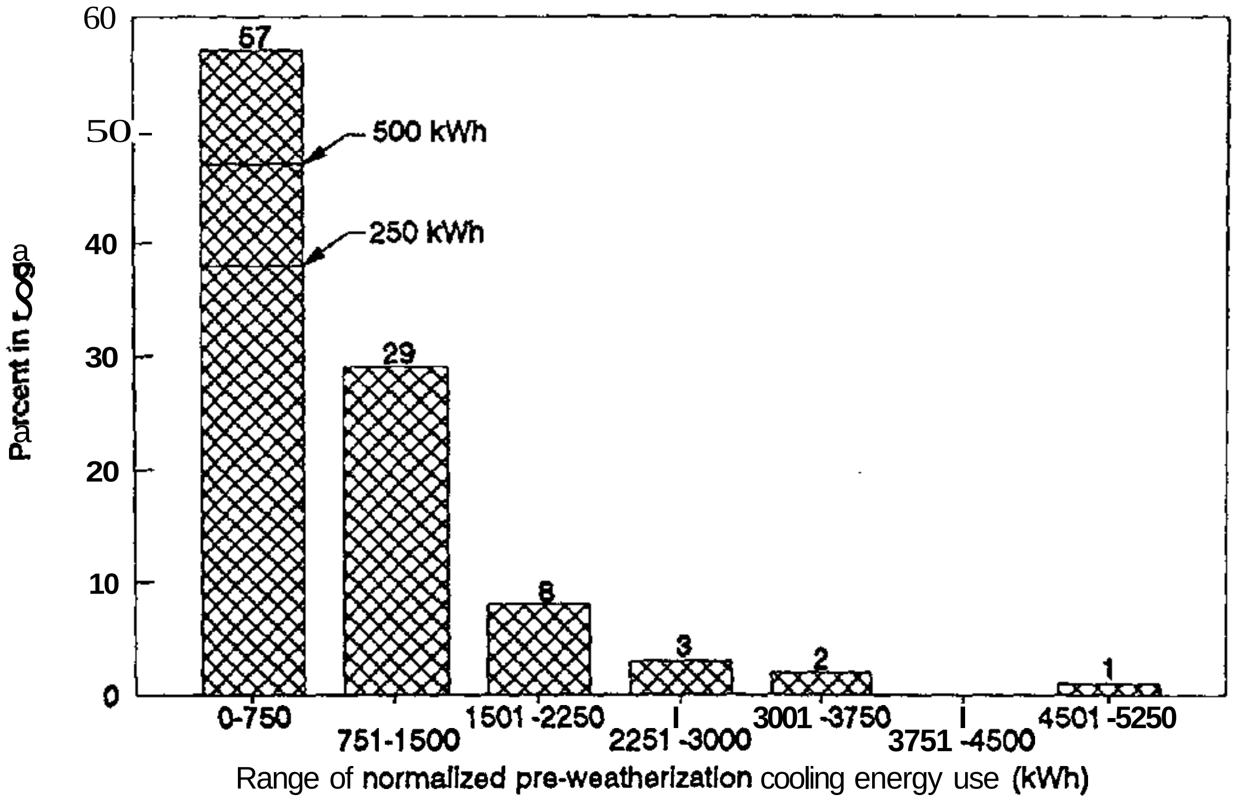


Fig. 9.7. Distribution of pre-weatherization cooling energy consumption for the 100-house data set

Cooling energy savings are shown as a function of pre-weatherization cooling energy use for each group in Fig. 9.8. The control group has slightly more houses below the zero savings line (negative savers) than above (savers); the standard group has about the same number above and below; and the FTA group has more savers than negative savers. Fig. 9.8 shows that the control and FTA groups have some higher pre-weatherization consumption houses than the standard group.

Statistics associated with group cooling energy savings for the 100-house sample are presented in Tables 9.5 through 9.7. Individual house cooling energy savings varied over a wide range for each group, and they were most widely distributed for the FTA group. Savings ranged from a low of −775 kWh in the control group (the minus indicates increased energy use) to a high of 2593 kWh in the FTA group. The minimum savings by individual houses in the control and standard groups were comparable, while the minimum savings in the FTA group was somewhat higher. The maximum savings achieved by individual houses varied greatly across groups, from 581 to 2593 kWh

The three houses with the largest cooling energy savings were the three largest pre-weatherization users of cooling energy (see Fig. 9.8). Two of these were in the FTA group and one was in the control group. The most extreme saver in the FTA group is more than

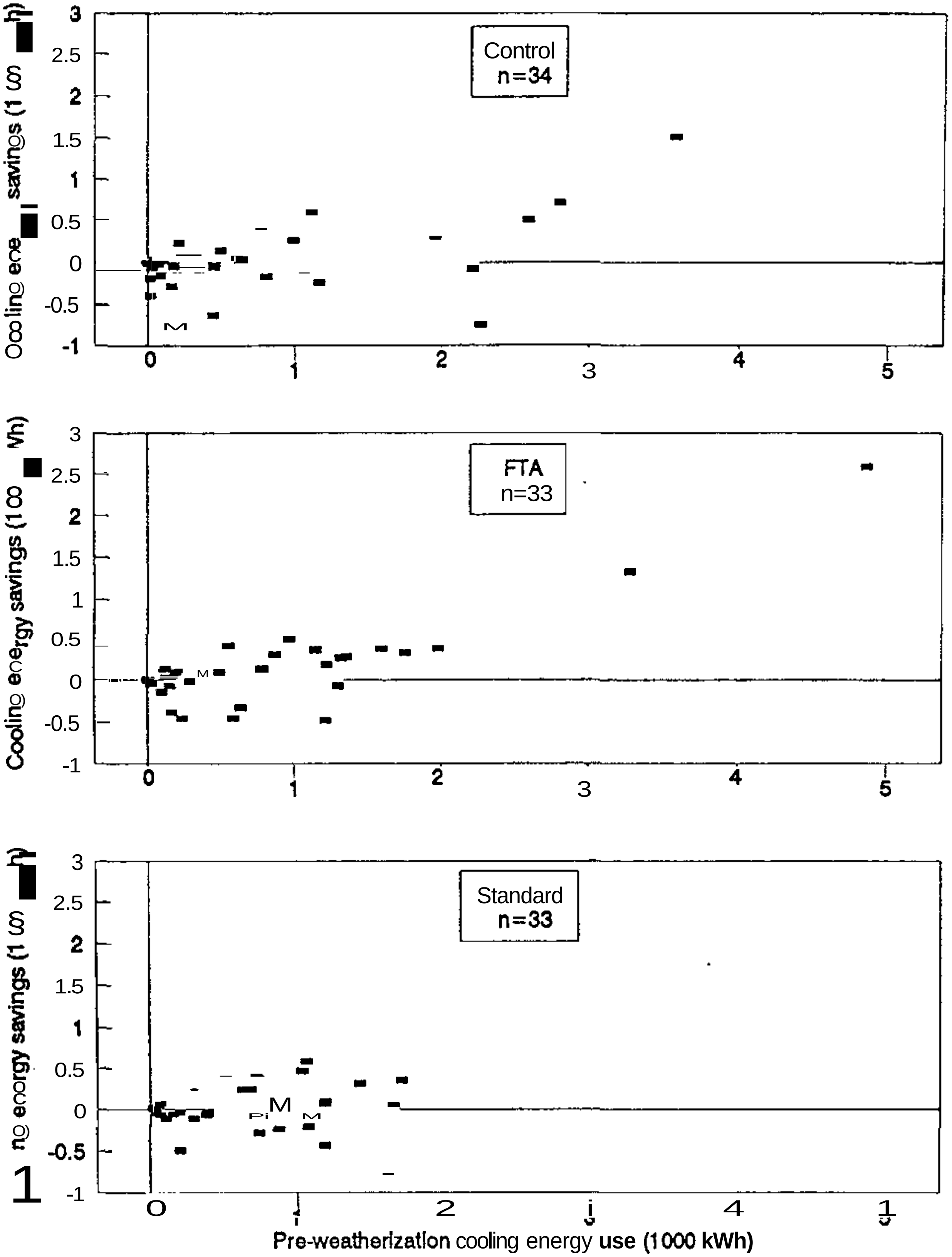


Fig. 9.8. Cooling energy savings as a function of pre-weatherization cooling energy use by group.

Table 93. Space cooling energy consumption, savings, and associated statistics for the control group

Control group							
House	**Pre-wx**[a] space cooling energy use (kWh)	**Post-wx** space cooling energy use (kWh)	Space cooling energy savings (kWh)	Primary air conditioner Model R^2		Secondary air conditioner Model R^2	
				Pre-wx	Post-wx	Pre-wx	Post-wx
12	230	418	-189	037	0.95		
14	1958	1650	307	0.74	0.74		
19	184	234	-50	0.16	0.23		
23	*111*	422	355	0.92	0.65		
35	368	525	-157	0.75	0.73		
38	4	9	~5	0.02	0.07		
39	519	374	145	0.71	0.23		
41	111	92	19	0.12	0.19		
42	1116	520	597	0.68	0.72		
43	627	582	46	0.70	0.86		
45	459	1090	-631	0.34	0.84	0.14	
51	8	9	-1	0.04	0.01		
57	31	89	-58	0.00	0.09		
60	1067	1226	-158	0.90	0.66		
64	7	403	-397	0.05	0.11		
66	243	183	60	0.85	0.59		
70	2804	2091	713	0.88	0.81		
74	821	991	-169	0.70	0.87		
80	994	733	262	0.92	0.93		
84	217	376	-158	0.71	0.57		
92	0	0	0				
98	16	204	-188	0.01	0.73		
101	142	917	-775	0.10	0.56	0.68	0.24
104	2267	3017	-750	0.83	0.37		
105	51	14	37	0.01	0.04		
106	3573	2063	1510	0.73	0.14	0.89	0.67
123	77	100	-23	0.04	0.14		
124	227	0	227	0.76			
126	2592	2081	510	0.83	0.95		
130	1168	1412	–244	0.96	0.79		
131	2213	2287	-75	0.54	0.80		
133	99	252	-153	0.90	0.95		
134	168	450	-282	0.09	0.11	0.80	0.83
136	454	502	-48	0.68	0.72		

Table 95 (continued)

Control group							
Statistic	Pre-wx space cooling energy use (kWh)	Post-wx space cooling energy use (kWh)	Space cooling energy savings (kWh)	Primary air conditioner Model R^2		Secondary air conditioner Model R^2	
				Pre-wx	Post-wx	Pre-wx	Post-wx
Based on 100-house data set							
Average	753	745	8	0.52	0.54	0.63	0.58
Standard Deviation	932	778	415	0.35	0.32	0.29	0.25
Observations	34	34	34	33[b]	32[b]	4	3[b]
Minimum	0	0	-775	0.00	0.01	0.14	0.24
Maximum	3573	3017	1510	0.96	0.95	0.89	0.83
Median	237	436	-36				
Based on 39-house refined data set							
Average	1409	1347	62	0.75	0.78	0.89	0.67
Standard deviation	819	795	388	0.16	0.15		
Observations	13	13	13	13	13	1	1
Minimum	230	418	-750	0.37	0.37		
Maximum	2804	3017	713	0.96	0.95		

[a] Wx = weatherization

[b] No R^2 available when energy use was zero.

Note:
Model R^2s for secondary air conditioners—House 45: pre, 0.14, post, none; House 101: pre, 0.68, post, 0.24; House 106: pre, 0.89; post, 0.67; House 134: pre, 0.80, post, 0.83.
Cooling energy savings for secondary air conditioners—House 45: 34 kWh; House 101: -22 kWh; House 106: 1690 kWh; House 134: -310 kWh.

Table 9.6. Space cooling energy consumption, savings, and associated statistics for the Field Test Audit group

Field Test Audit Group							
House	Pre-wx[a] space cooling energy use (kWh)	Post-wx space cooling energy use (kWh)	Space cooling energy savings (kWh)	Primary air conditioner Model R^2		Secondary air conditioner Model R^2	
				Pre-wx	Post-wx	Pre-wx	Post-wx
4	1375	1111	264	0.84	0.93		
9	607	1060	-453	0.28	0.56		
18	403	321	82	0.72	0.73		
21	876	586	290	0.59	0.70		
27	93	230	-136	0.34	0.16	0.70	0.01
30	1617	1302	356	0.86	0.72	0.00	
36	27	70	-44	0.01	0.00		
37	653	980	-327	0.65	0.84		
40	131	97	34	0.16	0.02		
46	122	0	122	0.03			
52	1984	1618	366	0.71	0.81		
58	1215	1694	-479	0.24	0.81		
61	977	495	482	0.66	0.38	0.89	0.50
62	512	420	93	0.89	0.85		
67	272	289	-17	0.82	0.51		
68	3277	1948	1330	0.39	0.71		
72	793	672	121	0.87	0.85		
73	205	112	93	0.44	0.53		
85	165	548	-383	0.09	0.35		
94	578	177	402	.92	0.75	0.06	0.40
95	1	0	1	0.00			
102	1158	812	346	0.84	0.68		
103	1306	1376	-70	0.89	0.77		
107	1230	1054	175	0.95	0.93	0.44	0.15
110	12	0	12	0.02			
111	157	226	-69	0.46	0.67		
118	4867	2274	2593	0.77	0.51	0.01	0.00
127	240	695	-455	0.28	0.42		
128	1334	1085	249	0.96	0.76		
137	1	0	1	0.15			
138	185	150	35	0.64	0.39	0.56	0.73
140	1762	1452	310	0.46	0.48		
145	801	674	127	0.71	0.79		

Table 9.6. (continued)

Field Test Audit Group							
Statistic	**Pre-wx**[a] space cooling energy use (kWh)	**Post-wx** space cooling energy use (kWh)	Space cooling energy savings **(kWh)**	Primary air conditioner Model R^2		Secondary air conditioner Model R^2	
				Pre-wx	Post-wx	**Pre-wx**	Post-wx
Based on **100-house** data set							
Average	877	713	165	0.54	0.61	0.38	0.30
Standard Deviation	1004	615	542	0.32	0.25	0.33	0.27
Observations	33	33	33	33	29[b]	7	6[b]
Minimum	1	0	-479	0.00	0.00	0.00	0.00
Maximum	4867	2274	2593	0.96	0.93	0.89	0.73
Median	607	586	93				
Based on **39-house** refined data set							
Average	1107	885	222	0.76	0.73	0.89	0.50
Standard deviation	454	415	147	0.14	0.15		
Observations	12	12	12	12	12	1	1
Minimum	403	321	-70	0.46	0.38		
Maximum	1984	1618	482	0.96	0.93		

[a] **Wx = weatherization**

[b] No R^2 available when energy use was zero.

Note: Model R^2s for secondary air conditioners:
House 27: pre, 0.70; **post**, 0.01; House 30: pre, 0.00, **post**, none; House 61: pre, 0.89; post, 0.50; House 94: **pre**, 0.06, **post**, 0.40; House 107: pre, 0.44, post, 0.15; House 118: pre, 0.01, post, 0.00; House 138: pre, 0.56, post, 0.73.

Table 9.7. Space cooling energy consumption, savings, and associated statistics for the standard group

Standard group							
House	Pre-wx[a] space cooling energy use (kWh)	Post-wx space cooling energy use (kWh)	Space cooling energy savings (kWh)	Primary air conditioner Model R^2		Secondary air conditioner Model R^2	
				Pre-wx	Post-wx	Pre-wx	Post-wx
3	411	459	-48	0.26	0.48		
5	1047	572	474	0.61	0.45		
6	213	245	-32	0.57	0.72		
7	1626	2364	-738	0,64	0.90		
8	404	464	-60	0.52	0.70		
13	75	137	-62	0.46	0.14		
15	24	0	24	0.04			
20	37	80	-42	0.01		0.46	0.24
28	1129	1203	-74	0.44	0.74		
29	1453	1138	315	0.78	0.86		
32	210	699	-489	0.09	0.88		
33	1092	1290	-199	0.67	0.82		
59	112	221	-109	0.87	0.95		
65	713	465	248	0.84	0.66		
77	325	0	325	0.22			
82	1073	492	581	0.92	0.86		
88	313	420	-107	0.91	0.85		
90	540	162	378	0.83	0.69		
91	164	219	-54	0.82	0.70		
96	905	893	12	0.97	0.98		
97	775	851	-75	0.30	0.70		
99	1206	1634	-428	0.93	0.82		
109	759	386	373	0.39	0.04		
112	744	346	398	0.99	0.16		
115	1192	1095	97	0.96	0.54		
116	896	1125	-230			0.81	0.67
117	766	1040	-274	0.77	0.81	0.01	0.01
120	59	0	59	0.10			
129	1730	1376	354	0.85	0.93		
135	662	423	240	0.37	0.12		
141	1189	1117	72	0.66	0.80		
143	1674	1626	48	0.94	0.57		
144	21	0	21	0.15			

Table 9.7. (continued)

Standard group							
				Primary air conditioner Model R^2		Secondary air conditioner Model R^2	
Statistic	Pre-wx[a] space cooling energy use (kWh)	Post-wx space cooling energy use (kWh)	Space cooling energy savings (kWh)	Pre-wx	Post-wx	Pre-wx	Post-wx
Based on 100-house data set							
Average	713	683	30	0.59	0.66	0.43	0.31
Standard Deviation	511	568	282	0.31	0.26	0.53	0.27
Observations	33	33	33	32[b]	27[b]	3	3
Minimum	21	0	-738	0.01	0.04	0.01	0.01
Maximum	1730	2364	581	0.99	0.98	0.81	0.67
Median	744	465	12				
Based on 39-house refined data set							
Average	1174	1124	50	0.77	0.76	0.81	0.67
Standard deviation	354	519	339	0.17	0.15		
Observations	14	14	14	14	14	1	1
Minimum	404	464	-738	0.44	0.45		
Maximum	1730	2364	581	0.97	0.98		

[a] Wx = weatherization

[b] Available when energy use was zero.

Note: Model R^2's for secondary air conditioners:
House 20: pre, 0.46, post, 0.24; House 116: pre, 0.81, post, 0.67; House 117: pre, 0.01; post, 0.01.

four standard deviations from the group average savings, while the most extreme saver in the control group is more than three standard deviations from the group average. As a result, these houses have a very strong influence on averages for these groups. Without its one extreme saver, the control group would have reported an average savings of −37kWh, which is much less than the 8 kWh reported in Table 9.5. Without its most extreme saver, average savings for the FTA group would be reduced to approximately half of the 165 kWh reported. Based on a modified three-sigma outlier test (Lipson and Sheth 1973), the largest savers in the control and FTA groups would be classified as outliers when compared with their group distributions. The second highest saver in the FTA group, also a considerable distance from the general distribution for this group, is not an outlier based on this test.

The average cooling energy savings for the three groups are summarized in Table 9.8. Savings for the control and standard groups were 8 kWh and 30 kWh, respectively. The average savings of 165 kWh for the FTA houses was higher than the savings for the other two groups, suggesting better performance by the FTA group. Compared with

Table 9.8. Cooling energy savings statistics by **group** for all houses and the **refined,** higher user data set

Group	Range (kWh)	Average (kWh)	Standard deviation of average (kWh)	Percent based on averages (%)	Number of houses
Based on the **100-house** data set					
Control	-775 to 1510	8	415	1.1	34
FTA[a]	-479 to 2593	165	542	18.8	33
Standard	-738 to 581	30	282	4.2	33
Based on the **39-house** refined data set of higher cooling energy **users**					
Control	-750 to 713	62	388	4.4	13
FTA	-70 to 482	222	147	20.1	12
Standard	-738 to 581	50	339	4.3	14

[a] **FTA** = Field Test Audit

pre-weatherization average cooling energy use, a 1% savings resulted for the control group, 19% for the FTA group, and 4% for the standard group. Adjusted for the control group change, the FTA group saved 18% (net savings), much higher than the 3% net savings for the standard group. Due to large standard deviations, a statistical difference between the average FTA savings and savings for the other two groups could not be detected at a *95%* confidence level.

Like the original heating data set, the 100-house cooling energy data set contains every house in the test for which measured **pre-** and **post-weatherization** cooling energy data were available. This includes a number of houses with very poor models. Unlike in the heating energy data set, however, the poor models normally were not due to bad data or a lack of data resulting from data collection problems. The lack of good fits to linear models simply resulted from the minimal and random use of air conditioning in many of the houses (numerous houses used little air conditioning energy, and many used it only for a few weeks). Examples of these are shown in Fig. 9.9. Many houses had even fewer weeks with cooling energy use than the houses in this figure. The minimum temperature difference at which air conditioning energy use first occurred was used as a cutoff temperature difference for normalization for models that did not go to zero within the temperature range where cooling energy use occurred. House 51 in Fig. 9.9, with its slightly negative model slope, is an example of a house where a cutoff was necessary. For many houses, the limited and random use of air conditioning energy resulted in minimal correlations between air conditioning energy use and indoor-outdoor temperature

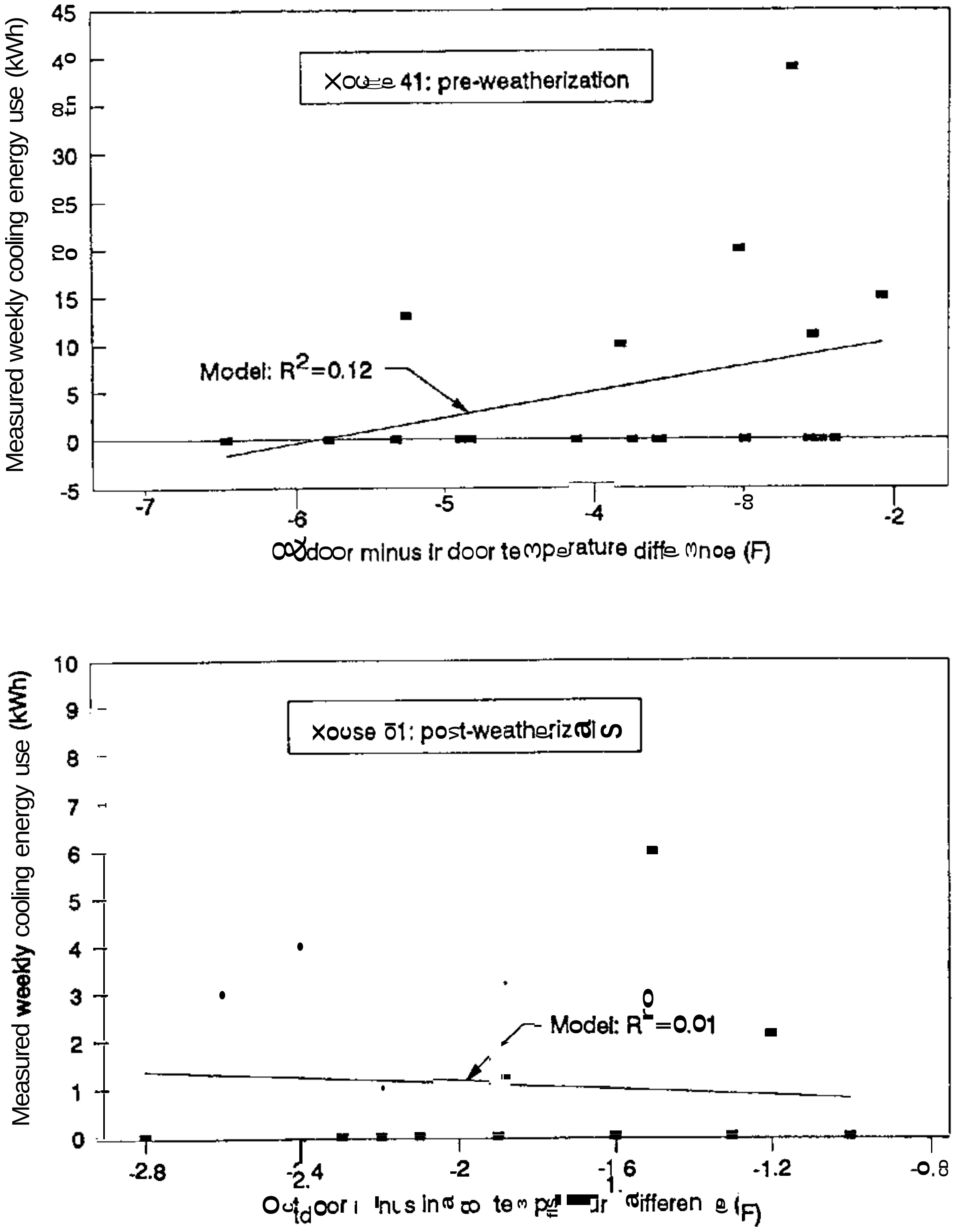


Fig. 9.9. Data plots for two houses having few weeks of cooling energy use and random cooling energy use pattern.

difference, or outdoor temperature. Low use of air conditioning energy appeared more driven by occupant behavior (or some other influence) than by outdoor temperature.

The use of a simple average was examined as a model for these low-consumption houses. Only weekly consumption that occurred above the indoor-outdoor temperature difference where air conditioning energy use was first measured was included in the average. Temperature normalization was then done by applying these averages to the TMY temperature data, producing temperature differences above the difference at which use of air conditioning energy was first detected. This approach provided savings for the three groups that were very similar to the results from the temperature-dependent models. The average models for these low consumers, like the temperature-dependent models, could easily depend strongly on the severity of the weather that occurred (a mild season would generally produce a lower average than a more severe season). Normalizing using this type of model still could not avoid the sizeable uncertainties for normalized consumption in some houses.

Houses with reliable temperature-dependent models (mostly those using more cooling energy) were analyzed separately from houses that used less cooling energy to better determine the cooling energy savings that could be achieved in houses where significant cooling energy is used. The same screening technique used in the heating energy analysis was used to separate these houses and produce a refined data set with better reliability, and perhaps reduced within-group variance so that statistically significant differences might be detectable. The 100-house data set is plotted as a function of the screening variables in Figs. 9.10 and 9.11. Houses in the lower right corner of these figures (high R^2 and small relative standard errors) are those that are the most reliable. The scatter shown for the cooling data is much different from that for the heating data. If the same quality criteria used for the heating results were applied to cooling results ($R^2 \leq 0.70$ and relative standard error ≤ 0.06), only ten houses would be left in the refined sample. Because this criterion was too restrictive and some degree of refinement was needed to at least remove the most unreliable models, relaxed screening criteria were chosen. The criteria selected for screening cooling data were $R^2 \geq 0.30$ and a relative standard error of normalized consumption ≤ 0.25. These values are considerably less stringent that those applied to the heating data. Applying these screening criteria resulted in a refined sample size of 39 houses (12 in the control group, 13 in the FTA group, and 14 in the standard group). Because both the pre- and post-weatherization models of each house had to satisfy the screening criteria to be included, doubling the standard error criteria and further relaxing the R^2 criteria would have increased the size of the refined data set only marginally.

The impact of the refinement can be seen by comparing the savings distributions for the refined data set in Fig. 9.12 with those for the original data set in Fig. 9.8. The refinement removed almost all of the low cooling energy users, the extreme savers, and some of the moderate savers and nonsavers in each group. In contrast to the refined standard and control groups with about the same number of savers and nonsavers, the FTA group has only one house with negative savings (see Fig. 9.12). The range of pre-weatherization consumption represented in the two treatment groups in the refined data set is very similar and covers most of the range represented in the control group.

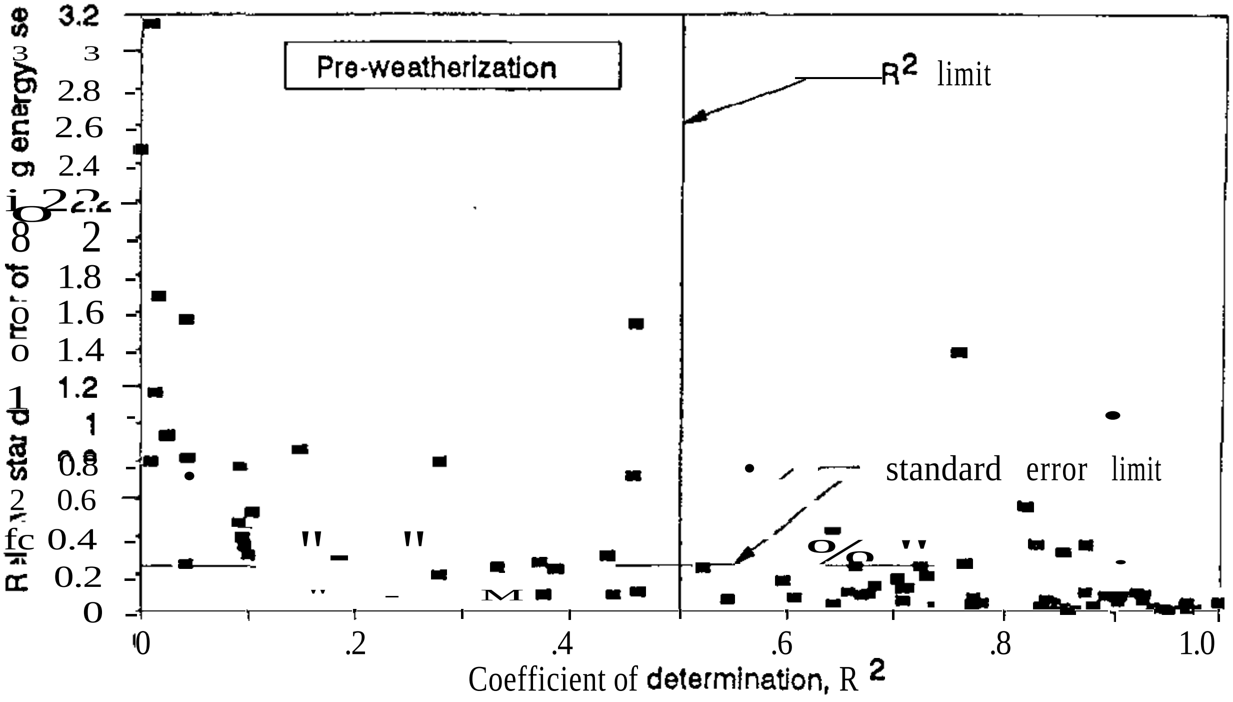


Fig. 9.10. Normalized post-weatherization cooling energy use as a function of reliability screening criteria (1 point with standard error = 10.3 not shown).

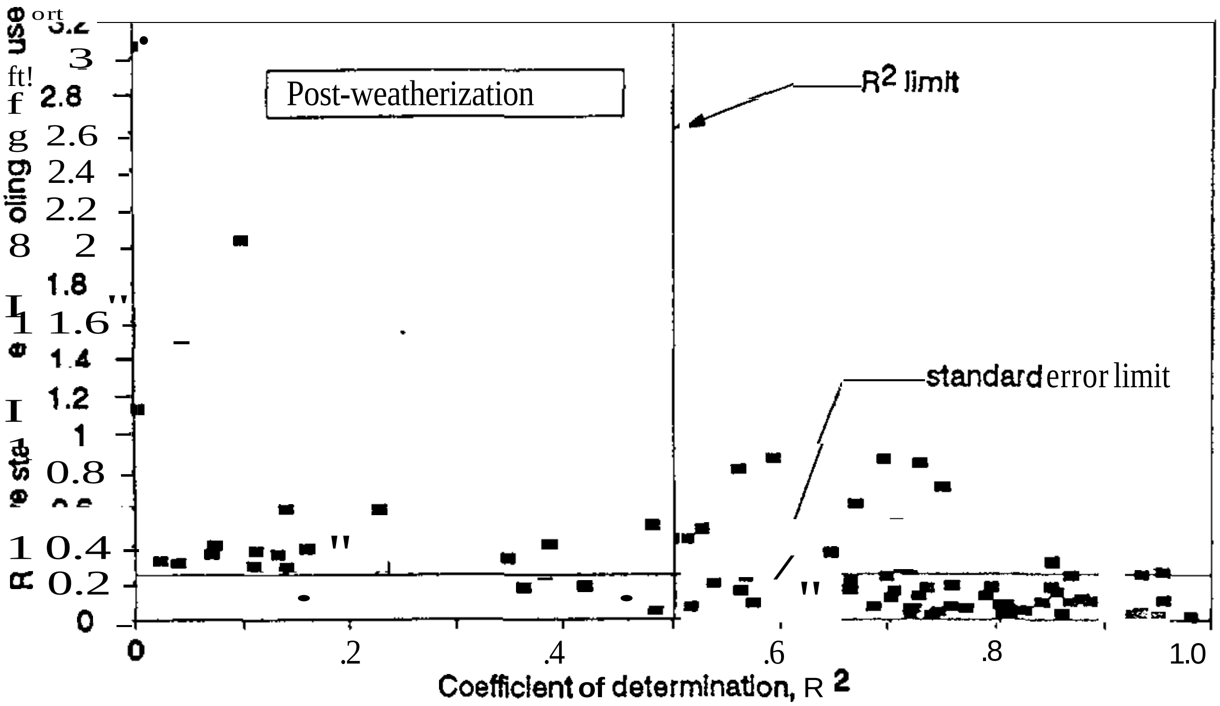


Fig. 9.11. Normalized post-weatherization cooling energy use as a function of reliability screening criteria.

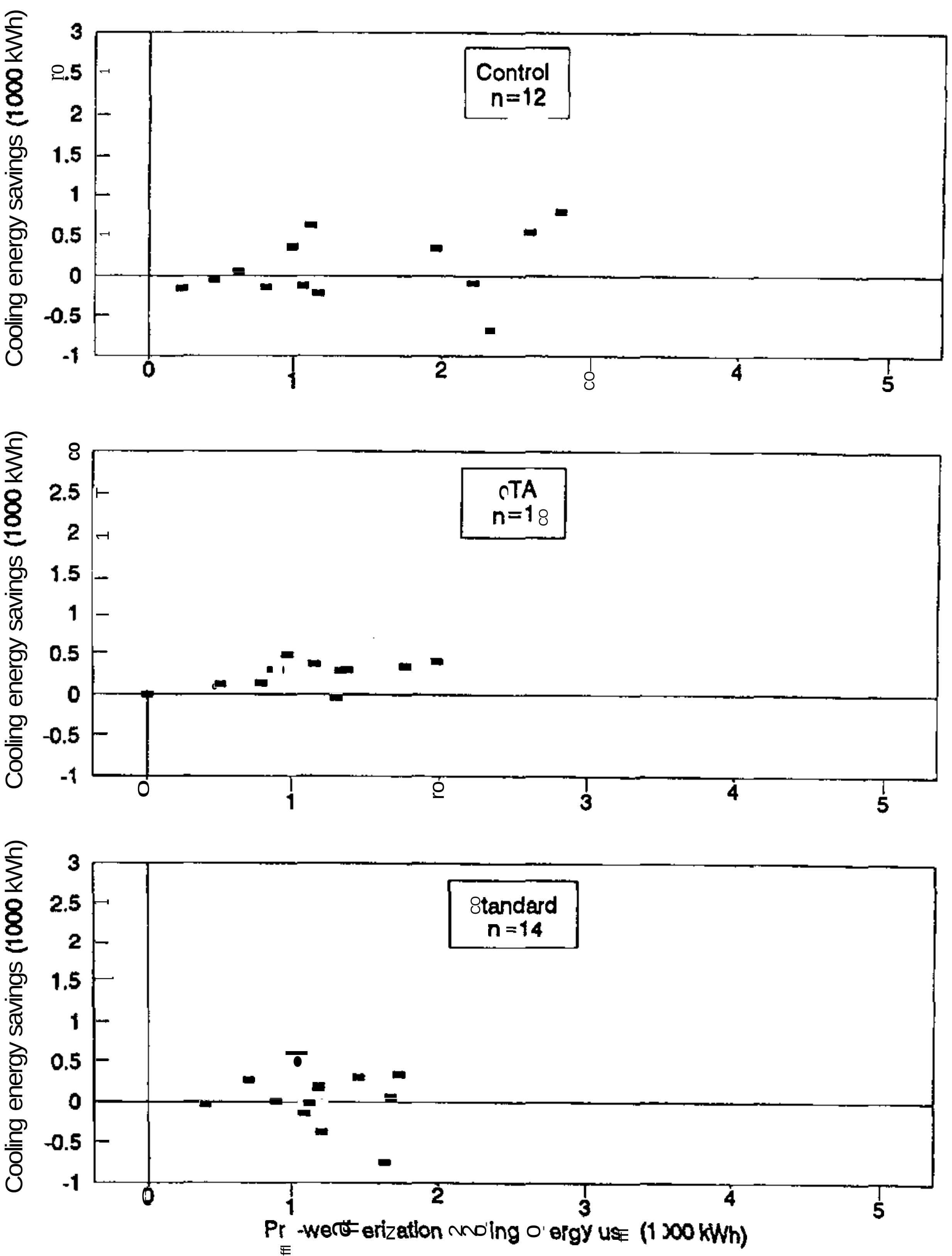


Fig. 9.12. Cooling energy savings as a function of pre-weatherization cooling energy use by group for the refined, higher cooling energy use group.

Statistics associated with the higher cooling energy use houses in the refined group are presented at the ends of Tables 9.5 through 9.7. Comparing the pre- and post-weatherization average consumption levels to those for the 100-house sample in the same tables confirms that these houses use much more cooling energy on average than the whole 100-house data set, around 60% more. Savings for the refined higher cooling energy use houses are shown along with those for the original 100-house data set in Table 9.8. As expected, the houses using more cooling energy had higher savings than the original data set, 62 kWh compared with 8 kWh for the control group, 222 kWh compared with 165 kWh for the FTA group, and 50 kWh compared with 30 kWh for the standard group. Although the differences between the refined group averages seem significant, these averages are still overwhelmed by the variability (standard deviation) within the sample. The FTA group is the only group that experienced a major reduction in the sample standard deviation as a result of the refinement to the more predictable houses using more cooling energy. Except for the refined FTA group where the ratio is <1, standard deviations are at least six times greater than group averages.

Compared with pre-weatherization average cooling energy use, savings were 4% for the control group, 20% for the FTA group, and 4% for the standard group. These results are very similar to those obtained from the original 100-house data set which contained very low cooling energy users as well. Adjusting for the control group savings produced net savings of 0 for the standard group and 16% for the FTA group for the houses with high cooling energy use. As with the results for the 100-house sample, the variability of cooling energy savings in each group was much too large to allow detection of any statistical difference.

10. WEATHERIZATION COSTS

Total weatherization costs for houses in the FTA and standard groups are summarized in Tables 10.1 and 10.2. The average cost for FTA weatherizations was $1056, almost identical to the average standard weatherization cost of $1059. When average weatherization costs are examined by test site, however, substantial differences between FTA and standard weatherization costs are apparent. The site averages in Table 10.2 indicate that the average FTA weatherization cost was 14% less than the average standard weatherization cost at Site A, and *1%* less at Site B. The cost comparison at Site C was much different from the others: the average FTA weatherization cost was 38% higher than the standard weatherization average. In the comparison of FTA versus standard weatherization costs, the much higher cost at Site C balanced the lower costs at Sites A and B, resulting in near identical cost averages for the overall group comparison.

Standard weatherization costs at Site C were not only much less than FTA weatherization costs, but also around 40% less than standard weatherization costs at the other two sites. The lower average standard weatherization cost at Site C is directly related to the fact that fewer measures were installed in the standard group at Site C than in the standard group at the other sites. This becomes apparent when the measures summary for Site C standard group houses, Houses 109 to 144, is compared with that for other standard group houses in Table 10.1. Attic and floor insulation measures were much more common at Sites A and B, houses 3 through 99.

Weatherization costs for individual houses in the FTA group ranged from a low of $77 to a high of $2510. The range of costs in the standard group was from $109 to $1998. The distribution of weatherization costs by group is shown in Fig. 10.1. The FTA spread individual house weatherization costs over a wider range than the standard weatherization approach. Standard weatherization costs fell into the lower four cost ranges, while FTA costs covered six cost ranges. Approximately 90% of the standard weatherizations cost between $500 and $1500. Only around 70% of the FTA weatherization costs were within this cost range. No weatherizations in the standard group exceed $2000, while four in the FTA group exceeded $2000. Because site C had a large number of houses with low-cost weatherizations, the distribution of weatherization costs for sites A and B was examined separately to ensure that the trend was not due solely to the site C houses. The distribution of weatherization costs for sites A and B only is shown in Fig. 10.2. Costs for the standard weatherizations at sites A and B were even more concentrated; they fell in three dominant ranges, and only one weatherization was outside the $500-$1500 range. In contrast, 25% of the FTA houses were outside this range.

There were significant differences in how the two weatherization audits directed money. Cost breakdowns for the two groups by expenditure type are illustrated in Fig. 10.3. Costs outside the labor category are for materials only. Several characteristics of the two approaches can be identified in this figure. The percentage of weatherization dollars spent on labor costs (including labor for repairs and air sealing) was about the same. This means that material expenditures were also similar, but the proportion spent on the different measures varies dramatically between groups. The percentage of costs

Table 10.1. Summary of weatherization costs and measures installed

Field Test Audit group			Standard group		
House	Total wx[a] cost ($)	Measures installed	House	Total wx cost (S)	Measures installed
2	558		3	1647	A30,F19,W
4	1036	A30,F19,DI	5	886	A30,SW
9	762	A30,F19	6	970	SW
10		(OUT OF TEST)	7	1432	F19,SW
18	1076	A30.W	8	862	A30,F19
21	1364	A30,F19,W,DI	13	1716	A30,SW
22		(OUT OF TEST)	15	1523	A30,F19,SW
26	1585	A30	20	721	A30,F19,SW
27	1071	F19	2S	996	A30
30	414		29	1425	A30,SW
36	S42	W,KW	31	429	A30,SW
37	1549	A30,F19,W	32	1963	F19,SW
40	S91	SW	33	798	F19,SW
46	1051	F19,W,PI	59	1089	A11,F11,SW
52	1778	A30,F19,PI	65	732	A30,SW
58	1322	A30,F19,S,PI	77	686	A11,SW
61	1571	A30,W	78	1272	A30,SW
62	370	A19	81	1998	A30,F11,PI,DI
67	486	A30	82	1265	A30,SW
68	2062	A30,F19,W	87	1040	A30,SW
69		(OUT OF TEST)	88	1909	A30,F11,SW,PI
72	941	F19,S	90	1386	A30,F11,SW
73	890	A30,W	91	948	A30,SW
79	708	A30	93	1120	A30,SW
85	2143	A30,F19,W,PI,DI	96	1223	SW
94	1461	A30,W	97	1596	A19,F11,SW,PI
95	338		99	1448	A30,F11,SW,PI
102	1228	A30,W	109	370	A30,SW
103	1063	A30,W	112	109	
107	473	W	114	1199	SW
110	248	A30	115	539	A30,SW
111	2054	A30,F19,W	116	1383	A30,UPIN,SW
113	840	A30,F19	117	522	SW
118	723	A30,F19	120	255	
127	2510	A30,F19,W	122	1319	UPIN,SW
128	1060	A30,W	129	509	SW
137	854	A30,F19,W	135	509	SW
138	578	A30,W	141	1775	A30,SW
140	1106	A30,W	143	170	SW
145	77		144	635	A30
Average	1056		Average	1059	

[a] wx = weatherization

Table 10.2 Total weatherization costs by group

Field Test Audit group			Standard group		
Site	Average total wx[a] cost (S)	Number of houses	Site	Average total wx cost (S)	Number of houses
A	1017	12	A	1182	13
B	1172	12	B	1265	14
C	986	13	C	715	13
A,B,C	1056	37	A,B,C	1059	40

attributable to insulating materials in the FTA houses was around 34%, compared with only 18% in the standard houses. The other major difference was in costs for storm windows, which accounted for approximately 1/3 of all material costs in the standard houses. Storm windows were almost unrepresented in the FTA material costs (less than 2%). Material costs for repairs and air sealing were very similar across groups.

At two sites, labor costs associated with caulking, weatherstripping, and general infiltration work in the standard audit were not reported separately from the labor reported for installing other measures. As a result, the costs of these measures could not be directly compared with the costs of the blower-door-directed air sealing procedure used in the FTA group. The costs for these infiltration measures were separated out at site B, however, where measures were contractor installed. Standard air sealing costs are summarized alongside blower-door-directed air sealing costs in Table 10.3 for site B. Average costs for the blower-door-directed air sealing procedure were about 25% higher than costs for the air leakage work done in the standard group, amounting to an extra cost of around $47 per house for the FTA group.

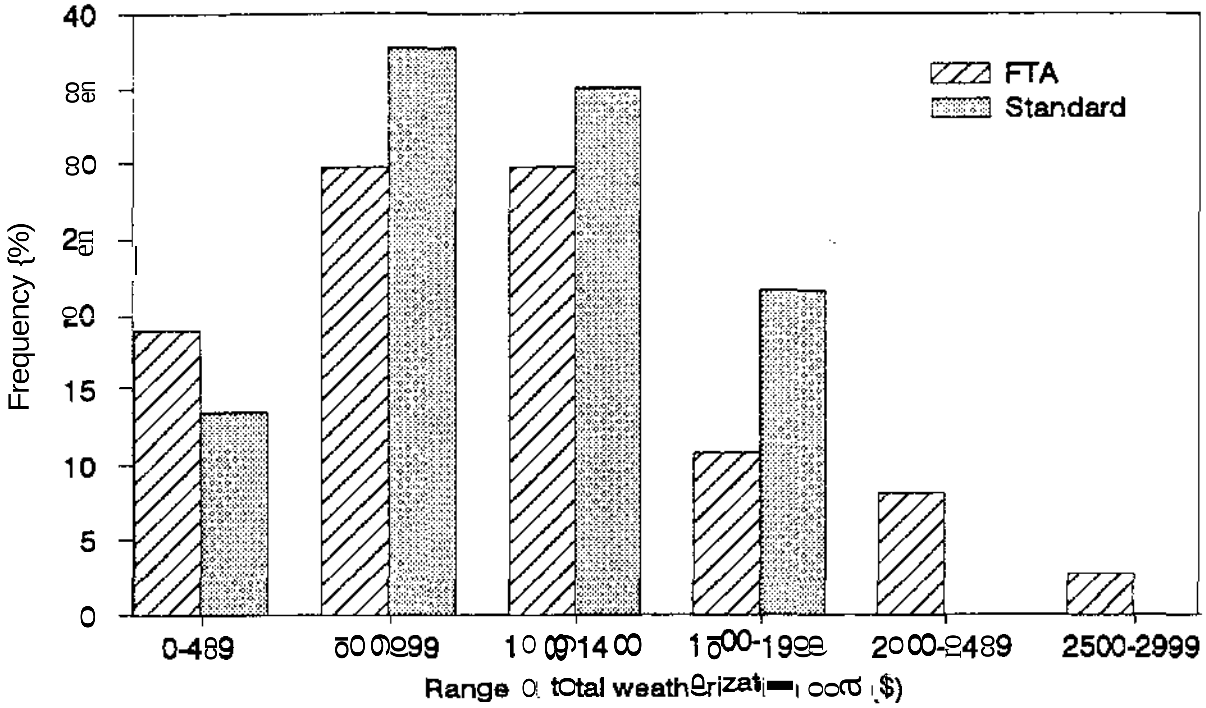


Fig. 10.1 Dis[redacted]ution of weatherization costs by group for [redacted] [redacted].

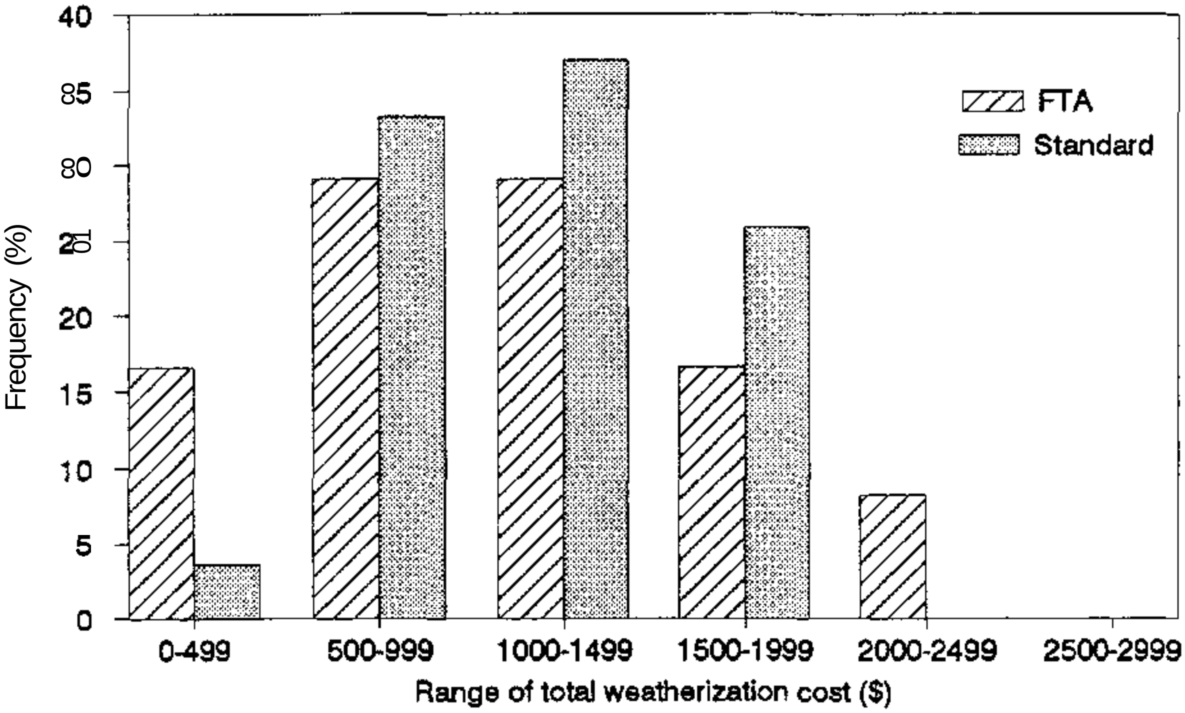


Fig. 10.2. Distribution of weatherization costs by group for sites A and B.

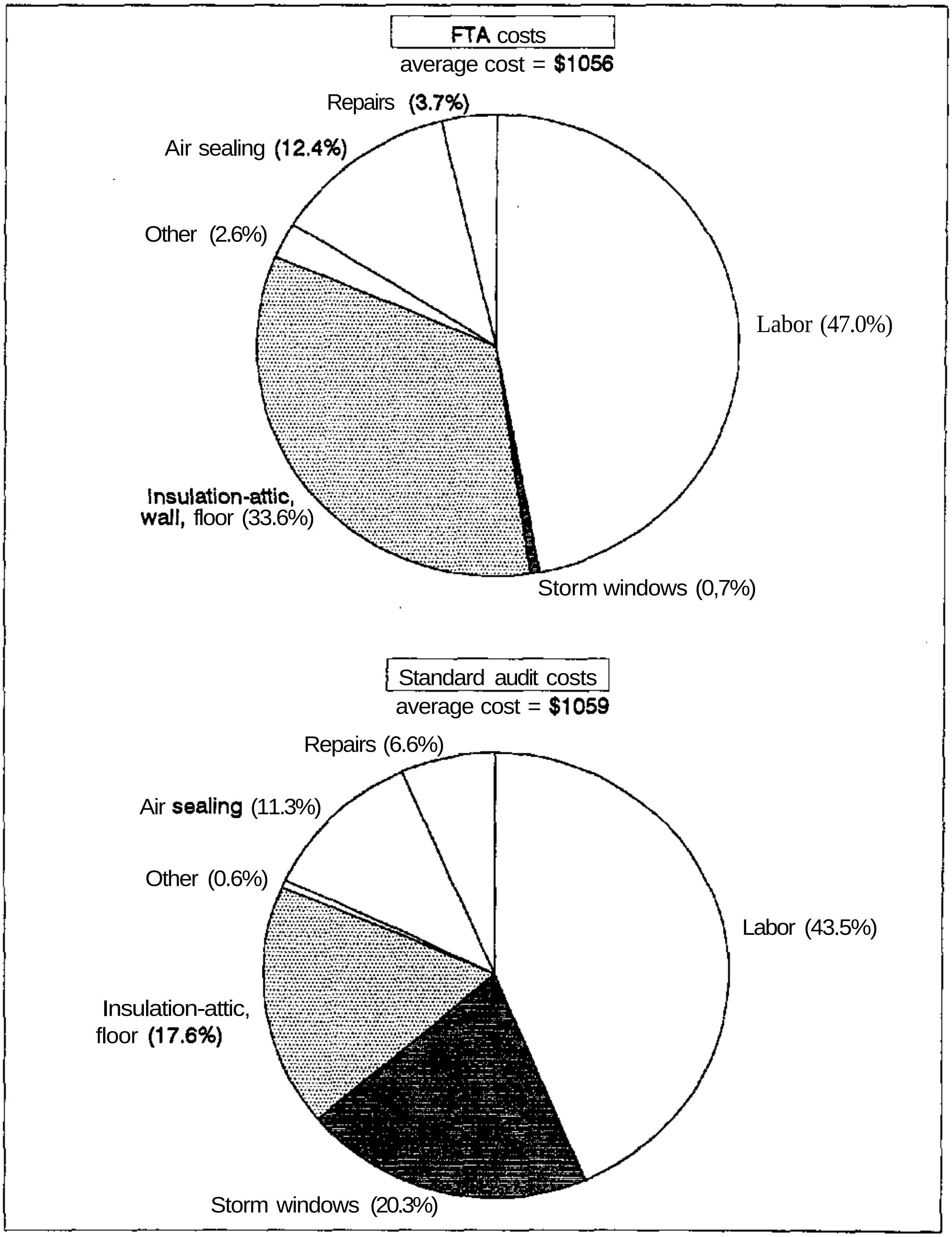


Fig. 103. Comparison of expenditures from the two **weatherization** approaches.

Table 103. Comparison of air sealing costs for the Field Test Audit and standard (Retro-Tech) groups at site B

Field Test Audit group		Standard group	
House	Cost for air sealing, with labor (S)	House	Cost for air sealing, with labor (S)
52	236	59	193
58	479	65	138
61	154	77	145
62	59	78	127
67	258	81	225
68	135	82	128
72	93	87	113
73	141	SS	154
79	372	90	199
85	239	91	202
94	188	93	169
95	321	96	170
		97	210
		99	293
Average	223	**Average**	176

11. HELD TEST AUDIT PREDICTIONS VERSUS MEASURED PERFORMANCE

The ability of the FTA to predict weatherization savings for both heating and cooling energy use was examined. Because accurate savings predictions depend on the ability of the audit to predict initial heating and cooling loads accurately, predicted annual energy consumption for heating and cooling was compared with pre-weatherization weather-normalized measured consumption. These analyses used the higher-quality refined heating and cooling data sets.

11.1 PRE-WEATHERIZATION SPACE-HEATING CONSUMPTIONS

Space-heating energy consumption (pre-weatherization) and savings from audit predictions are presented alongside measured performance data in Table 11.1. Statistics associated with these values are included at the bottom of this table. FTA-predicted pre-weatherization heating consumption ranged from 29.4 to 109.2 MBtu. In comparison, normalized consumption ranged from 18.2 MBtu to 81.1 MBtu. Pre-weatherization heating consumption predicted from the FTA averaged 74.8 MBtu, compared with a 49.8 MBtu average for measured data. The differences between predicted and normalized consumption are shown in Fig. 11.1. FTA predictions were close to normalized values (within 15 MBtu) for half the houses and were considerably higher (more than 30 MBtu) for most of the remaining half (8 of 9). Eighty-three percent of FTA predictions were larger than normalized consumptions, and 17% were below.

The relationship between predicted and normalized consumption for each house is shown in Fig. 11.2. If predicted consumption matched normalized consumption, data points in this figure would lie along the line with a slope equal to 1. Over-predictions fall to the right of this line, and under-predictions fall to the left. This figure shows that FTA predictions are approximately equally distributed about the slope = 1 line when FTA predictions are below 80 MBtu. This distribution indicates that on the average, FTA predictions are almost equal to normalized values when FTA predictions are below 80 MBtu. When FTA predictions are greater than 80 MBtu, however, many FTA predictions are much larger than normalized consumption.

Because larger consumption is often related to larger houses, and larger houses are often only partially heated, the relationship between heated and total floor area was examined. Many houses had significant differences between heated and total floor areas, as can be seen in Fig 11.3. This discrepancy occurred because room space heaters, the prevalent heating system, normally cannot provide uniform heating throughout a house and because rooms often were closed off.

Because the FTA version that was tested assumed the whole house to be heated, while normalized consumption represented heating only a portion of the total floor area in many cases, predicted values were adjusted for heated floor area in an attempt to improve the agreement between predictions and normalized consumption. When adjusted for heated area, FTA-predicted consumption averages 47.9 MBtu, almost identical to the normalized average of 49.8 MBtu.

Table 11.1. Predicted and normalized pre-weatherization annual space-heating energy consumption and savings in the refined data set

House	FTA[a]-predicted heating energy use (MBtu)	Normalized heating energy use (MBtu)	FTA-predicted heating energy savings (MBtu)	Normalized heating energy savings (MBtu)
9	105.5	67.4	74.9	5.2
37	85.1	44.7	68.1	0.3
46	84.3	44.4	34.1	21.4
52	109.2	29.3	46.9	12.7
61	95.0	37.5	61.5	10.7
62	29.4	25.3	2.7	4.1
68	103.4	40.5	75.7	28.3
73	84.1	60.8	51.1	10.8
79	70.7	64.2	25.0	18.5
85	83.1	69.2	61.8	36.7
94	62.0	65.3	37.9	33.3
95	98.2	51.1	0.0	1.6
102	64.4	61.7	35.8	36.8
103	70.9	81.1	40.1	53.0
107	29.8	18.2	10.0	2.7
110	45.7	34.0	3.8	-11.6
111	82.5	49.9	53.5	13.3
145	43.0	52.0	0.0	-27.3
Average	74.8	49.8	37.9	13.9
Median	82.8	50.5	39.0	13.0

[a] FTA = Field Test Audit.

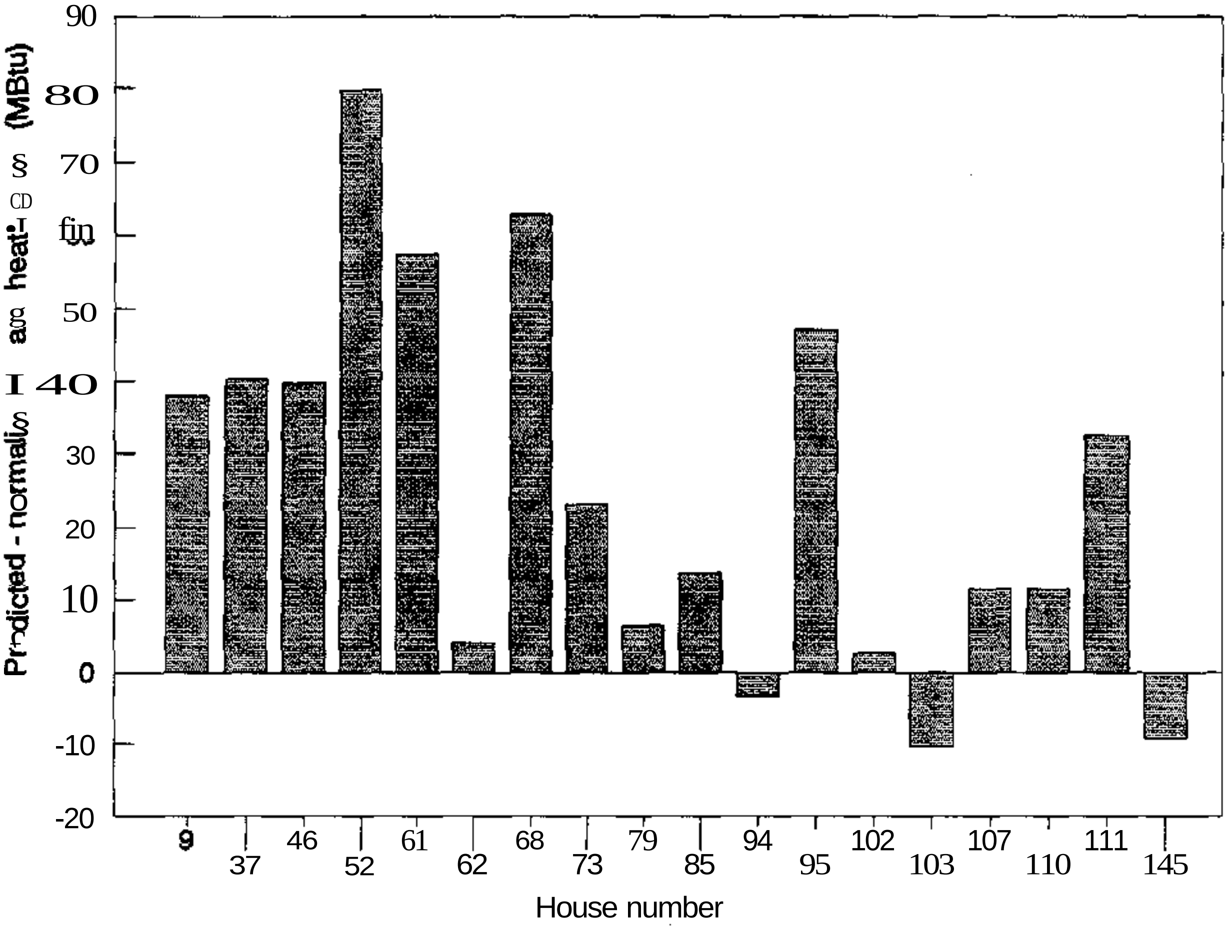


Fig. 11.1 Differences between Field Test Audit-predicted and normalized pre-weatherization space heating energy consumption.

The relationship between heated-area-adjusted predictions and normalized consumption for each house is shown in Fig. 11.4. This figure has several differences from the similar figure based on the whole house being heated (Fig. 11.2). Most of the highest consumption predictions dropped following the adjustment. In addition, the pattern of consistent FTA overprediction for the largest consumers (above 80 MBtu) is no longer evident. Although sizeable differences remain between many FTA predictions and normalized values, overpredictions are comparable in number to underpredictions. Both over- and underpredictions occurred for houses using room space heaters and for those using central furnaces.

11.2 SPACE-HEATING ENERGY SAVINGS

FTA-predicted space-heating energy savings, measured savings, and associated statistics for each house are also summarized in Table 11.1. FTA-predicted space heating

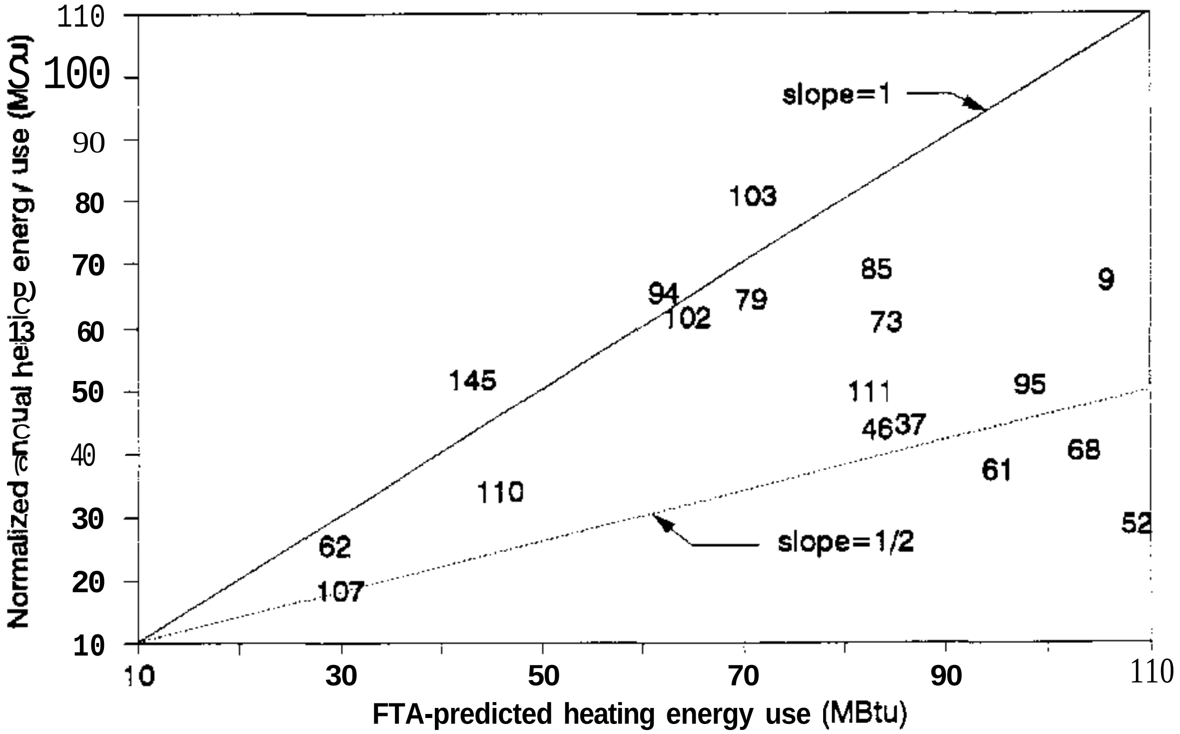
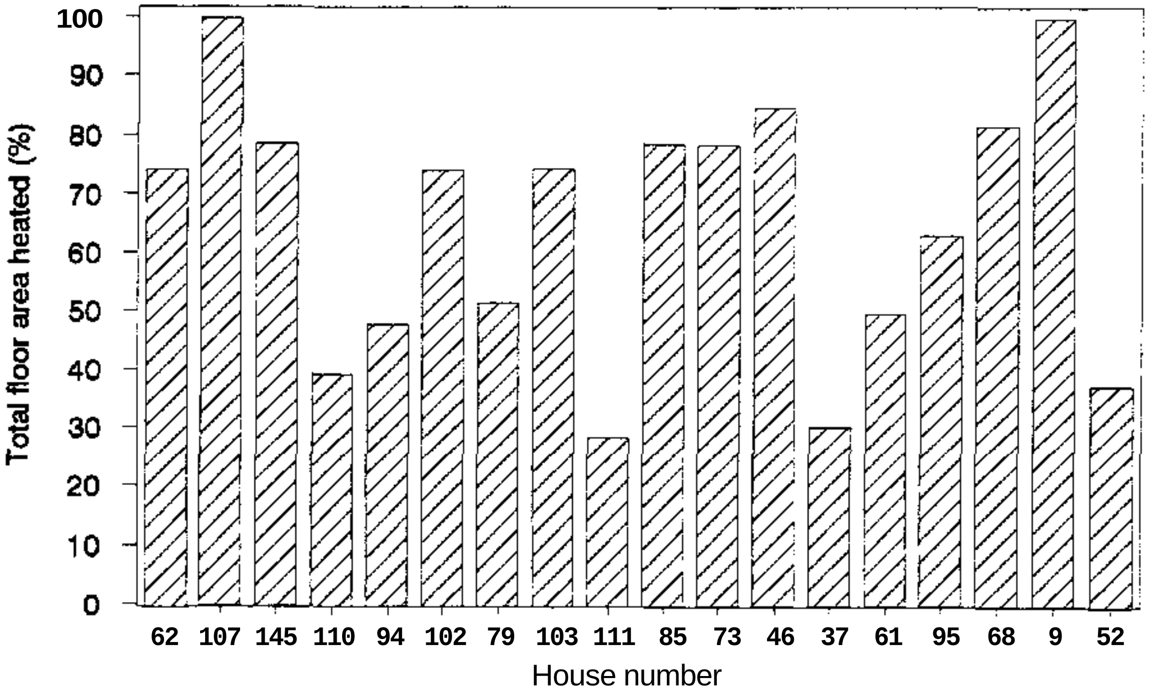


Fig. 11.2. Plot of normalized vs. Field Test audit-predicted pre-weatherization heating energy consumption by house number.



Hg. 113. Distribution of the percentage of total floor area heated by house number (ordered left to right by increasing Field Test Audit-predicted pre-weatherization heating energy use.

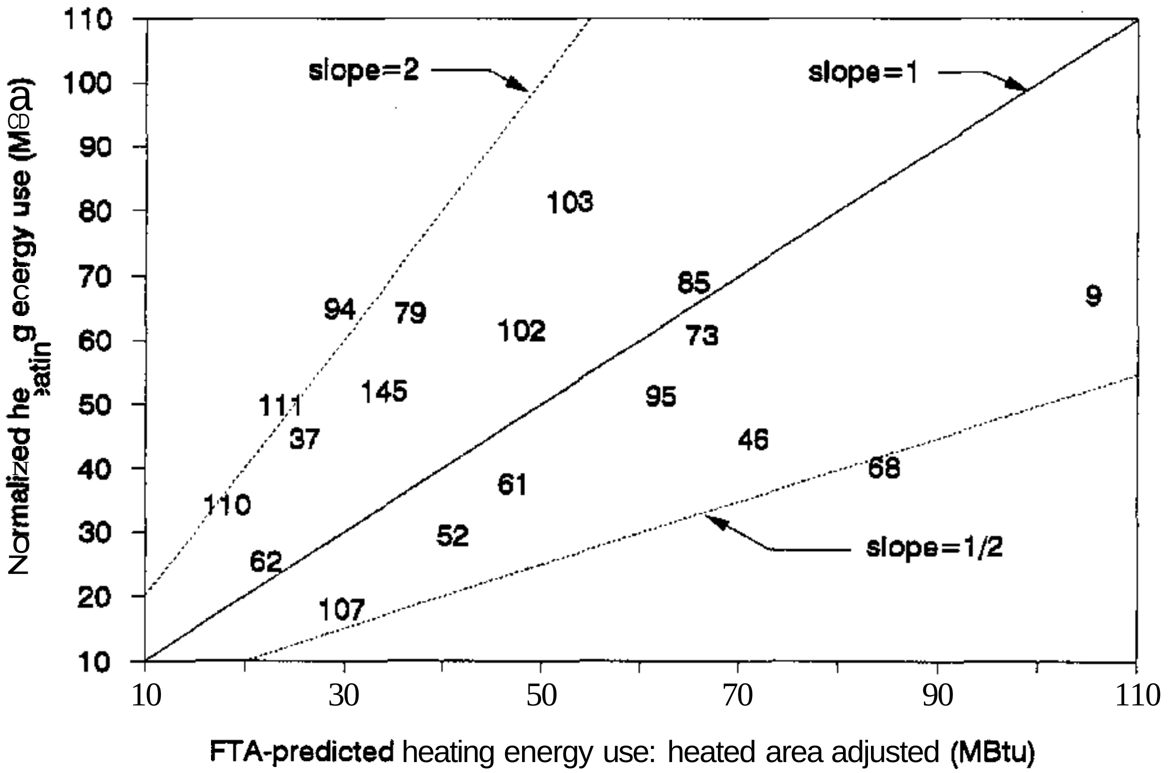


Fig. 11.4. Plot of normalized vs. Field Test Audit-predicted pre-weatherization heating energy use with Held Test Audit predictions adjusted for heated area.

savings ranged from 0.0 MBtu in house 145, where only air sealing was performed (the FTA version tested did not predict savings from air sealing), to 75.7 MBtu in house 68 where numerous measures were installed. Normalized savings ranged from −27.3 MBtu (an increase in energy use) for house 145 to 53.0 MBtu in house 103. FTA-predicted space-heating energy savings averaged 37.9 MBtu, compared with an average of 13.9 MBtu based on measured data.

Normalized values for heating energy savings show two negative savers (houses 110 and 145); these increases in energy use likely are due to significant changes in occupant behavior. As a result, FTA predictions, on average, would likely be larger than the average of normalized values because the FTA normally would not predict an increase in total space-heating energy use due to weatherization. Some specific cooling energy measures can result in increased heating energy use, but those increases are normally small compared with the heating savings resulting from the package of weatherization measures applied to a house.

The relationship between predicted and normalized savings for each house is shown in Fig 11.5. As in the similar figure for consumption, FTA-predicted savings on average are approximately equal to normalized values in one area of Fig. 11.5 and substantially different in another. When FTA-predicted savings exceed 40 MBtu, predicted values

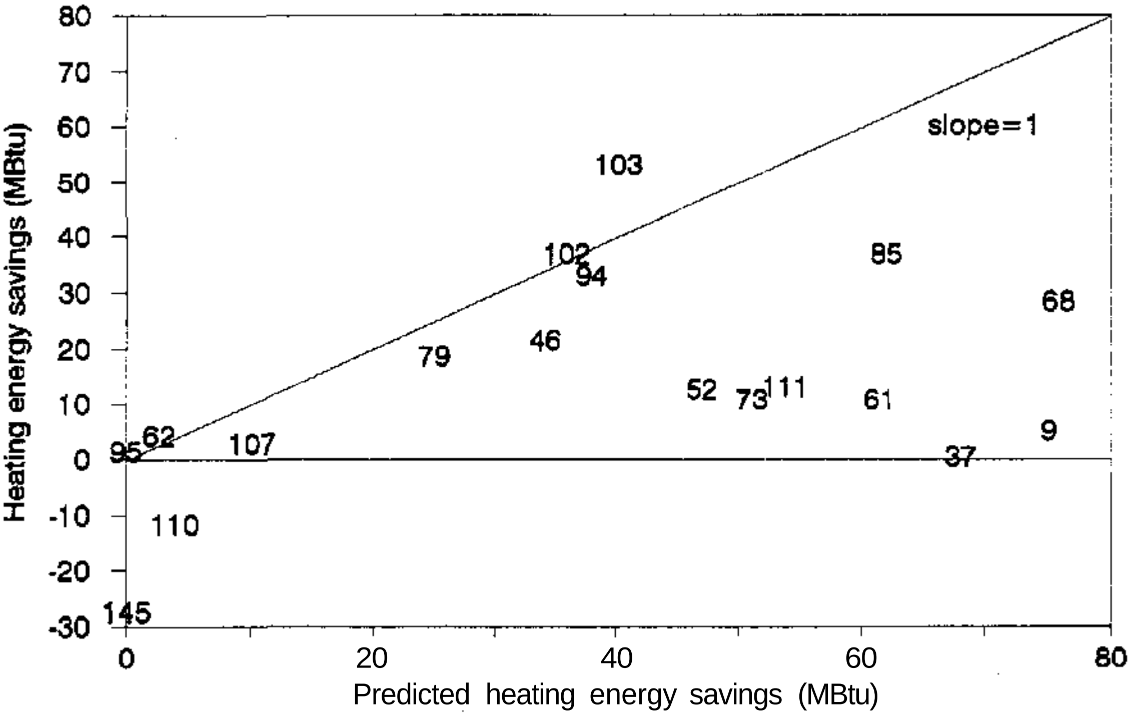


Fig. 11.5. Plot of normalized vs. Field Test Audit-predicted heating energy savings.

exceed normalized values considerably. Many of the houses with the highest FTA-predicted savings are those with the highest FTA-predicted pre-weatherization energy consumption (Fig. 11.2). FTA predictions are predominantly higher than normalized values, and the higher predictions appear to be the ones most out of line with normalized values.

An adjustment for heated area was also applied to predicted savings to see if values could be brought more in line with measured results. Heated-area-adjusted FTA savings predictions are plotted as a function of normalized heating energy savings in Fig. 11.6. The adjustment moved most of the predictions to between 0 and 50 MBtu, similar to the spread of the normalized values. The average of the adjusted FTA predictions is 24.4 MBtu, still higher than the 13.9 MBtu average for normalized savings. Around half of this difference is accounted for by the high predictions for houses 9 and 68.

113 PRE-WEATHERIZATION SPACE-COOLING CONSUMPTION

Space-cooling energy consumption (pre-weatherization) and savings from audit predictions are presented alongside measured performance data in Table 11.2. Statistics associated with these values are included at the bottom of this table. FTA-predicted

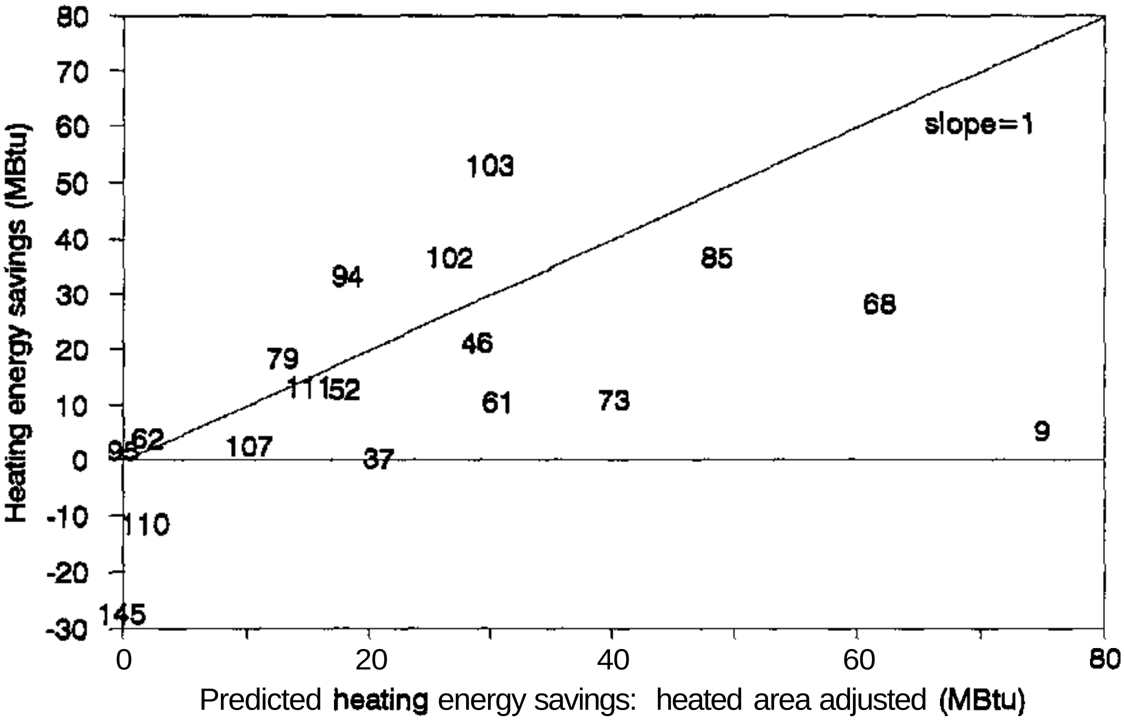


Fig. 11.6. Plot of normalized vs. Held Test Audit-predicted heating energy savings with Field Test Audit predictions adjusted for heated area.

pre-weatherization cooling energy consumption ranged from a low of 589 kWh to a high of 4182 kWh. In contrast, normalized consumptions ranged from a low of 122 kWh to a high of 1984 kWh. Half the houses used less than 1100 kWh ($70 at $0.07/kWh) of cooling energy in the pre-weatherization period. Pre-weatherization cooling consumption predicted from the FTA averaged 2323 kWh, compared with a 1023 kWh average for normalized values. Medians are considerably different at 82.8 and 50.5 kWh for predicted and normalized values, respectively. The differences between predicted and normalized consumption are shown in Fig. 11.7. FTA predictions were within 300 kWh for 17% of the houses (2 of 12), within 1100 kWh for 42%, and over 1100 kWh for 58%.

The relationship between predicted and normalized cooling consumption for each house is shown in Fig. 11.8. If predicted consumption matched normalized consumption, data points in this figure would lie along the line with a slope equal to 1. Overpredictions fall to the right of this line, and underpredictions fall to the left. This figure shows that FTA predictions are consistently above normalized values when predictions exceed 2000 kWh. Because the FTA required the percentage of total floor area cooled as input, the data shown in Fig. 11.8 are already adjusted for cooled floor area.

Table 11.2. **Predicted** and **normalized pre-weatherization** annual cooling energy **consumption** and savings in the **refined** data set by house

House	FTA[a]-predicted cooling energy use (MBtu)	Normalized cooling energy use (MBtu)	FTA-predicted cooling energy savings (MBtu)	Normalized cooling energy savings (MBtu)
4	2383	1375	-56	264
18	2693	403	1023	82
21	3587	876	888	290
30	1890	1617	0	356
46	2934	122	26	122
52	982	1984	217	366
62	1155	512	70	93
72	589	793	-62	121
102	2477	1158	891	346
103	2705	1306	1023	-70
128	4182	1334	1471	249
145	2301	801	0	127
Average	2323	1023	458	196
Median	2430	1017	144	188

[a] FTA = Field Test Audit

11.4 SPACE-COOLING ENERGY SAVINGS

FTA-predicted cooling energy savings, measured savings, and associated statistics for each house are also summarized in Table 11.2. FTA-predicted space cooling savings ranged from −62 kWh (increased cooling energy use) in house 72 to 1471 kWh in house 128. Normalized savings ranged from −70 kWh to 366 kWh. FTA-predicted cooling savings averaged 458 kWh, compared with an average of 196 kWh for normalized values. Note in Table 11.2 that the FTA predicted an increase in cooling energy use for two houses. This prediction was due to the addition of floor insulation to houses that already had a significant amount of attic insulation. When attic insulation was not present, the cooling savings offered by installing attic insulation more than offset the increase in cooling energy use created by adding floor insulation. When attic insulation was present,

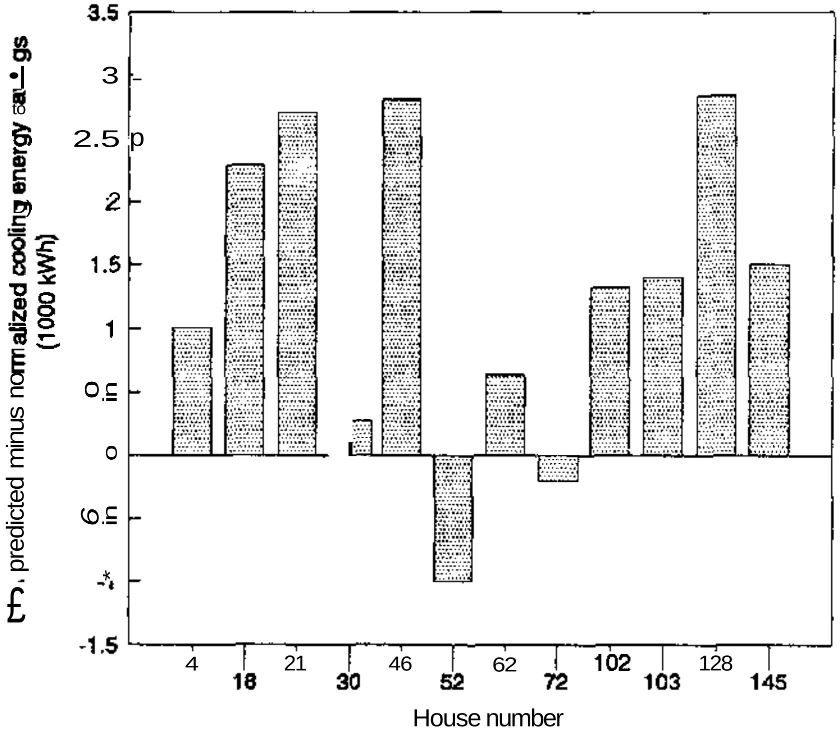


Fig. 11.7. Differences between Field Test Audit-predicted and normalized pre-weatherization cooling energy consumption.

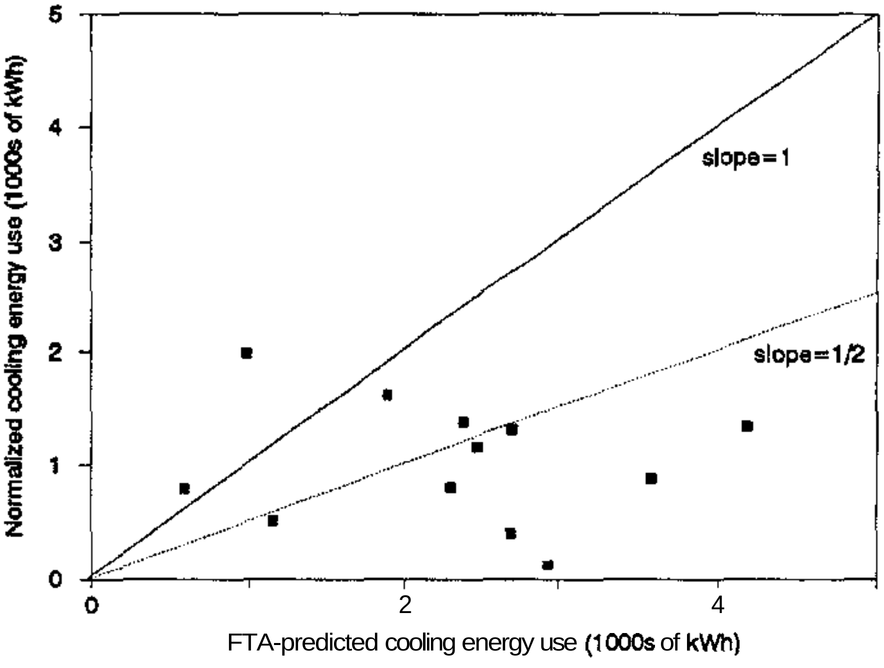


Fig. 11.8. Plot of normalized vs. Field Test Audit-predicted pre-weatherization cooling energy consumption.

the FTA recommended floor insulation because the heating energy savings from this measure were much larger than the resulting cooling energy increase.

Fig. 11.9 shows no apparent relationship between predicted and normalized cooling energy savings. Because the FTA uses a percentage of floor area cooled in its computations, a cooled-area adjustment is already reflected in these results.

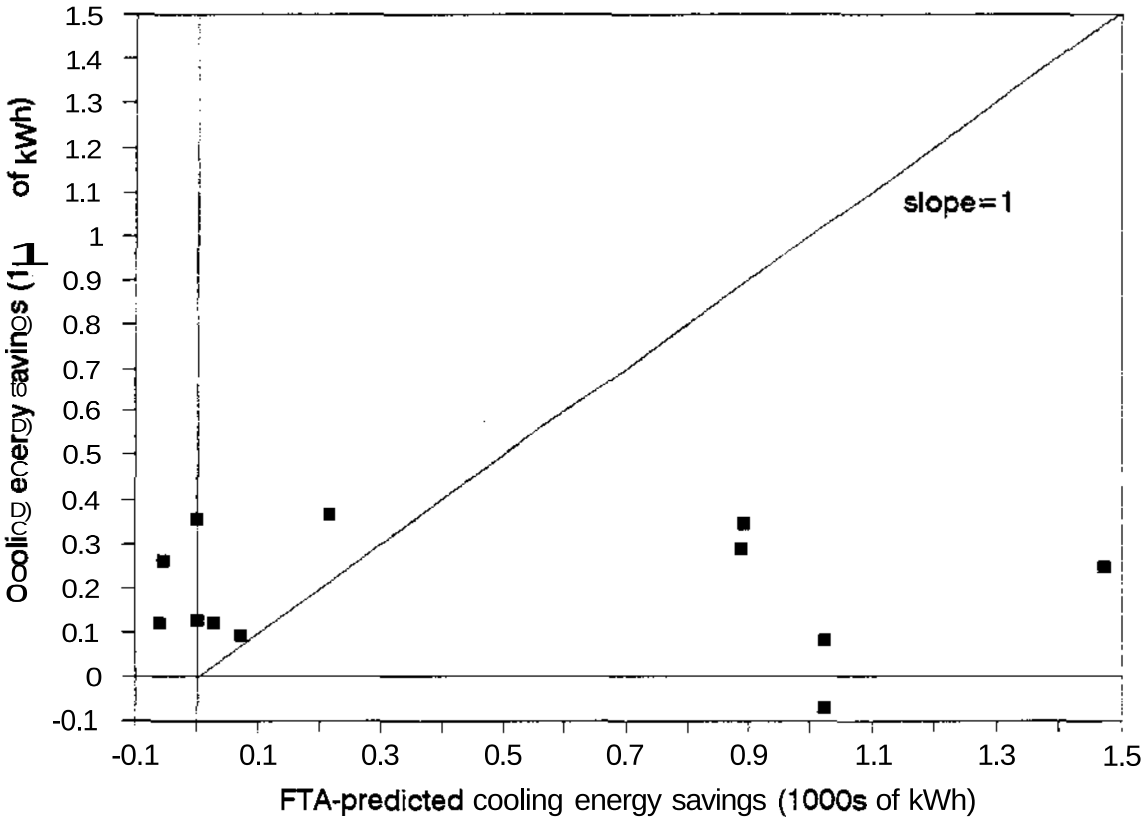


Fig. 11.9. Plot of normalized vs. Field Test Audit-predicted cooling energy savings.

12. SUMMARY AND CONCLUSIONS

Space-heating energy savings achieved in houses weathenzed using the FTA appear to be much larger than those achieved using North Carolina's current Retro-Tech-based program.

When adjusted for the control group change, the FTA provided 33% (16.5 MBtu) heating energy savings at a cost of $1056 per house. This savings corresponds to $116 annually at a heating fuel cost of $7 per MBtu. The percentage savings achieved is larger than the 19 to 24% heating energy savings reported in previous demonstration programs in Michigan, Minnesota, and Virginia (Greely et al. 1992) and larger than previous field test savings of 25% in New York (Ternes et. al. 1991) and 19% in Wisconsin (Ternes et. al. 1988). For approximately the same cost, FTA weatherizations provided 43% greater heating energy savings than standard weatherizations. Although this improvement is sizeable, no statistical difference between heating energy savings for the two groups could be determined at a 95% confidence level. This suggests that FTA-based weatherizations may not always outperform standard weatherizations in North Carolina. This result could be related to close similarities between FTA and standard weatherization packages that occur for some North Carolina houses. Although the air sealing method is different, in cases such as where limited air sealing is performed, the air sealing method may be insignificant.

Standard weatherizations achieved 23% (11.5 MBtu) heating energy savings at a nearly identical cost of $1059 per house. This percentage savings corresponds to $81 annually at a heating fuel cost of $7 per MBtu. This savings is higher than the 9 to 17% savings reported for 11 previous evaluations conducted between 1981 and 1988 (Greely et al. 1992). Although the savings are higher, weatherization costs are comparable to those in the previous evaluations—within 10% for 7 of the 11 evaluations (Cohen 1991).

The low cooling energy savings achieved using the FTA were not statistically different from zero or from those achieved by standard weatherizations.

The FTA provided around 18% (156 kWh) cooling energy savings compared with only 3% (22 kWh) from standard weatherizations. At $0.085 per kWh, these savings correspond to only $13 and $2 savings per year, respectively. Although a sizeable percentage of the cooling energy is saved, at least in the FTA group, cost savings are low because cooling energy use is small. House-to-house variability was so large that no statistical difference could be detected between these groups or when their difference from zero was tested. The cooling energy savings achieved are all attributable to shell measures (including air leakage reduction), because no replacement air conditioners were installed in this test. A significant barrier to achieving greater, more consistent cooling energy savings is initial consumption; initial consumption is highly variable among houses and, on average, low for the moderate cooling climate in North Carolina. Average pre-weatherization consumption was 781 kWh or $66. Despite the potential contribution to indoor comfort, air conditioning is used very little in low-income North Carolina houses. This trend is consistent with results found in Oklahoma (Ternes and Levins 1992). In North Carolina, energy consumption for window air conditioners does not present good opportunities for cooling energy savings in most cases.

The FTA recommends different conservation measures from standard North Carolina audits, although many major measures are the same.

Both similarities and wide variances exist among measures installed by the two audits. Generally, in North Carolina, both FTA and standard audits often recommend shell insulation for attics and floors (this was not the case for standard audits at site C). Major differences between the two audits were due primarily to two factors: (1) the FTA often recommended wall insulation, which was not an option in the standard audit; and (2) the FTA almost never recommended storm windows, which were installed frequently in standard audit houses. Unlike standard audits, the FTA also evaluated mechanical measures, although few were actually recommended. This is more a result of the types of systems in North Carolina than of the cost-effectiveness of the measures. As a result, heating system measures could be much more frequently recommended in states dominated by other heating system types. Programmable thermostats were recommended often by the FTA for houses with compatible heating systems (around 10% of the FTA group).

FTA weatherizations cost approximately the same as standard weatherizations on average, but cost less at two of the three sites.

Although average group weatherization costs were almost identical, FTA weatherizations cost less than standard weatherizations by 7 to 14% at two of the three sites. FTA weatherization costs at the third site were 38% higher than for standard weatherizations. The higher costs were directly related to the small number of measures installed in standard weatherizations at this site; they were not simply due to FTA weatherizations being more expensive. This conclusion was reached because standard weatherizations at the other two sites installed many more measures than at the site where FTA costs exceeded standard weatherization costs.

Energy savings are more widely distributed in FTA houses than in standard houses. The FTA tends to spend more money on less efficient houses and less on more efficient houses. Standard weatherizations tended to lump expenditures more closely around a central average.

Air leakage reductions resulting from FTA weatherizations using blower-door-directed air sealing far exceeded those resulting from standard weatherizations using standard air sealing techniques, provided much lower final air leakage rates, and did not increase total weatherization costs.

The 37% average air leakage reduction achieved in the group using blower-door-directed air sealing was more than the 16% reduction achieved in the standard group using standard infiltration, caulking, and weatherstripping techniques. On average, most of the reduction can be achieved in the first 2 hours of air sealing. Crews using a blower-door-directed air sealing procedure should expect to reduce house air leakages to below 3000 cfm50 for around 75% of North Carolina houses. Crews using standard air leakage reduction techniques should expect similar results with a 4000 cfm50 limit. Using a blower-door-directed air-sealing procedure does not increase weatherization costs beyond those of standard North Carolina weatherizations.

North Carolina low-income housing has much more leakage than the low-income houses tested in New York (over 30% higher leakage on average). This extra leakage can be sealed using a blower-door-directed air sealing procedure, producing post-weatherization leakage rates comparable to or lower than those achieved in the previous New York test. This fact indicates that the pre-weatherization air leakage rate does not dictate the post-weatherization air leakage rate that can be achieved.

As tested in North Carolina, FTA-predicted heating consumption rates below 80 MBtu and savings below 40 MBtu are very close to measured values in most cases: when above these limits, predicted consumption and savings often are considerably higher than measured values.

For annual heating energy use predictions below 80 MBtu, FTA predictions were within 15 MBtu of actual consumption in almost all cases. Fifty percent (four of eight) of the predictions below 80 MBtu matched actual consumption within 14%. Above 80 MBtu, predictions were always higher than actual consumption and were much higher in many cases. The same phenomenon occurred for heating energy savings at around 40 MBtu. FTA annual heating energy use and savings predictions matched actual measured results much more closely when they were based on heated floor area, but only on an average basis. This basis does not offer a larger number of more accurate predictions, but rather produces results more balanced around the point of agreement. As a result, although this basis improves predictions on average, it may not necessarily be appropriate. Additional work is needed to pinpoint the source(s) creating these overpredictions.

As tested in North Carolina, the audit overpredicts cooling energy consumption and savings for houses with higher cooling loads.

The FTA consistently overpredicted cooling energy use when predicted consumption exceeded 2000 kWh. The FTA predicted consumption over this limit most of the time. Below 2000 kWh, consistent overprediction did not occur. The same phenomenon occurred for predicted cooling energy savings above 800 kWh. The frequent overprediction of cooling energy use and savings in North Carolina is due largely to the fact that most households in this test rarely operated their air conditioners (annual cooling costs were $21 or less for almost 40% of the households). Occupants either depended on fans for comfort or tolerated the higher indoor temperatures during the summer.

This field test led to dramatic improvements in the FTA that will make it a much better tool for weatherization auditors.

Many major and minor recommendations and resulting improvements to the FTA and how it is applied have resulted from this test. This experience will substantially reduce complexities and problems in future use. The field application experience with existing weatherization agencies and the FTA changes that resulted from it will be major contributors to the future success of this audit, to what it becomes, and to the success of others who use it.

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