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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.**  
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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 cfm<sub>50</sub> [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 cfm<sub>50</sub> 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 cfm<sub>50</sub>. 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 cfm<sub>50</sub> for the control group (no treatment), 1710 cfm<sub>50</sub> for the FTA group, and 716 cfm<sub>50</sub> 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<sup>2</sup>s** (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  $\leq 0.06$ . 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, 139 **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**.

### 1.3 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.

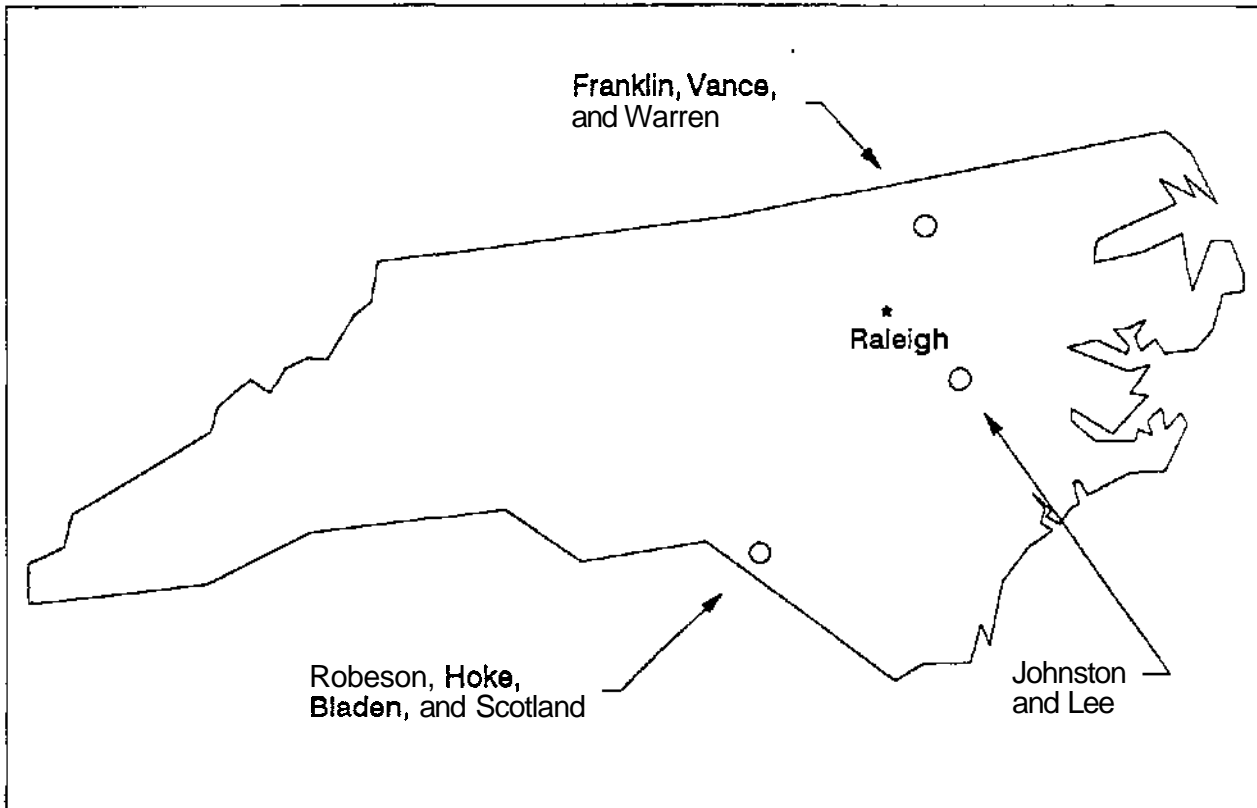


Fig. 2.1. North Carolina test site locations and the counties included in each.

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-11 or R-30 blown cellulose or fiberglass insulation. Wall insulation was **nominally** 3.5 inches of blown cellulose and R-11 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<br>(MBtu/year) | Interacted savings<br>(\$/year) | Cost<br>(\$) | B/C   |
|---|----------------------------|------------------------------|---------------------------------|--------------|-------|
| * Attic ins. <b>R-11</b>                    | a1                         | 20.69                        | 213.93                          | 193.04       | 12.56 |
| Attic ins. <b>R-30</b>                      | 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. <b>R-19</b>                      | f1                         | 9.25                         | 64.40                           | 380.00       | 1.92  |
| * Storm windows                             | wdw4                       | 0.53                         | 4.26                            | 61.90        | 0.67  |
| * Window shading                            | wdw1,wdw2,w                | −0.01                        | 12.59                           | 165.00       | 0.57  |
| * Smart thermostat                          |                            | 1.36                         | 10.95                           | 220.00       | 0.48  |
| * Replace window <b>A/C</b>                 | ac1                        | 0.65                         | 12.09                           | 512.50       | 0.23  |
| * <b>Elect.</b> vent dmp <del>r</del> ./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— <b>R-30</b> | 760 ft <sup>2</sup>          |                                 |              |       |
| Wall insulation                             | Celluls, Blwn— <b>3.5"</b> | 813 ft <sup>2</sup>          |                                 |              |       |
| Floor insulation                            | Faced <b>Batt—R-19</b>     | 760 ft <sup>2</sup>          |                                 |              |       |
| User Comments                               |                            |                              |                                 |              |       |



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

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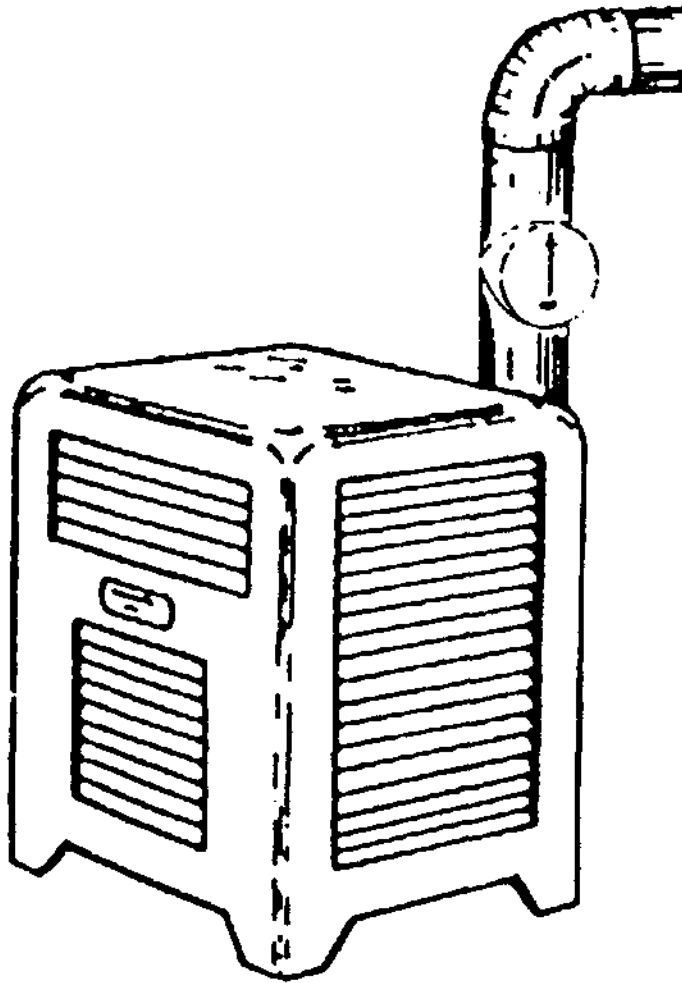
| Measure  |
|--|
| Ceiling insulation:                                      |
| <b>R-11</b> blown cellulose                              |
| <b>R-30</b> blown cellulose                              |
| <b>R-11</b> blown fiberglass                             |
| <b>R-30</b> blown fiberglass        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

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The typical room space **heater**<sup>1</sup> 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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<sup>1</sup>**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 **cfm**<sub>50</sub><sup>2</sup> was used for every **FTA** house [the unit **cfm**<sub>50</sub> 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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<sup>2</sup>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<br>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 (\$/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 **cfm**<sup>50</sup> 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 4.3b. 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 |      | Secondary 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. Eliminating 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<sup>3</sup>) 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.

#### 5.4.3 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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<sup>3</sup>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 **nouses** 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<sup>2</sup> 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

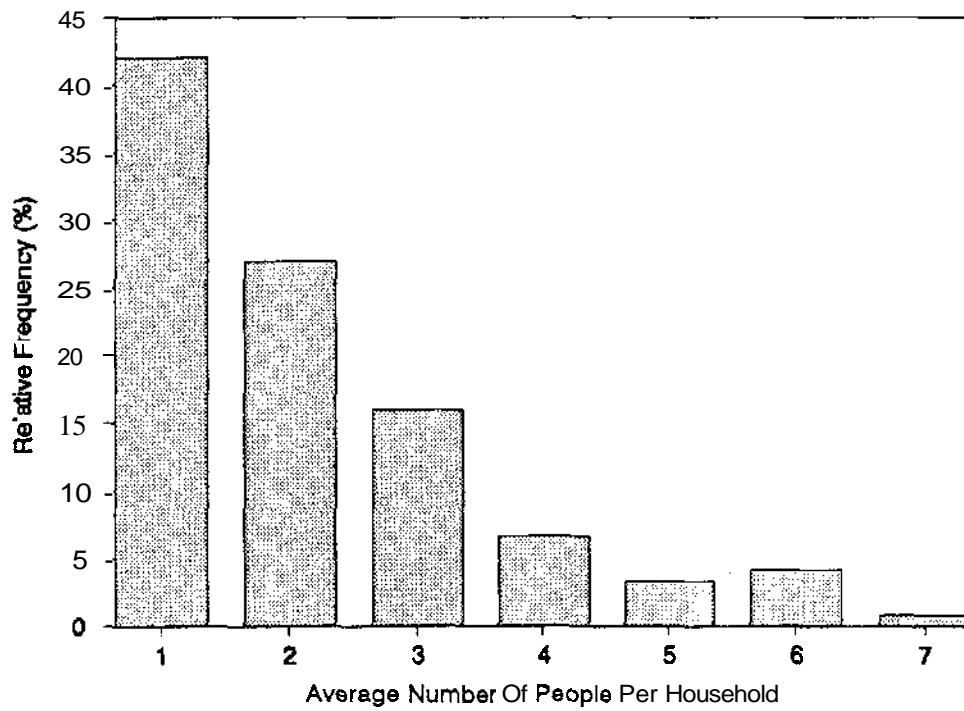
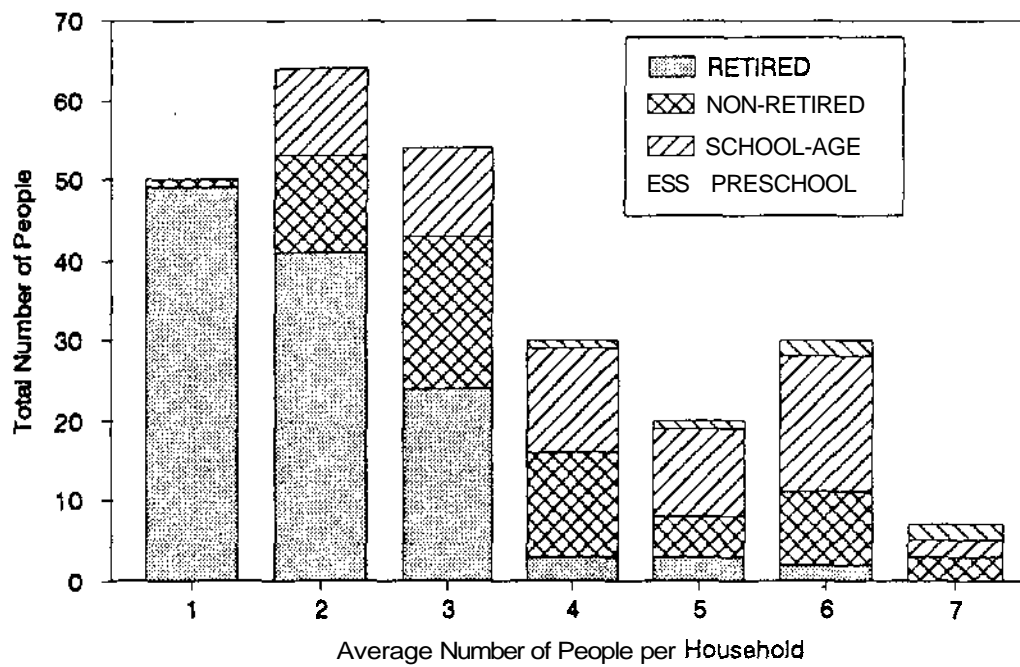


Fig. 6.1. Occupancy histogram for the field test houses.



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

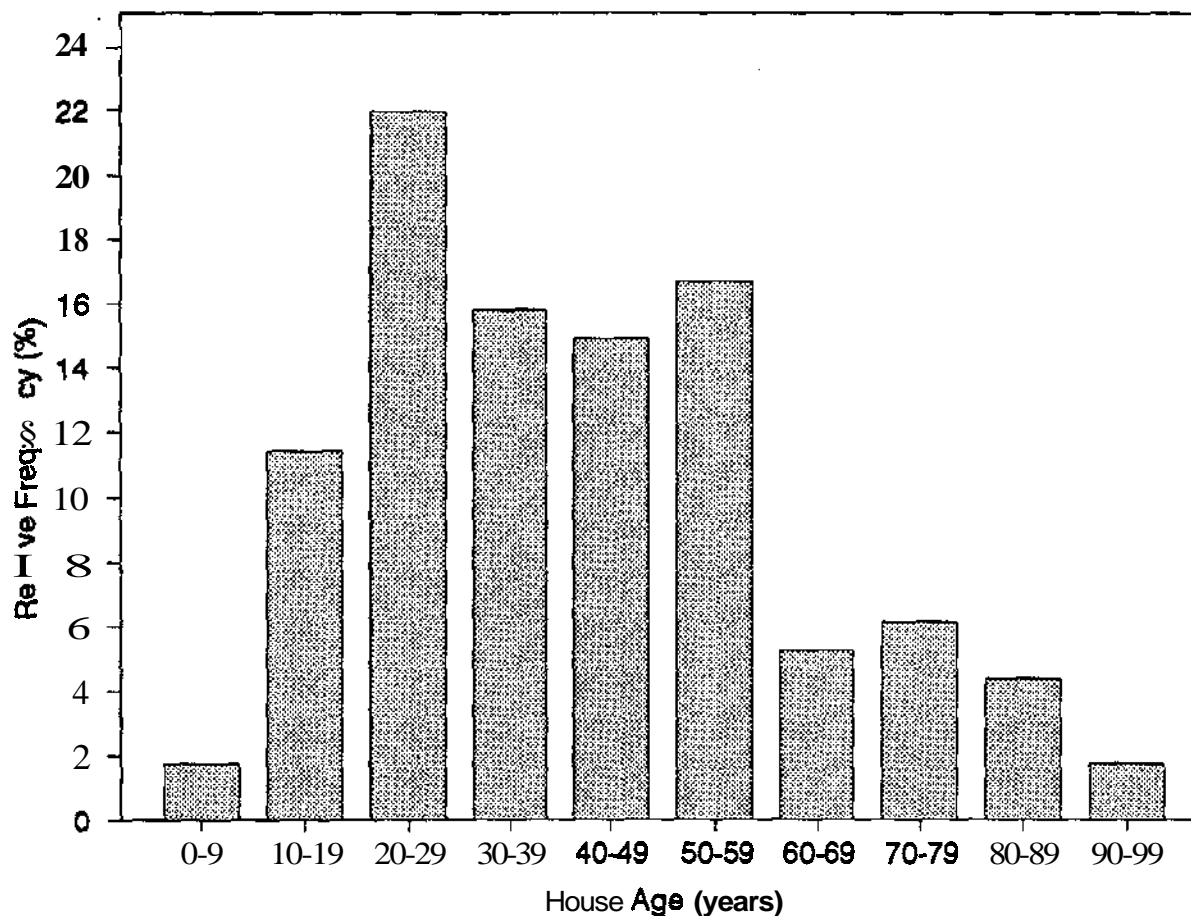


Fig. 63. Histogram of the house ages for the field test houses.

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<sup>2</sup> and averaged 1144 ft<sup>2</sup>. Eighty percent of the test houses were between 700 and 1400 ft<sup>2</sup> in size. Only 8% were larger than 1600 ft<sup>2</sup>.

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<sup>2</sup> had their total floor area heated. Approximately 17% of all participants heated less than one-half of their houses.

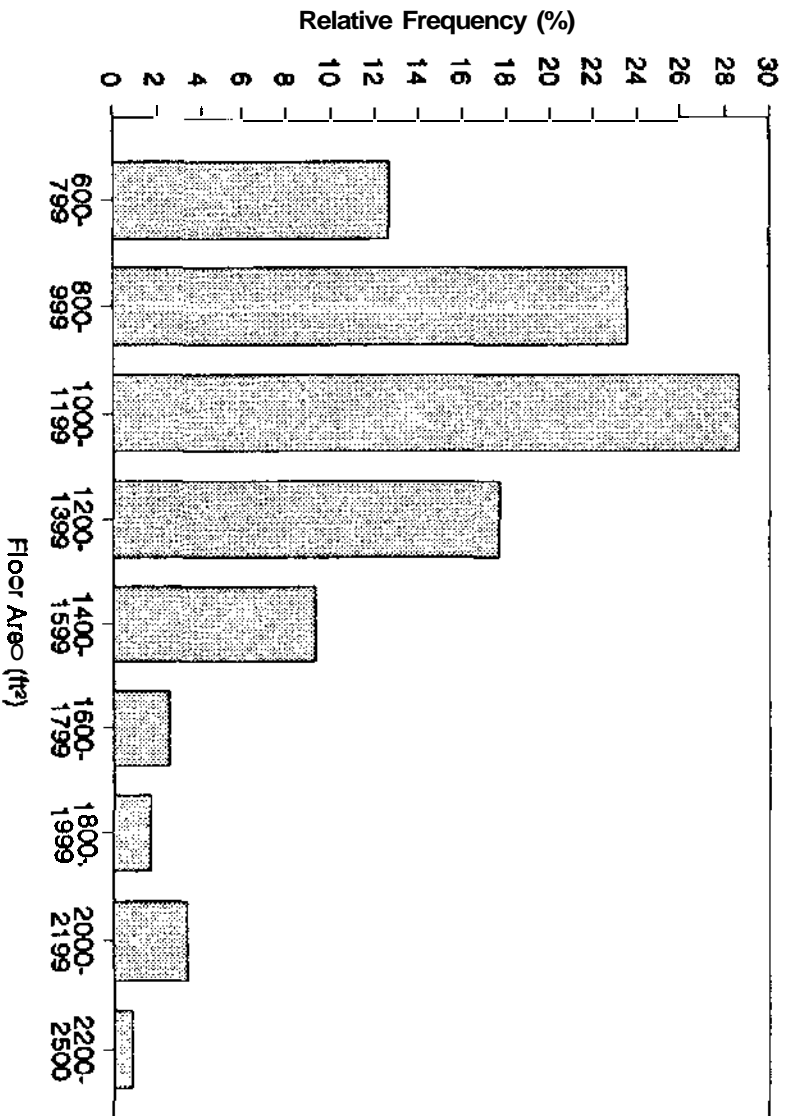


Fig. 6.4. Histogram of the floor areas for the field test houses.

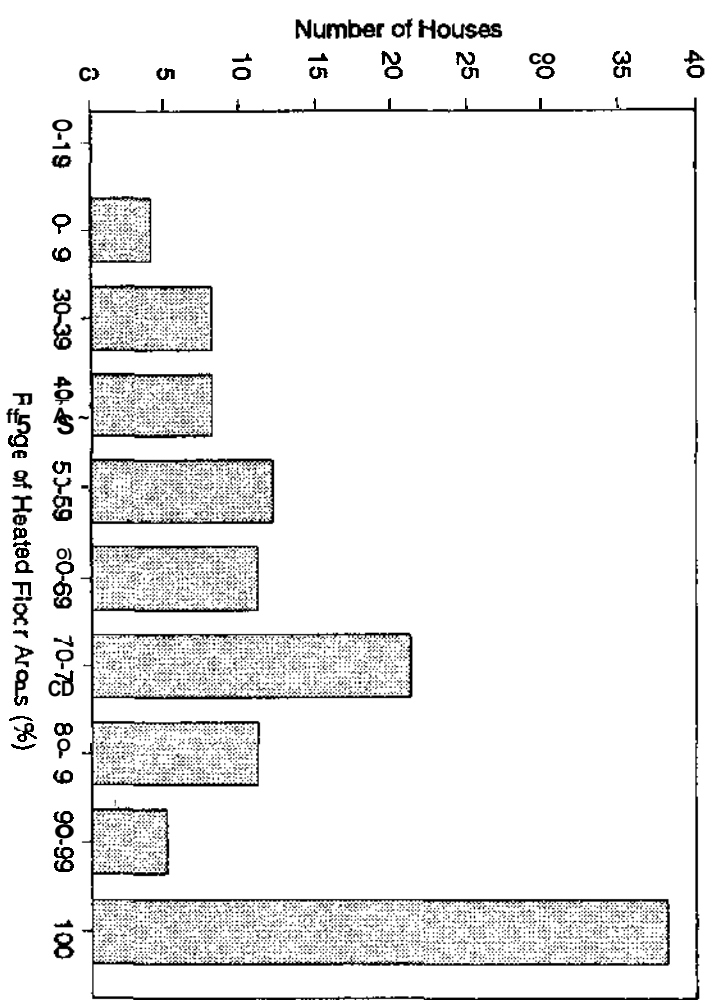


Fig. 6.5. Histogram of the percentage of heated floor area for the field test houses.

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<sup>2</sup>, varying between 612 and 2160 ft<sup>2</sup>. 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                                  |

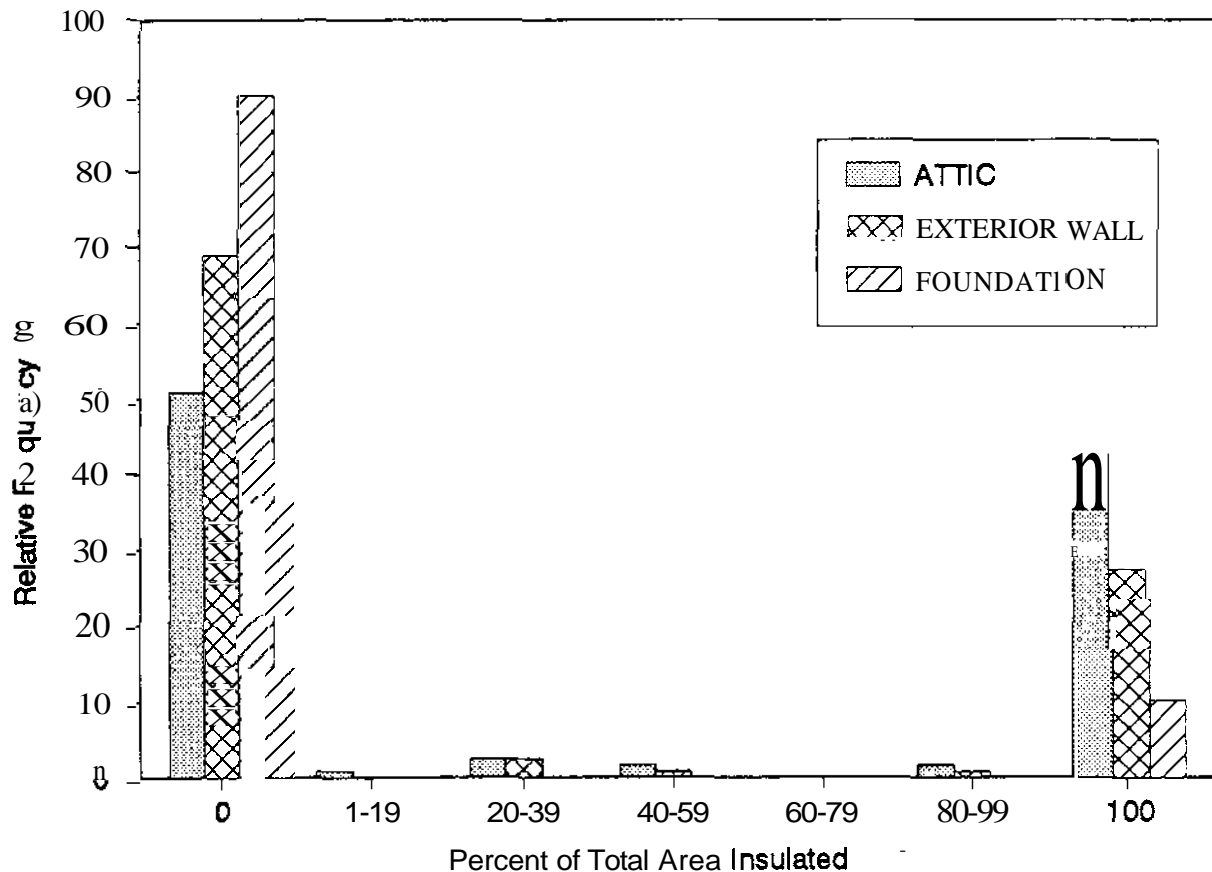


Fig. 6.6. The percentage of field test houses with specific percentages of insulation in attics, **walls**, and foundations at the start of the **experiment**.

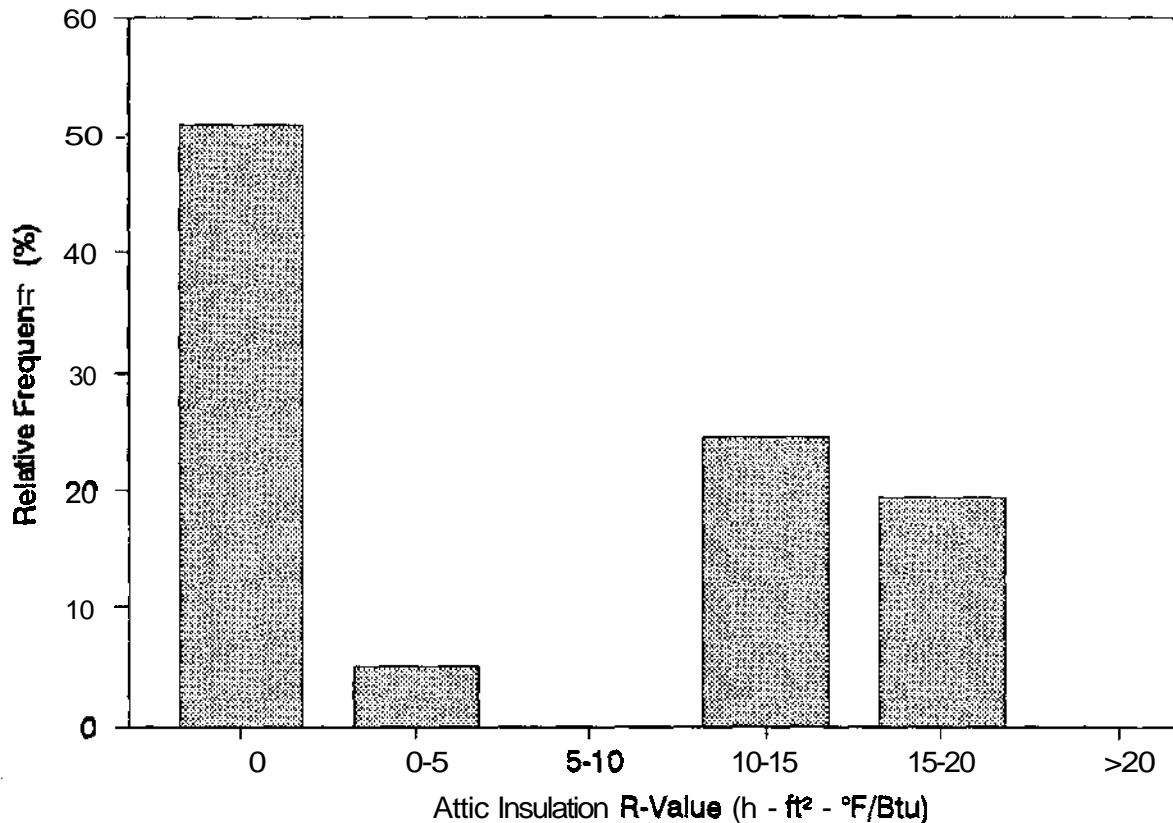
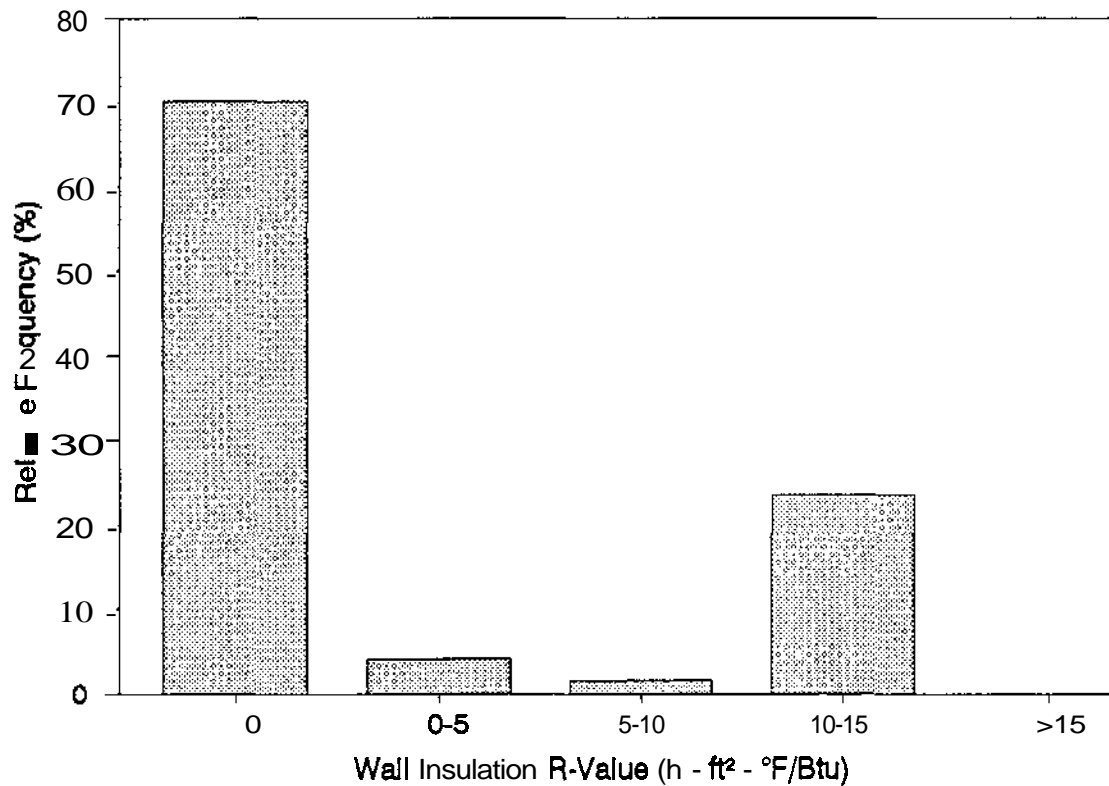


Fig. 6.7. Histogram of the amount of attic insulation (average **R-value** of the insulation only) present in the field test houses at the start of the experiment

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 **ft²** and averaged 1173 **ft²**. 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 • ft² • 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<sup>2</sup> and varied from 38 to 334 ft<sup>2</sup>. 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       | <b>R-30</b> attic insulation    | All  | R-11 attic insulation       |
| W         | Wall insulation                 | F19  | R-19 floor insulation       |
| <b>KW</b> | <b>R-11</b> 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-11. Ninety-one percent of the attic insulation recommendations were for R-30, and only 9% were for R-11. All uninsulated attics were recommended for R-30. For six houses that already had R-11 in their attics, an additional R-30 was recommended for three, R-11 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

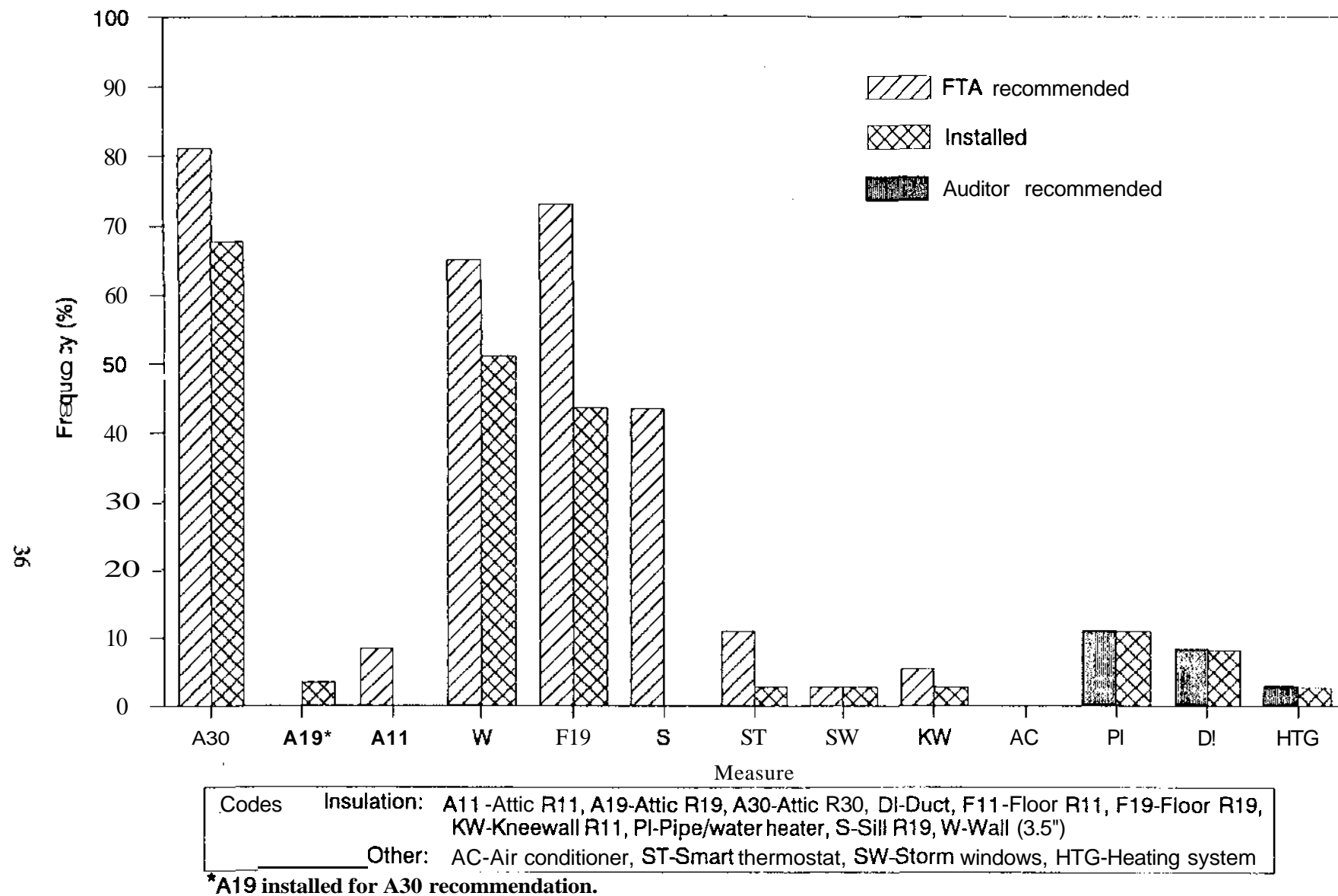


Fig. 7.1. Measures recommended and installed in the Field Test Audit houses based on all houses in the group (n=37).

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**.<sup>4</sup> 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**.<sup>5</sup>

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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<sup>4</sup>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.

<sup>5</sup>The audit has been changed since this test to account for this duplication,

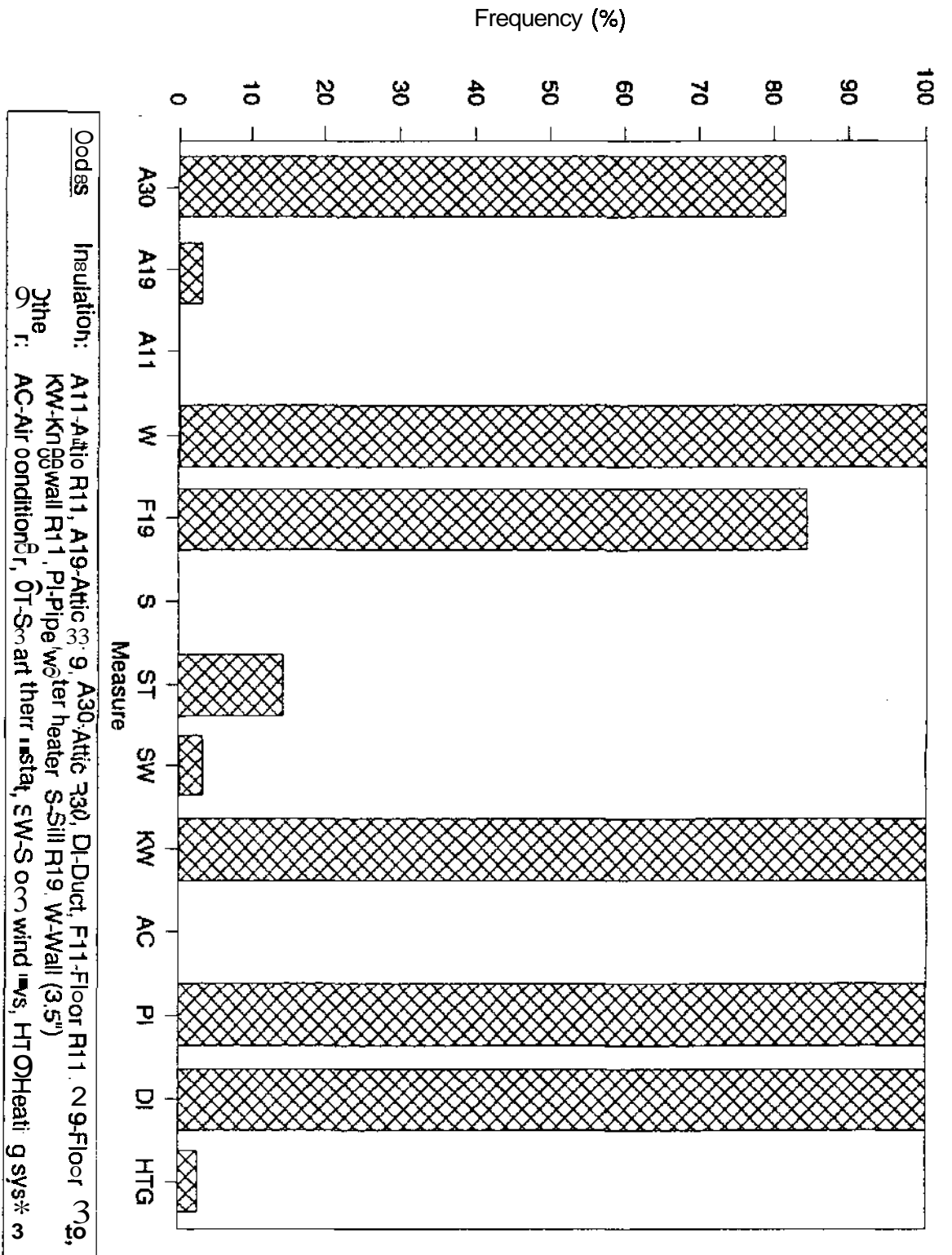


Fig. 7.2. Measures in the Field Test Audit houses based on the number of houses that had them

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

| House | Existing insulation | FTA-recommended measures installed <sup>a</sup> | 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=airconditioner  
                       ST=Smartthermostat  
                       SW=Storm window

\*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.

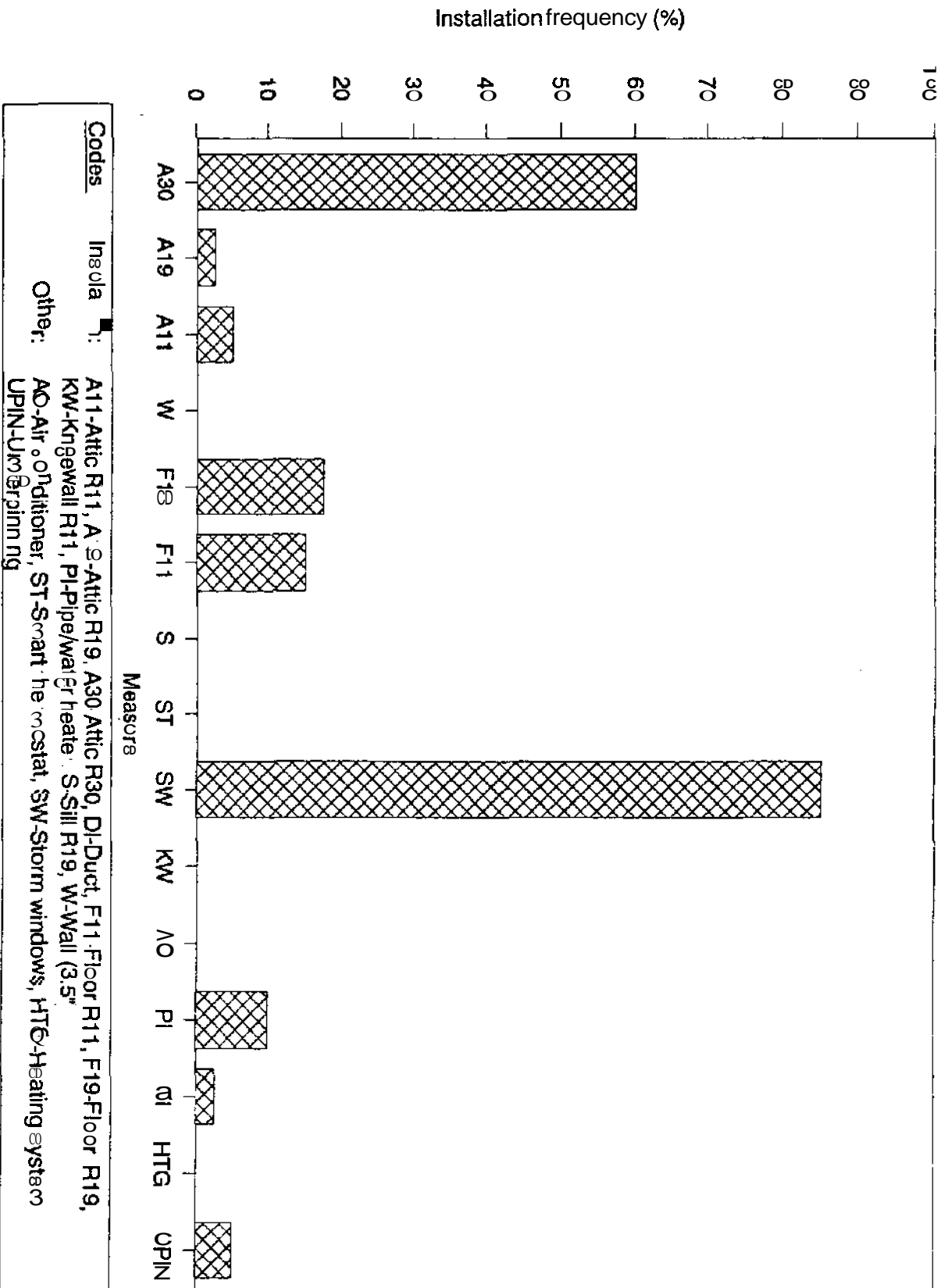


Fig. 7.3. Measures in the study.



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.

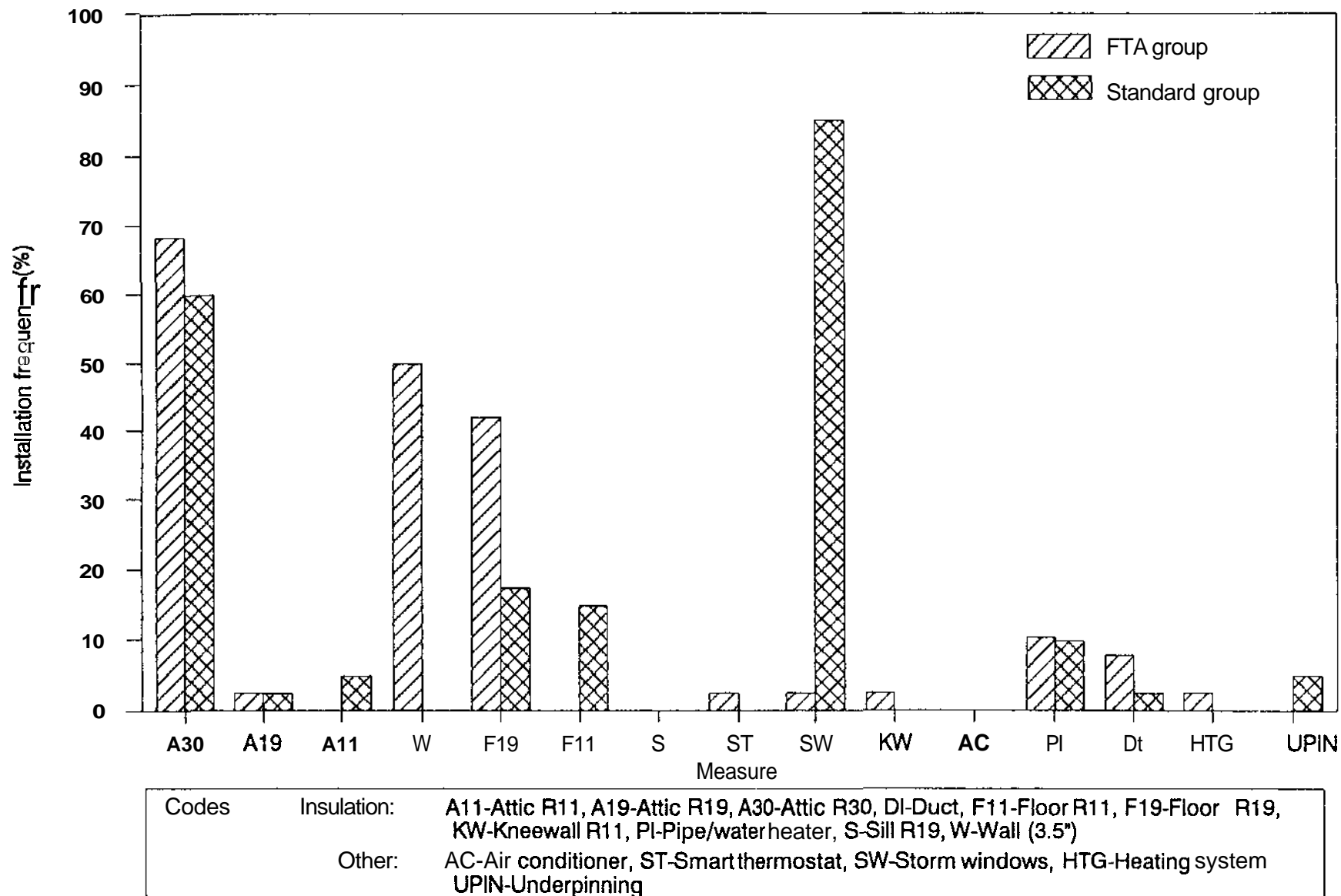


Fig. 7.4. Comparison of measures installed in the Field Test audit and standard groups.

## & 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 1500 cfm50. 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 <sup>a</sup> | 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 <sup>b</sup> |                           | 4400   | 2690    | 1710   |                           | 4091   | 3374    | 716    |
| Observations              | 38     | 12      | 12              |                           | 36     | 36      | 36     |                           | 37     | 37      | 37     |
| Median                    | 3728   |         | 133             |                           | 4441   |         | 1566   |                           | 3527   |         | 451    |

<sup>a</sup>wx = weatherization.

<sup>b</sup>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.

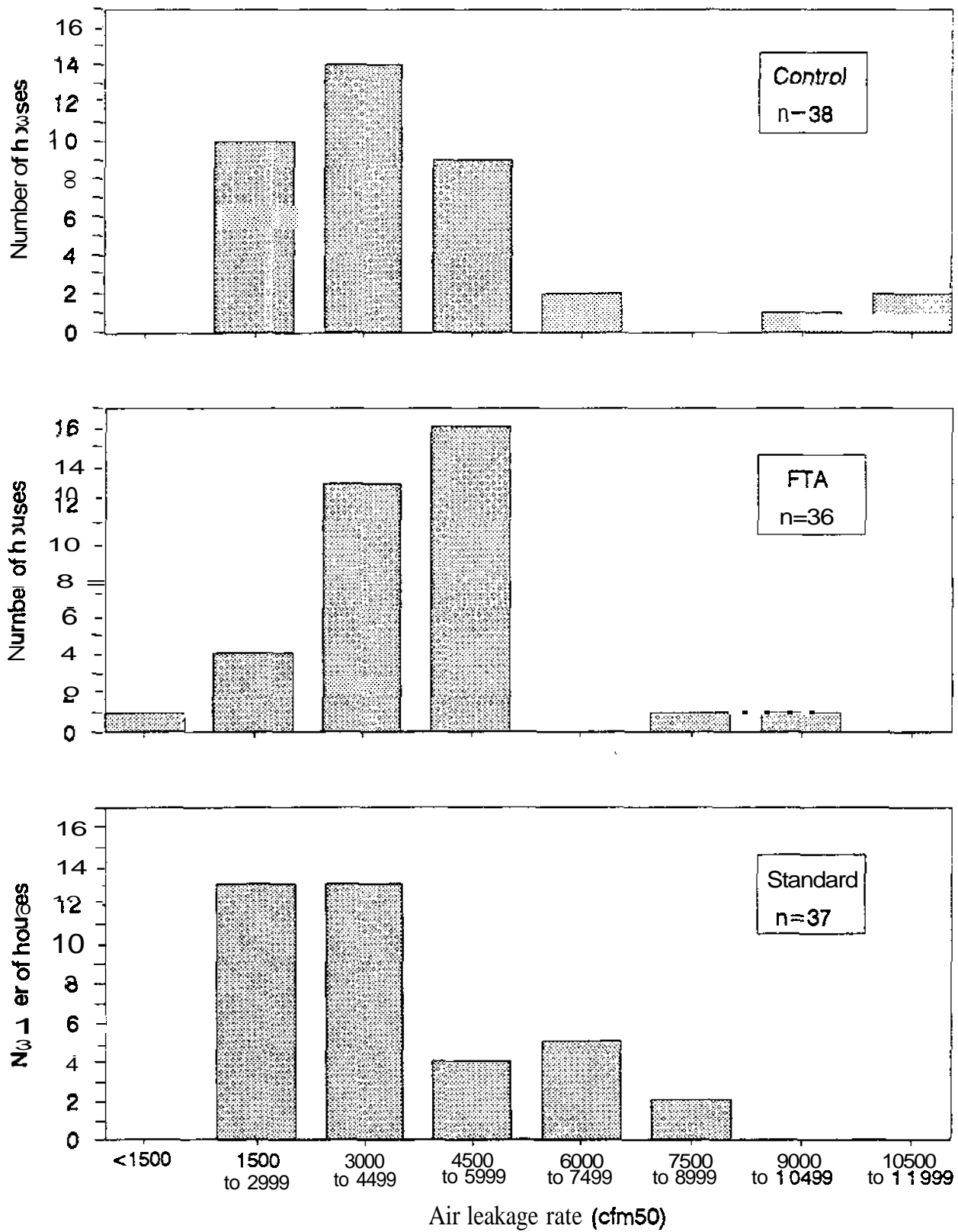
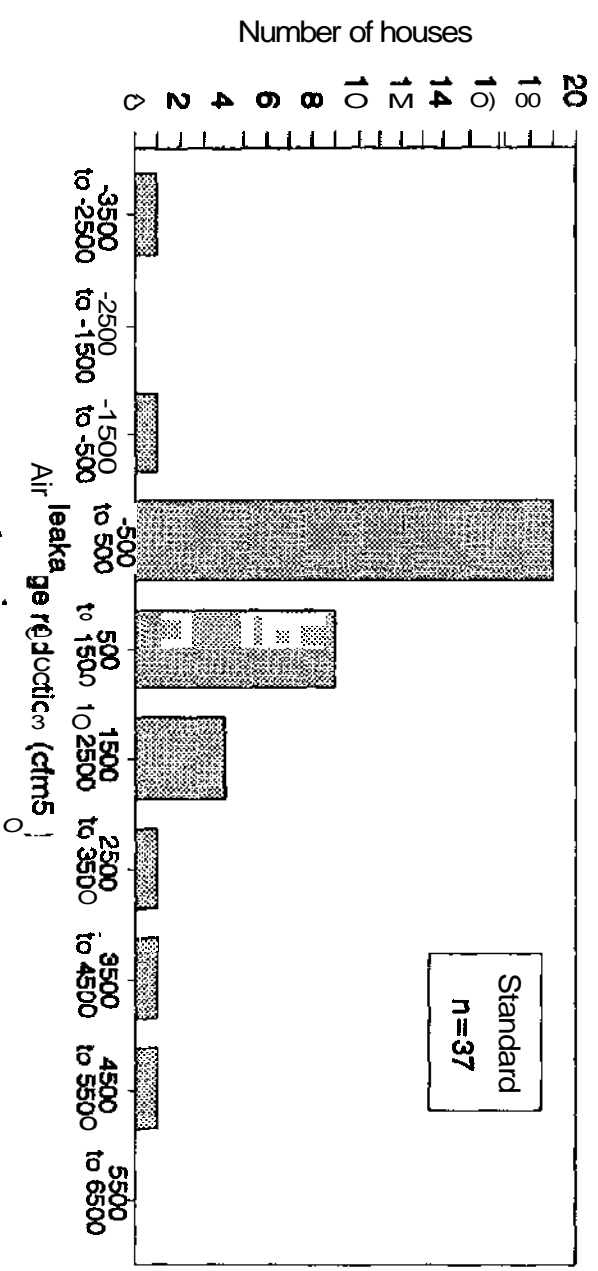
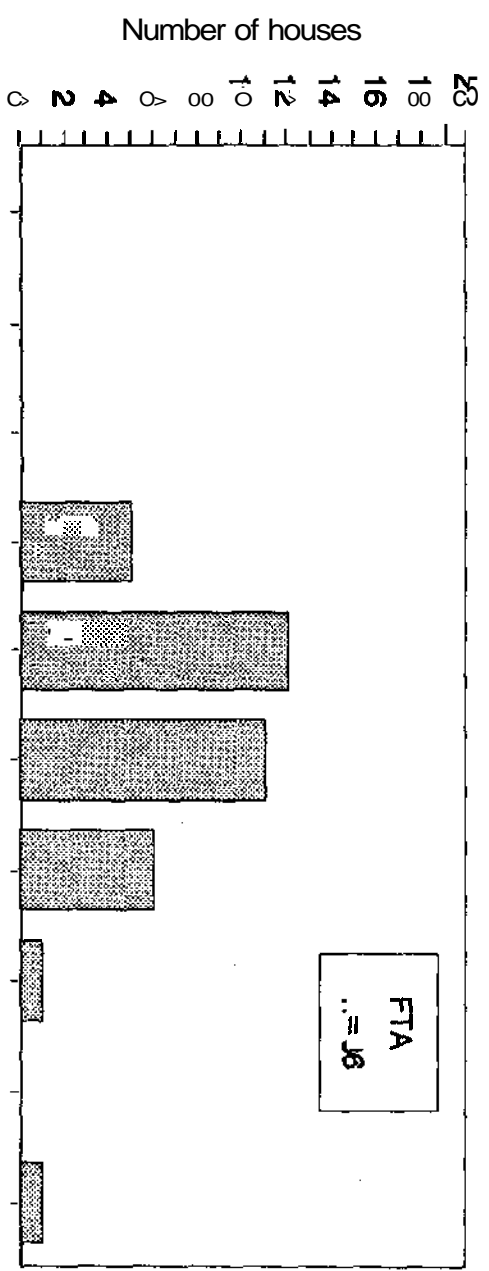
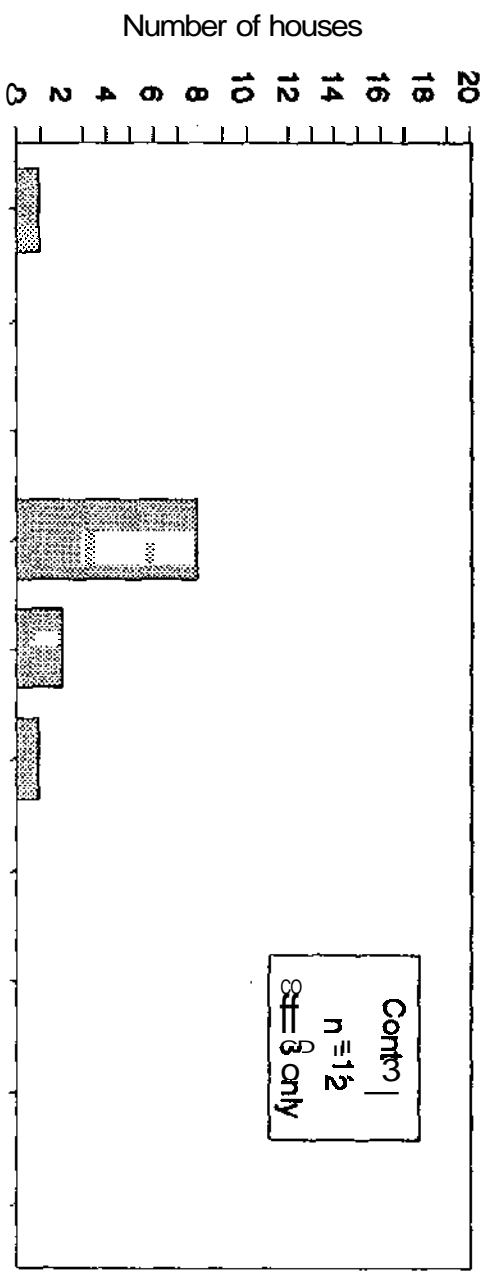


Fig. 8.1. Distribution of pre-weatherization air leakage rates by group



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

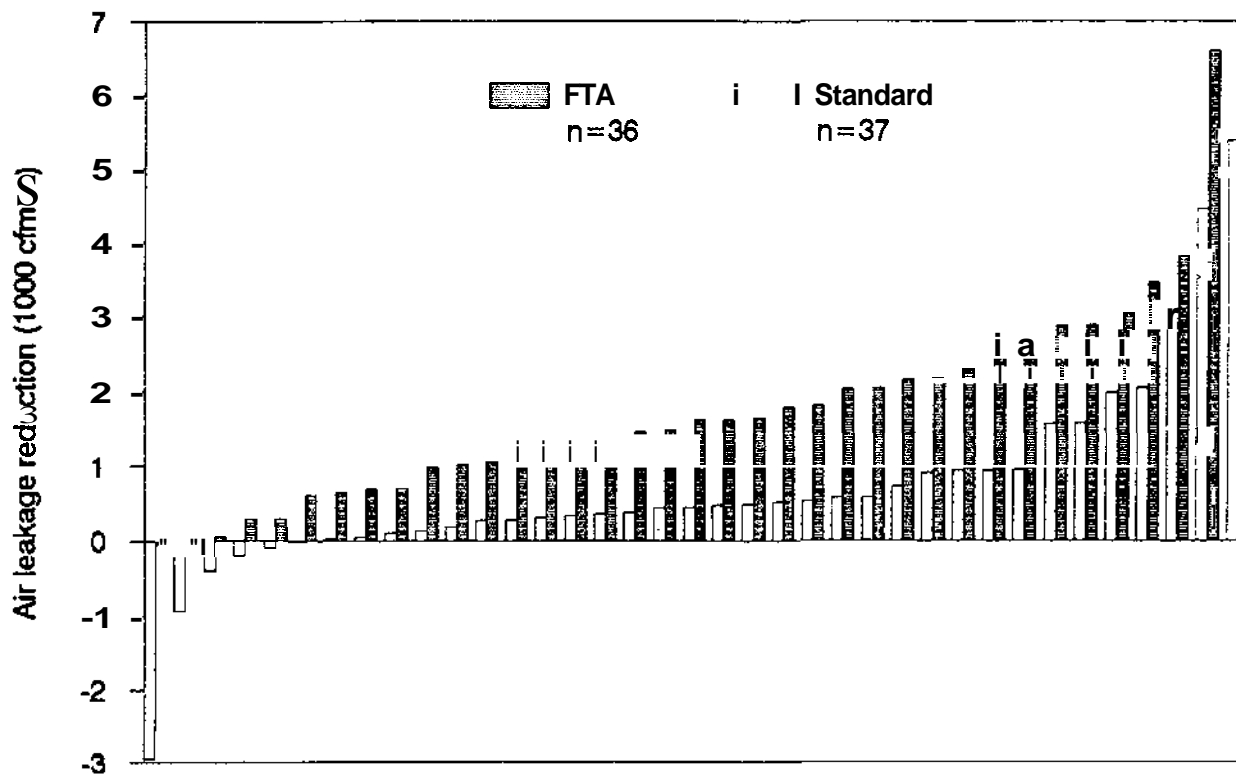


Fig. 83. **Comparison** of the air leakage **reductions** achieved in the standard and Field Test Audit groups.

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

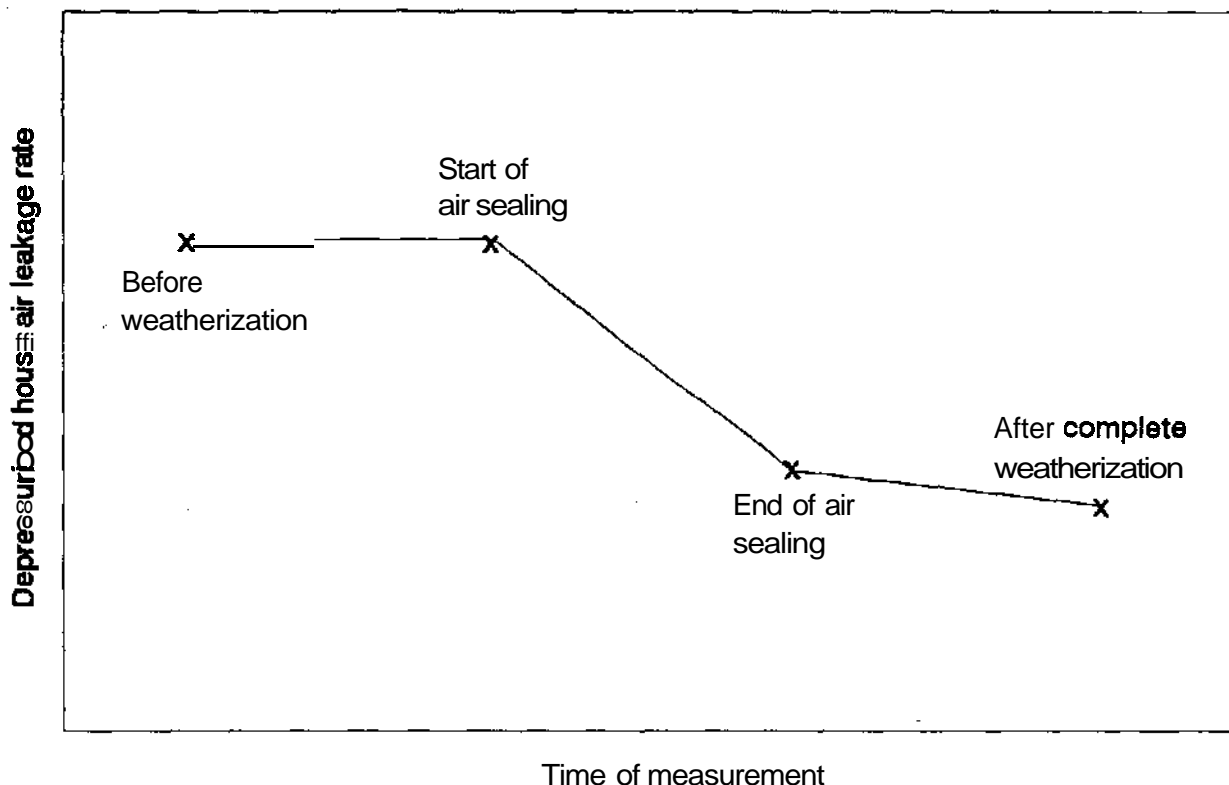
The use of a blower-door-directed air sealing procedure in FTA houses offered the opportunity to make additional house air leakage measurements beyond the pre- and post-weatherization measurements for this group. By making leakage measurements at the start and end of air sealing, the first measure installed,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

<sup>a</sup>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 houses

| 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 <sup>a</sup> |
|--|------------------------------|---------------------------|---------------------------|------------------|---|--|
| 2                                      | 5244                         | 1588                      | 3656                      | 6                | 609                                     | 8.1  |
| 4                                      | <b>4119</b>                  | 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                                     | <b>3.8</b>                                     |
| 62                                     | 1588                         | 1411                      | 177                       | 2                | 89                                      | 1.2  |
| 67                                     | 4490                         | 3400                      | 1090                      | 4                | 273                                     | 3.6  |
| 68                                     | 3849                         | 2449                      | 1400                      | 8                | 175                                     | 2.3  |
| 72                                     | 3479                         | 2069                      | 1410                      | <b>8</b>         | 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                | <b>48</b>                               | 0.6  |
| 118                                    | 5342                         | 2967                      | 2375                      | 12               | 198                                     | <b>2.6</b>                                     |
| 128                                    | 5144                         | 4119                      | 1025                      | 6                | 171                                     | 2.3  |
| 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 <sup>b</sup> | 4528                         | 2319                      | 2209                      | 9                | 266                                     | 3.5  |
| Average for houses 52-140 <sup>b</sup> | 4550                         | 2682                      | 1869                      | 9                | 218                                     | 2.9  |

<sup>a</sup>Based on cost-effectiveness guideline of 75 cfm50/person-h = benefit-cost ratio of 1.

<sup>b</sup>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 ( $R^2$ s—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 tile control group**

| Control group    |   |   |   |                          |         |                      |         |
|------------------|---|---|---|--------------------------|---------|----------------------|---------|
| House            | Pre-wx <sup>a</sup> space<br>heating energy<br>use (MBtu) | Post-wx space<br>heating energy<br>use (MBtu) | Space heating<br>energy savings<br>(MBtu) | Number of data<br>points |         | Model R <sup>2</sup> |         |
|                  |   |   |   | Pre-wx                   | Post-wx | Pre-wx               | Post-wx |
| 12 <sup>b</sup>  | 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 <sup>b</sup>  | 52.8  | 25.9  | 26.9                                      | 14                       | 17      | 0.89                 | 0.32    |
| 23 <sup>b</sup>  | 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 <sup>b</sup>  | 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 <sup>b</sup>  | 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 <sup>?</sup>  | 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      | <b>0.92</b>          | 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    |
| 80               | 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 <sup>b</sup> | 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              | <b>52.9</b>   | 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*             | 52.6  | 24.7  | 28.0                                      | 8                        | 19      | 0.77                 | 0.70    |
| 130              | 44.5  | 56.1  | -11.6                                     | 23                       | 14      | 0.96                 | 0.88    |
| 132 <sup>b</sup> | 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 <sup>b</sup> | 71.1  | 35.4  | 35.7                                      | 14                       | 15      | 0.92                 | 0.18    |

**Table 9.1** (continued)

| Control group                             |  |   |                                     |                       |         |                      |         |
|---|--|---|-------------------------------------|-----------------------|---------|----------------------|---------|
| 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 <sup>2</sup> |         |
|   |  |   |                                     | Pre-wx                | Post-wx | Pre-wx               | Post-wx |
| Based on <b>104-house</b> data set        |  |   |                                     |                       |         |                      |         |
| Average                                   | 53.0                                   | 53.5                                    | -0.5                                | 20                    | 16      | 0.90                 | 0.70    |
| Standard deviation                        | 164                                    | 22.8                                    | 160                                 | 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 <b>65-house</b> refined data set |  |   |                                     |                       |         |                      |         |
| Average                                   | 51.5                                   | 54.2                                    | -2.7                                | 22                    | 18      | 0.94                 | 0.89    |
| Standard deviation                        | 178                                    | 186                                     | 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                                |                       |         |                      |         |

<sup>a</sup>wx = weatherization.

<sup>b</sup>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 <sup>a</sup> space heating energy use (MBtu) | Post-wx space heating energy use (MBtu) | Space heating energy savings (MBtu) | Number of data points |         | Model R <sup>2</sup> |             |
|                        |   |   |                                     | Pre-wx                | Post-wx | Pre-wx               | Post-wx     |
| <b>2<sup>b</sup></b>   | 25.6  | 20.8                                    | 4.8                                 | 15                    | 13      | 0.90                 | 0.32        |
| <b>4<sup>b</sup></b>   | 45.0  | 25.0                                    | 20.0                                | 20                    | 14      | 0.59                 | 0.57        |
| 9                      | 67.4  | 62.2                                    | <b>5.2</b>                          | 17                    | 17      | 0.85                 | <b>0.95</b> |
| 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        |
| <b>27<sup>b</sup></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        |
| <b>40<sup>b</sup></b>  | 53.2  | 33.0                                    | 20.2                                | 14                    | 13      | 0.31                 | <b>0.57</b> |
| 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        |
| <b>67<sup>b</sup></b>  | 22.5  | 41.7                                    | -19.1                               | 22                    | 15      | 0.66                 | 0.88        |
| 68                     | 40.5  | 12.2                                    | 28.3                                | 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                 | <b>0.96</b> |
| 79                     | 64.2  | 45.7                                    | 18.5                                | 26                    | 18      | <b>0.81</b>          | 0.76        |
| 85                     | 69.2  | 32.5                                    | 36.7                                | 25                    | 20      | 0.91                 | 0.88        |
| 94                     | <b>65.3</b>   | 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                                    | <b>-11.6</b>                        | 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        |
| <b>127<sup>b</sup></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  | 79.3                                    | -27.3                               | 22                    | 19      | 0.86                 | 0.87        |

**Table 9.2.** (continued)

| Field Test Audit group             |  |   |                                     |                       |         |                      |         |
|------------------------------------|--|---|-------------------------------------|-----------------------|---------|----------------------|---------|
| 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 <sup>2</sup> |         |
|                                    |  |   |                                     | Pre-wx                | Post-wx | Pre-wx               | Post-wx |
| 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                                |                       |         |                      |         |

<sup>a</sup>wx = weatherization.

<sup>b</sup>Excluded from the refined data set by the screening criteria.

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

| House            | Standard group                                      |   |                                     |                       |         |                      |         |
|------------------|---|---|-------------------------------------|-----------------------|---------|----------------------|---------|
|                  | Pre-wx <sup>a</sup> space heating energy use (MBtu) | Post-wx space heating energy use (MBtu) | Space heating energy savings (MBtu) | Number of data points |         | Model R <sup>2</sup> |         |
|                  |   |   |                                     | Pre-wx                | Post-wx | Pre-wx               | Post-wx |
| 3 <sup>b</sup>   | 1003  | 50.7                                    | 49.6                                | 17                    | 20      | 0.83                 | 0.04    |
| 5 <sup>b</sup>   | 86.8  | 62.2                                    | 24.6                                | 16                    | 18      | 0.92                 | 0.58    |
| 6 <sup>b</sup>   | 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 <sup>b</sup>  | 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               | 1063  | 87.8                                    | 185                                 | 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 <sup>b</sup> | 70.5  | 183                                     | 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 <sup>b</sup> | 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 <sup>2</sup> |         |
|---|--|---|-------------------------------------|-----------------------|---------|----------------------|---------|
|   |  |   |                                     | Pre-wx                | Post-wx | Pre-wx               | Post-wx |
| Based on <b>104-house</b> 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 <b>65-house refined</b> 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                                 |                       |         |                      |         |

<sup>a</sup>Wx = weatherization<sup>b</sup>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).  $R^2$ s near 1 (perfect correlation) indicate strong correlations, while those near 0 (no correlation) indicate very weak correlations.  $R^2$ s in Tables 9.1 through 9.3 indicate that strong model correlations resulted for most houses. Over 50% of the models had  $R^2$ s greater than or equal to 0.90, and 80% had  $R^2$ s 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.

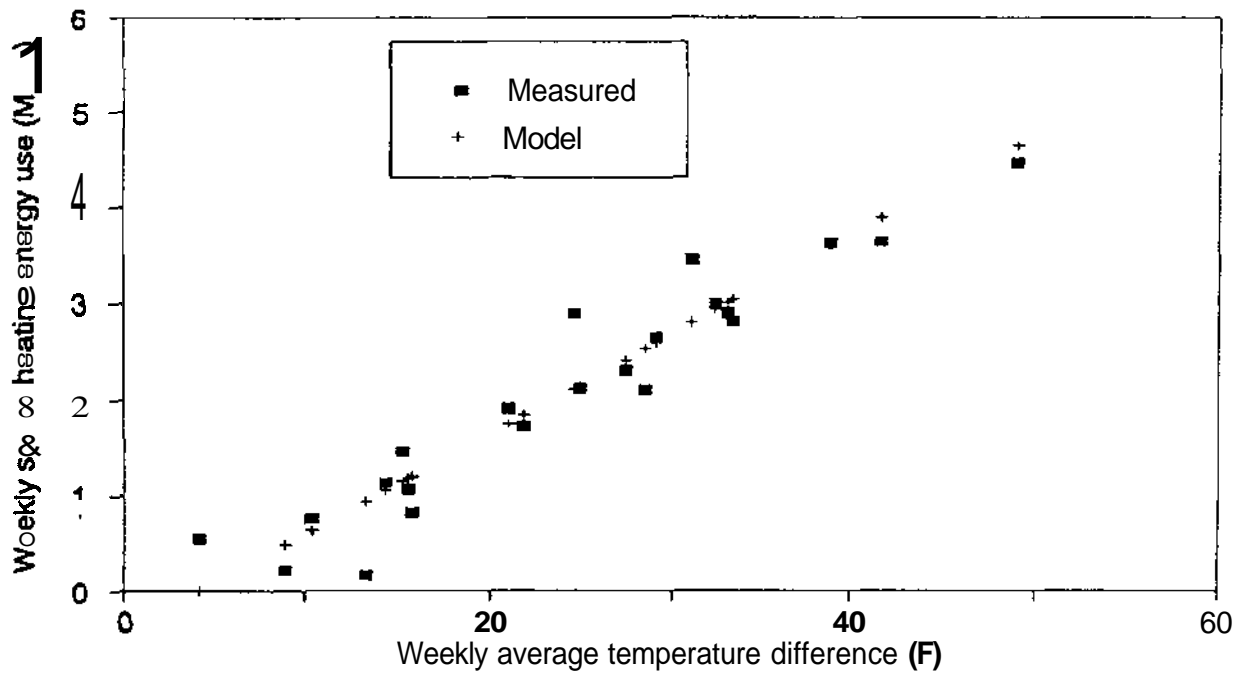


Fig. 92. Pre-weatherization space heating energy consumption data and the model fit for house 51.

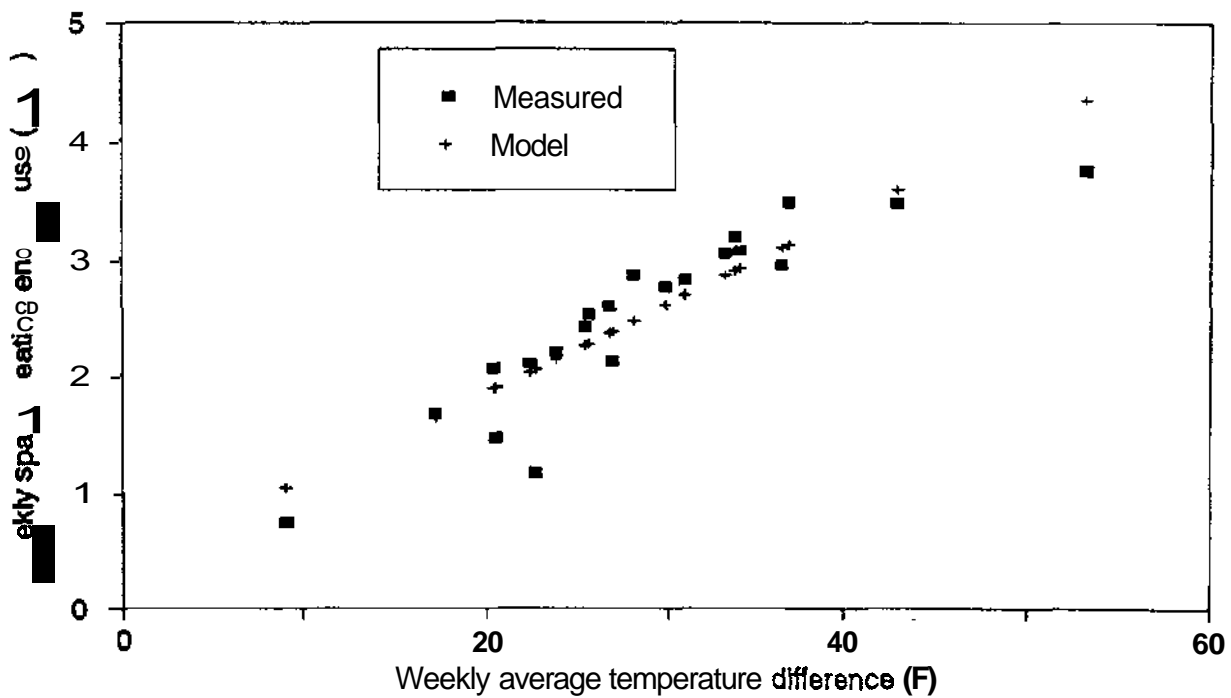


Fig. 93. Pre-weatherization space heating energy consumption data and the model fit for house 66.

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<sup>2</sup>s** 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<sup>2</sup>s** (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<sup>2</sup>** 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<sup>2</sup> ≥ 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

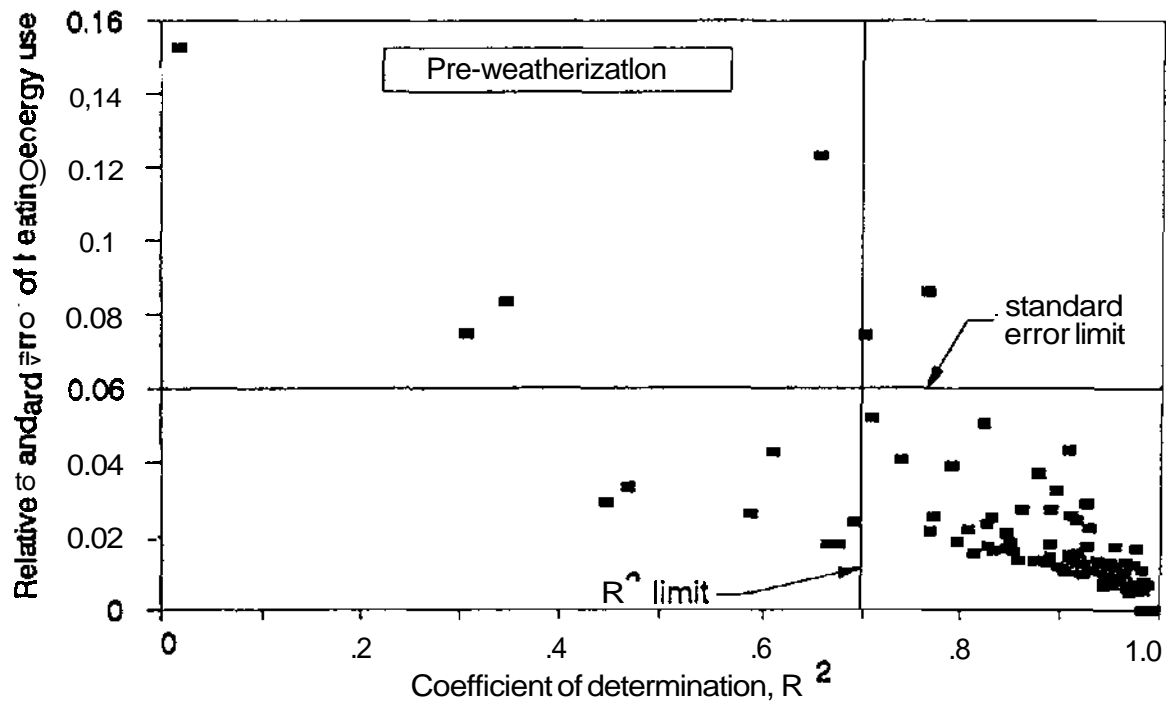


Fig. 9.4. Normalized pre-weatherization heating energy consumption as a function of reliability screening criteria.

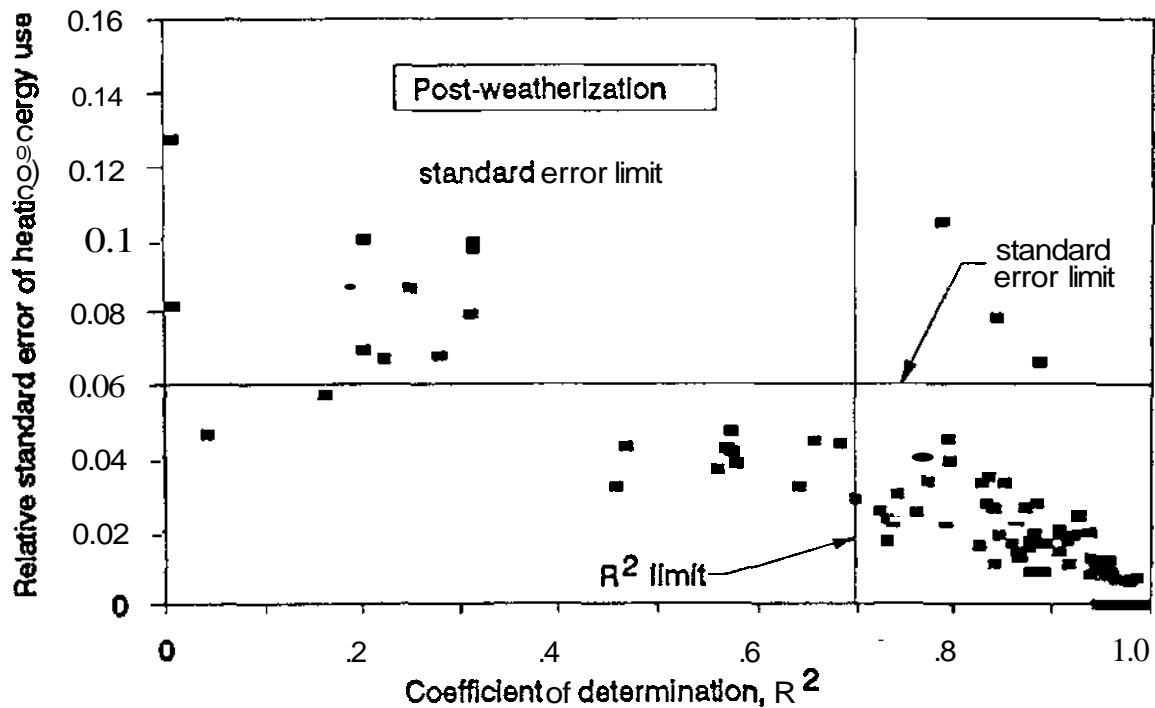


Fig. 9.5. Normalized post-weatherization heating energy consumption as a function of reliability screening criteria.



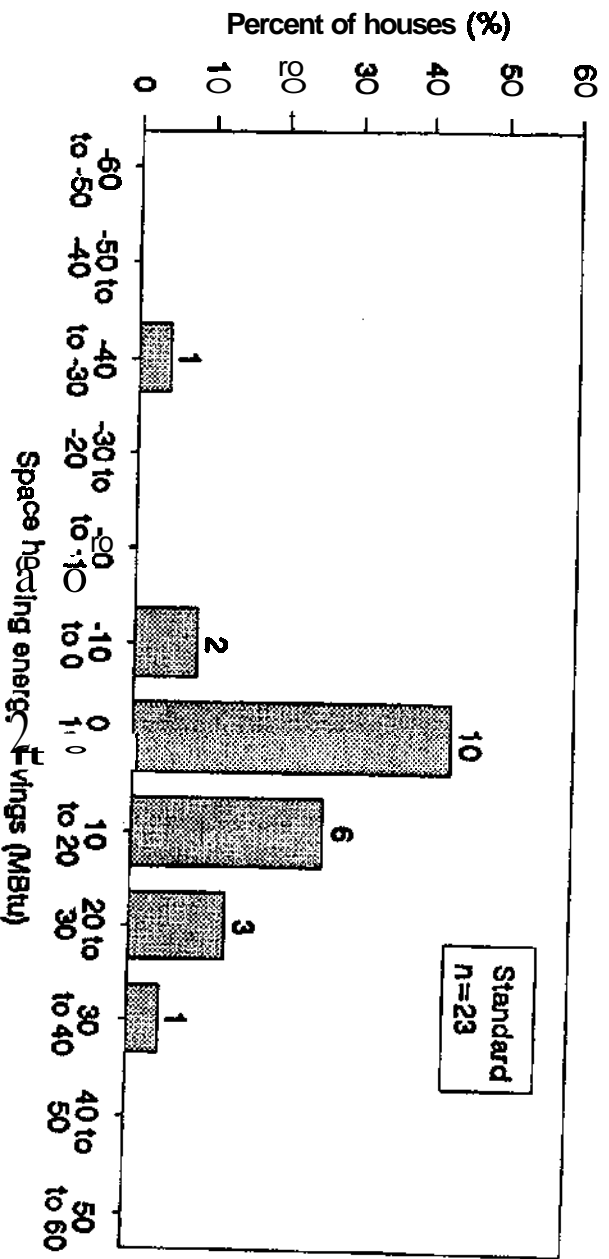
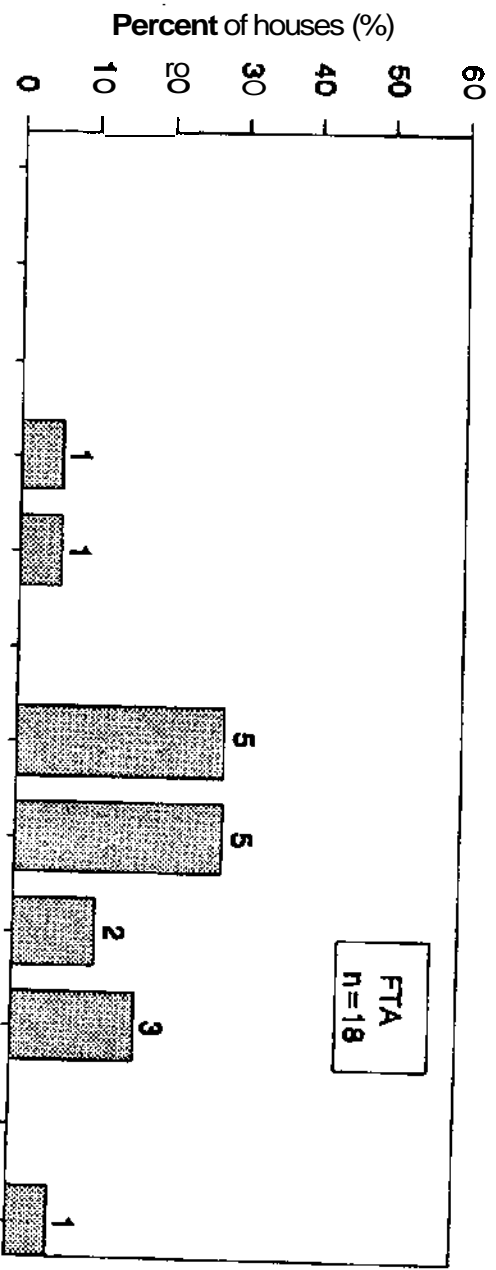
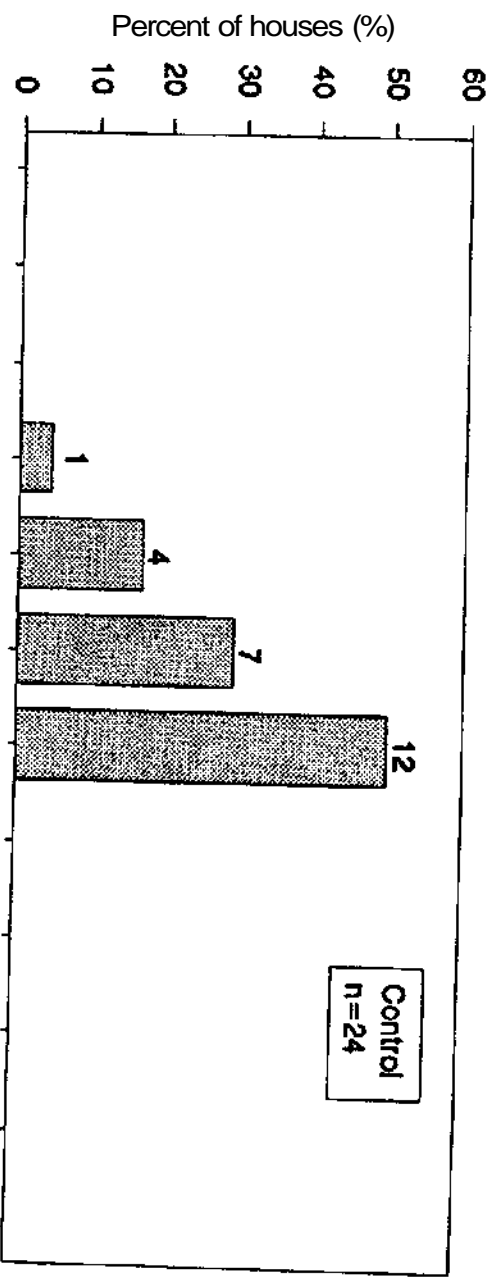


Fig. 9.6. Space heating energy savings distributions by group for the refined 65-house data set.

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 <sup>a</sup> | -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                         |

<sup>a</sup> 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  $R^2$ s 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  $R^2$ s ranged from 0.00 to 0.99. The  $R^2$ s 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  $R^2$ s 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  $R^2$ s 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  $R^2$ s > 0.70.

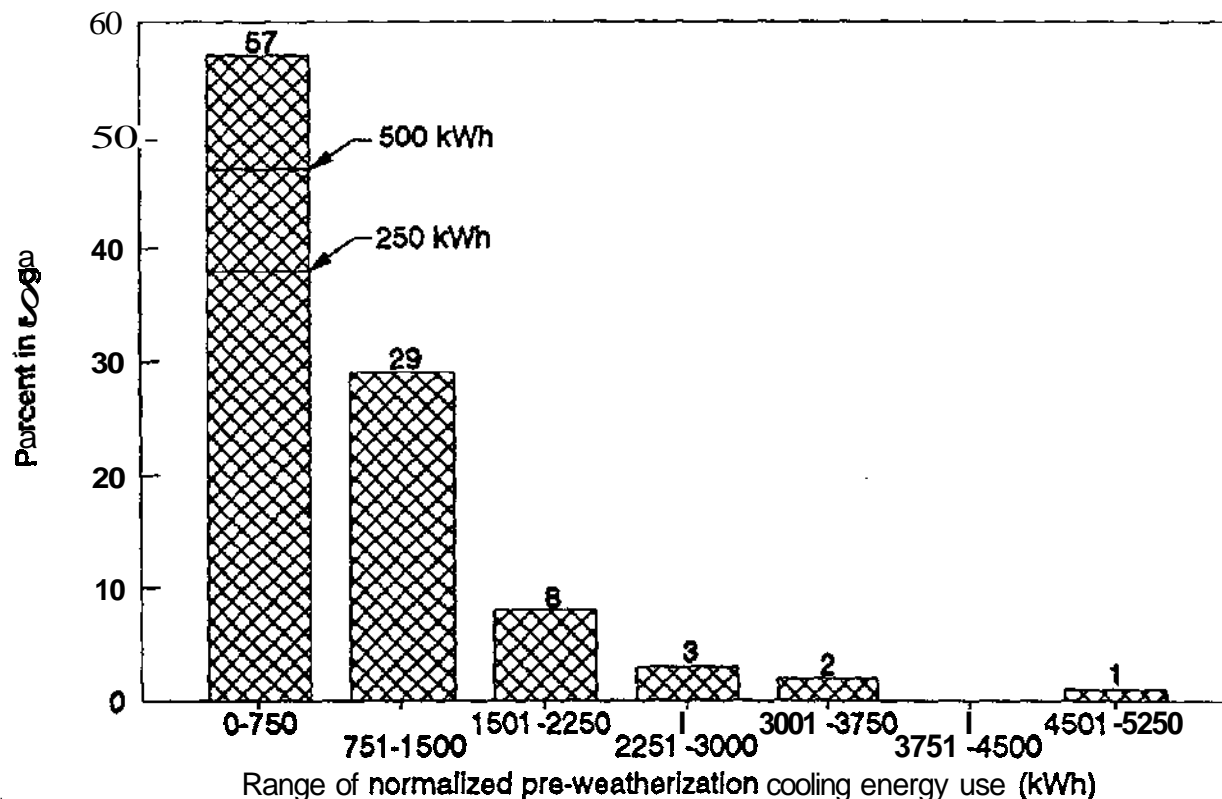


Fig. 9.7. Distribution of pre-weatherization cooling energy consumption for the 100-house data set

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

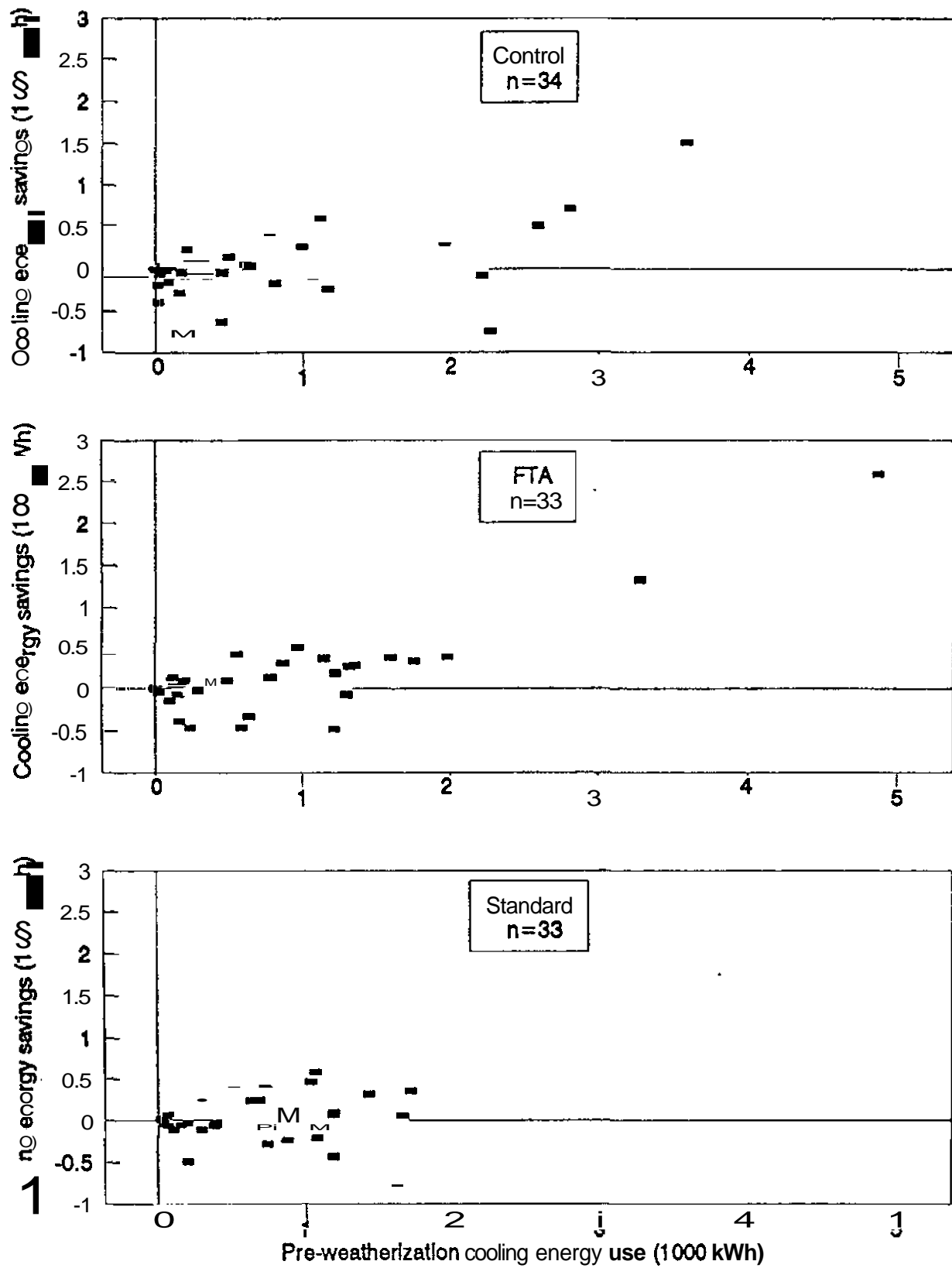


Fig. 9.8. Cooling energy savings as a function of pre-weatherization cooling energy use by group.

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

| House | Pre-wx <sup>a</sup> space cooling energy use (kWh) | Post-wx space cooling energy use (kWh) | Space cooling energy savings (kWh) | Control group                                |         |  |         |
|-------|--|--|------------------------------------|--|---------|--|---------|
|       |  |  |                                    | Primary air conditioner Model R <sup>2</sup> |         | Secondary air conditioner Model R <sup>2</sup> |         |
|       |  |  |                                    | Pre-wx                                       | Post-wx | Pre-wx   | Post-wx |
| 12    | 230  | 418                                    | -189                               | 0.37   | 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 <sup>2</sup> |                 | Secondary air conditioner Model R <sup>2</sup> |                |
|                                    |                                       |  |                                    | 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 <sup>b</sup>                              | 32 <sup>b</sup> | 4  | 3 <sup>b</sup> |
| 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            |  |                |

<sup>a</sup>Wx = weatherization

<sup>b</sup>No R<sup>2</sup> available when energy use was zero.

**Note:**

Model R<sup>2</sup>s 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 <b>Audit</b> Group |   |   |  |   |         |   |         |
|-------------------------------|---|---|--|---|---------|---|---------|
| House                         | Pre-wx <sup>a</sup><br>space cooling<br>energy use<br>(kWh) | Post-wx space<br>cooling<br>energy use<br>(kWh) | Space cooling<br>energy savings<br>(kWh) | Primary air<br>conditioner Model R <sup>2</sup> |         | Secondary air<br>conditioner Model R <sup>2</sup> |         |
|                               |   |   |  | 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                                      | <b>0.82</b>                                     | 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 <sup>a</sup><br>space<br>cooling<br>energy use<br>(kWh) | Post-wx<br>space<br>cooling<br>energy use<br>(kWh) | Space<br>cooling<br>energy<br>savings<br>(kWh) | Primary<br>air conditioner<br>Model R <sup>2</sup> |                 | Secondary<br>air conditioner<br>Model R <sup>2</sup> |                |
|   |  |  |  | Pre-wx   | Post-wx         | Pre-wx   | Post-wx        |
| Based on <b>100-house</b> data set        |  |  |  |  |                 |  |                |
| Average                                   | 877  | 713  | 165  | 0.54   | 0.61            | 0.38   | 0.30           |
| Standard<br>Deviation                     | 1004   | 615  | 542  | 0.32   | 0.25            | 0.33   | 0.27           |
| Observations                              | 33   | 33   | 33   | 33   | 29 <sup>b</sup> | 7  | 6 <sup>b</sup> |
| 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 <b>39-house</b> refined data set |  |  |  |  |                 |  |                |
| Average                                   | 1107   | 885  | 222  | 0.76   | 0.73            | 0.89   | 0.50           |
| Standard<br>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            |  |                |

<sup>a</sup>Wx = weatherization

<sup>b</sup>No R<sup>2</sup> available when energy use was zero.

**Note:** Model R<sup>2</sup>s 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 <sup>a</sup><br>space cooling<br>energy use<br>(kWh) | Post-wx space<br>cooling<br>energy use<br>(kWh) | Space cooling<br>energy savings<br>(kWh) | Primary air<br>conditioner Model R <sup>2</sup> |         | Secondary air<br>conditioner Model R <sup>2</sup> |         |
|                |   |   |  | 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                     |   |   |  |  |                 |  |         |
|------------------------------------|---|---|--|--|-----------------|--|---------|
| Statistic                          | Pre-wx <sup>a</sup><br>space cooling<br>energy use<br>(kWh) | Post-wx space<br>cooling<br>energy use<br>(kWh) | Space cooling<br>energy savings<br>(kWh) | Primary<br>air conditioner<br>Model R <sup>2</sup> |                 | Secondary<br>air conditioner<br>Model R <sup>2</sup> |         |
|                                    |   |   |  | 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<br>Deviation              | 511   | 568   | 282                                      | 0.31   | 0.26            | 0.53   | 0.27    |
| Observations                       | 33  | 33  | 33                                       | 32 <sup>b</sup>                                    | 27 <sup>b</sup> | 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<br>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            |  |         |

<sup>a</sup>Wx = weatherization<sup>b</sup>Available when energy use was zero.Note: Model R<sup>2</sup>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 <b>100-house</b> data set  |              |               |                                     |                               |                  |
| Control   | -775 to 1510 | 8             | 415                                 | 1.1                           | 34               |
| FTA <sup>a</sup>  | -479 to 2593 | 165           | 542                                 | 18.8                          | 33               |
| Standard  | -738 to 581  | 30            | 282                                 | 4.2                           | 33               |
| Based on the <b>39-house</b> refined data set of higher cooling energy <b>users</b> |              |               |                                     |                               |                  |
| 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               |

<sup>a</sup>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

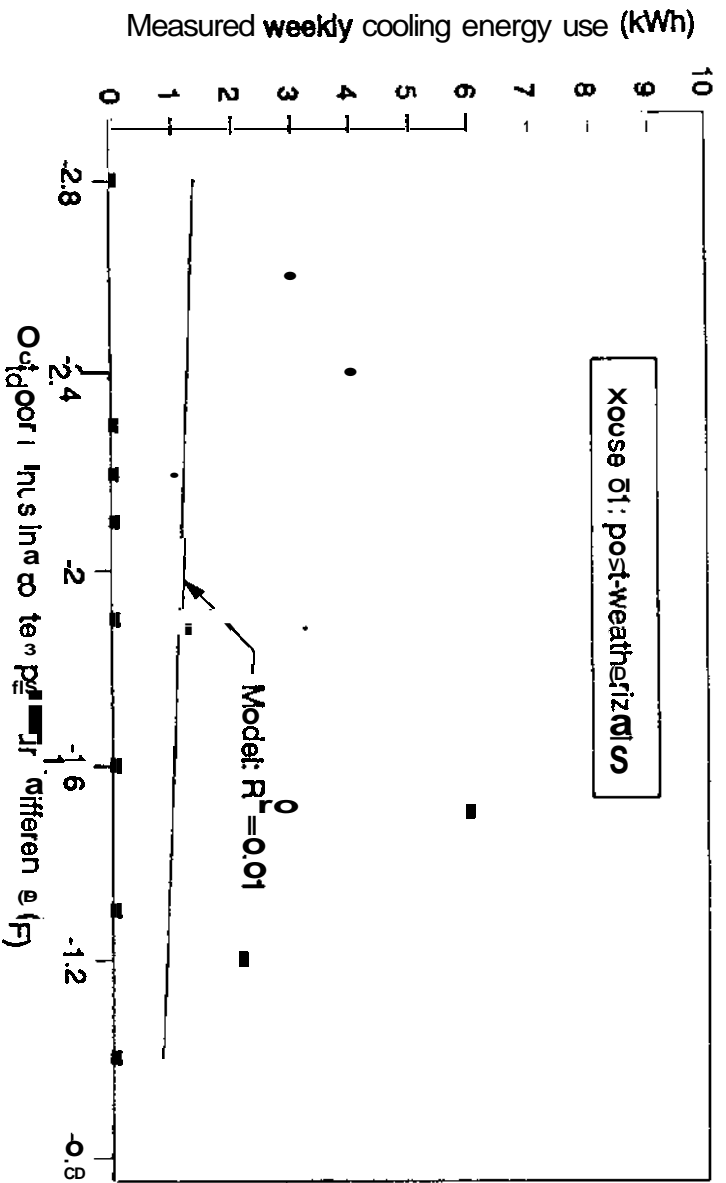
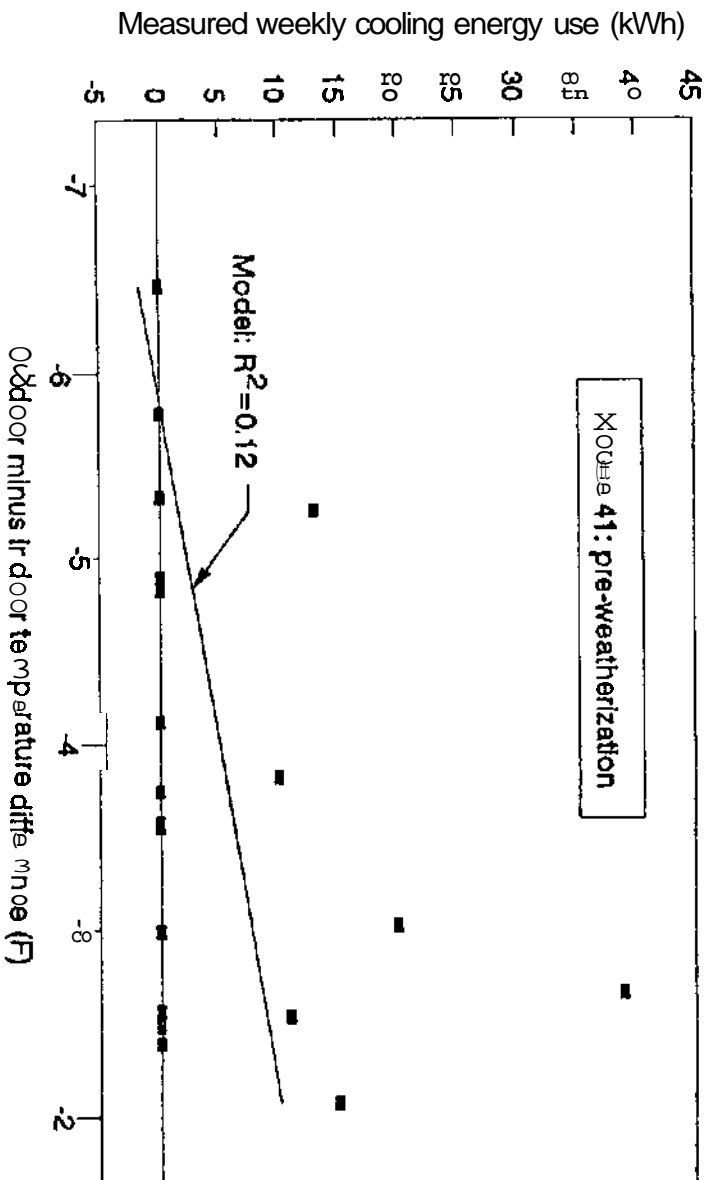


Fig. 9.9. Data plots for two houses having different levels of cooling energy use and random cooling energy use pattern.

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  $\leq 0.06$ ), 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  $\leq 0.25$ . These values are considerably less stringent than 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.

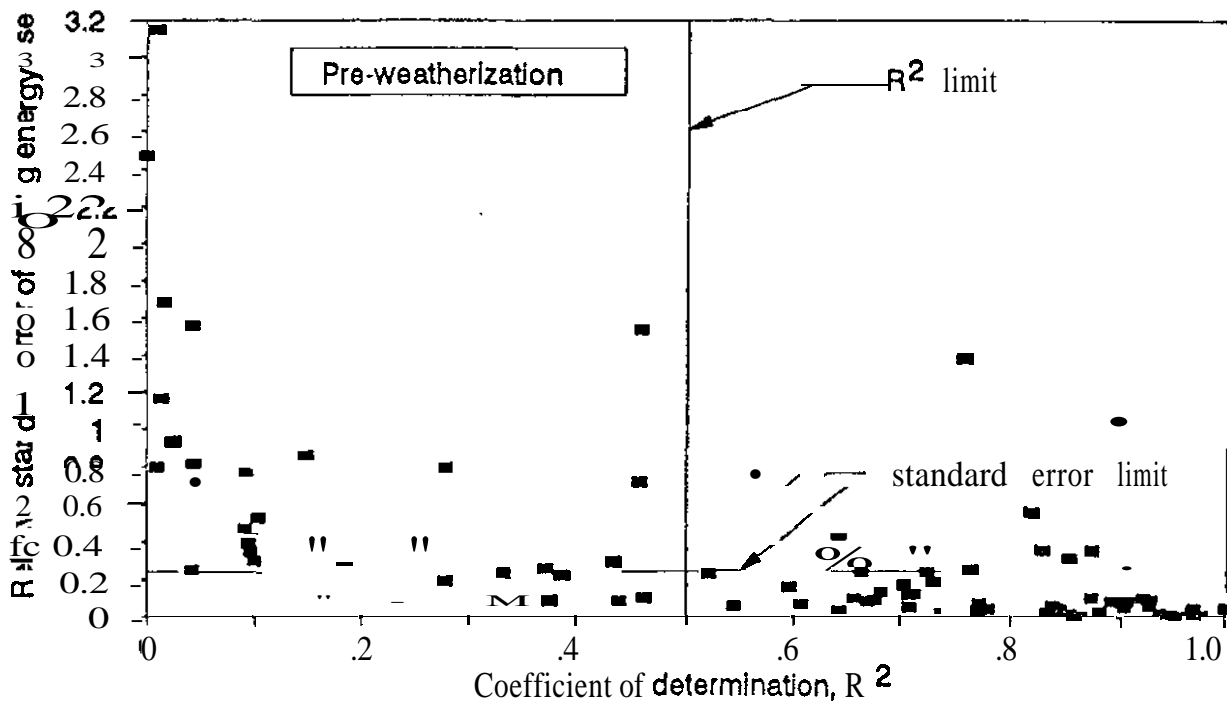


Fig. 9.10. Normalized post-weatherization cooling energy use as a function of reliability screening criteria (1 point with standard error = 103 not shown).

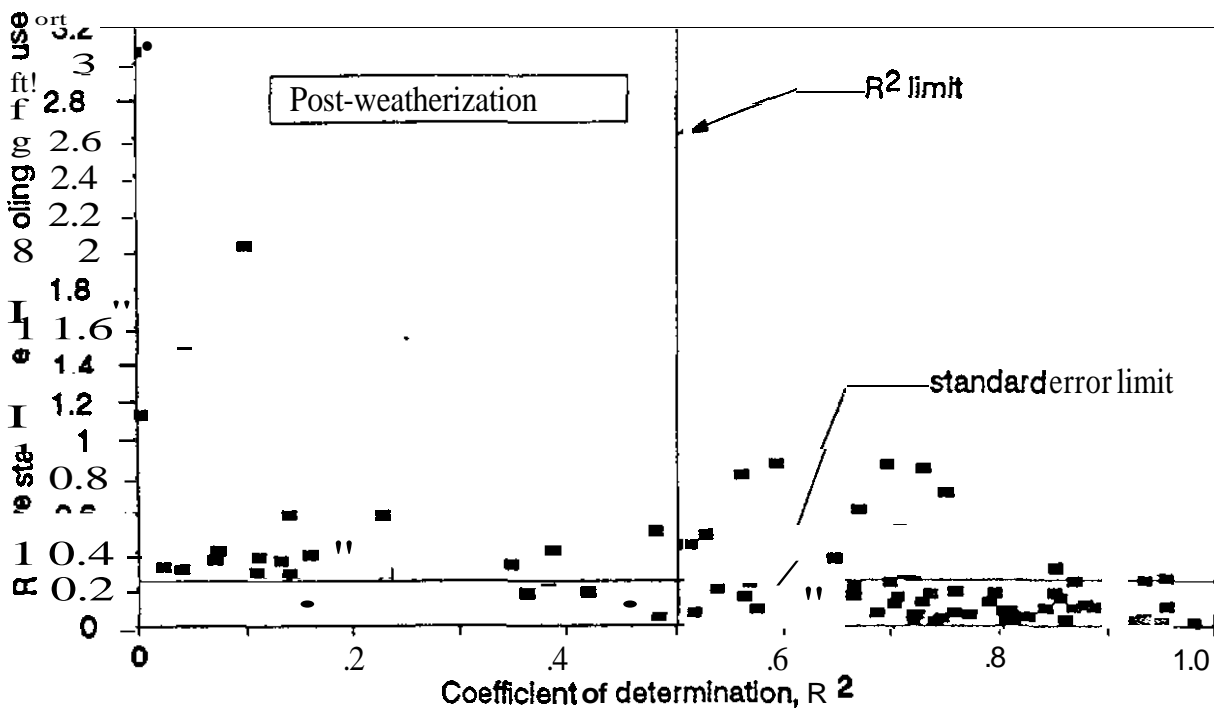


Fig. 9.11. Normalized post-weatherization cooling energy use as a function of reliability screening criteria.



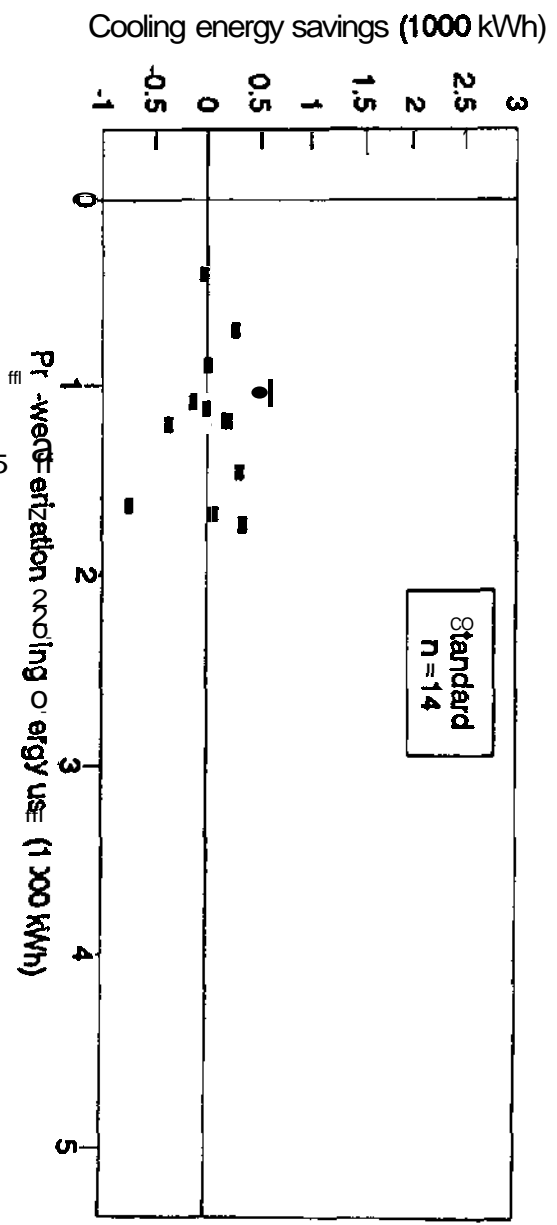
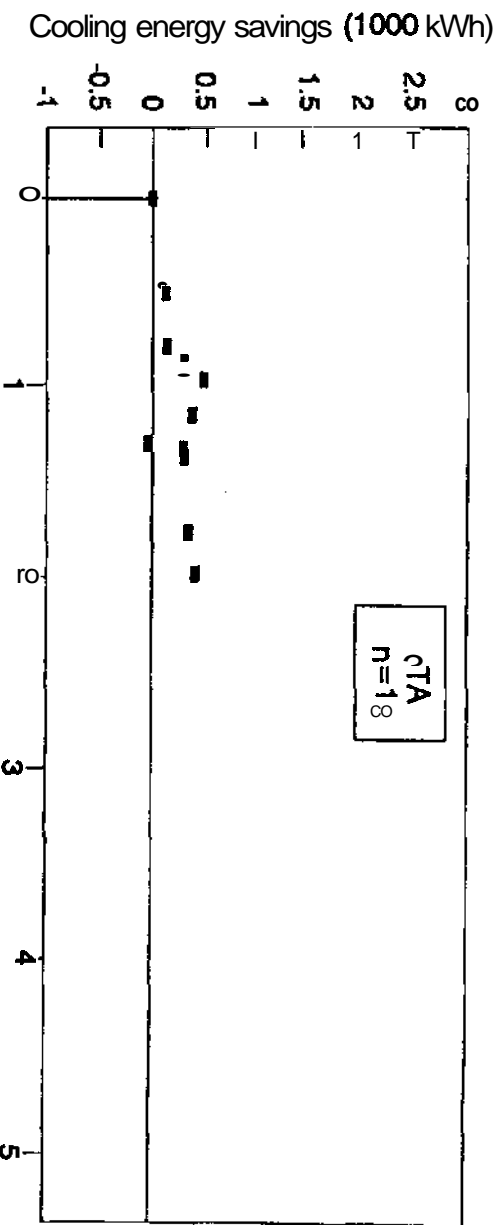
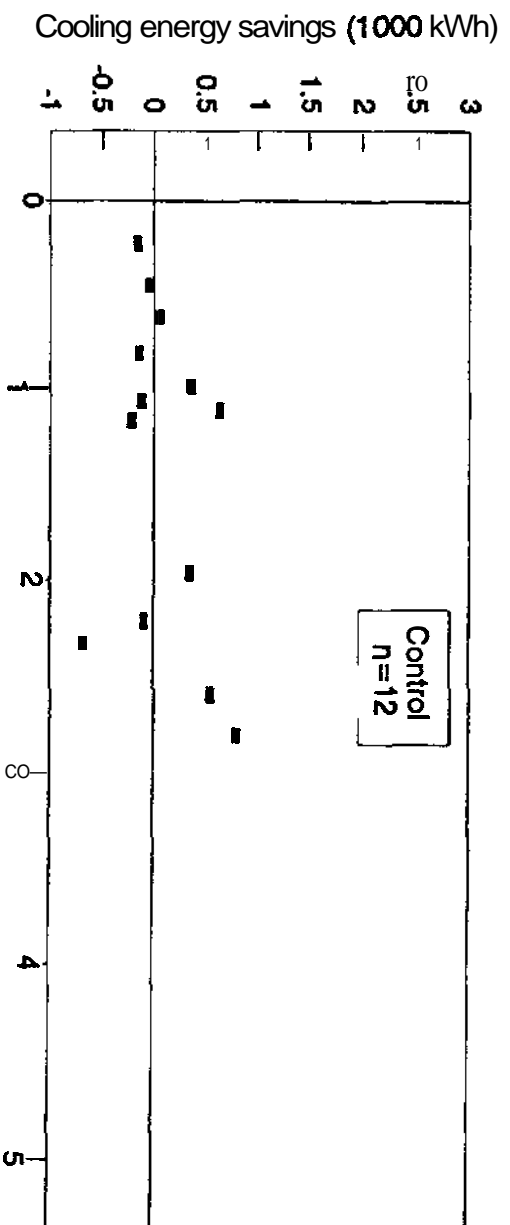


Fig 9.12. Cooling energy savings as function of pre-weatherization cooling energy use by group for the refined, higher cooling energy use group.

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 <sup>a</sup> cost (\$) | Measures installed | House          | Total wx cost (\$) | 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                     | 542                             | W,KW               | 31             | 429                | A30,SW             |
| 37                     | 1549                            | A30,F19,W          | 32             | 1963               | F19,SW             |
| 40                     | 591                             | 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               |                    |

<sup>a</sup> wx = weatherization

Table 102 Total **weatherization** costs by group

| Field Test Audit group |   |                     | Standard group |                                      |                     |
|------------------------|---|---------------------|----------------|--------------------------------------|---------------------|
| Site                   | Average total<br><b>wx</b> <sup>a</sup> cost (\$) | Number of<br>houses | Site           | Average total<br><b>wx</b> cost (\$) | Number of<br>houses |
| A                      | 1017  | 12                  | A              | 1182                                 | 13                  |
| B                      | 1172  | 12                  | B              | 1265                                 | 14                  |
| C                      | 986   | 13                  | C              | 715                                  | 13                  |
| <b>A,B,C</b>           | 1056  | 37                  | <b>A,B,C</b>   | 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 103 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.

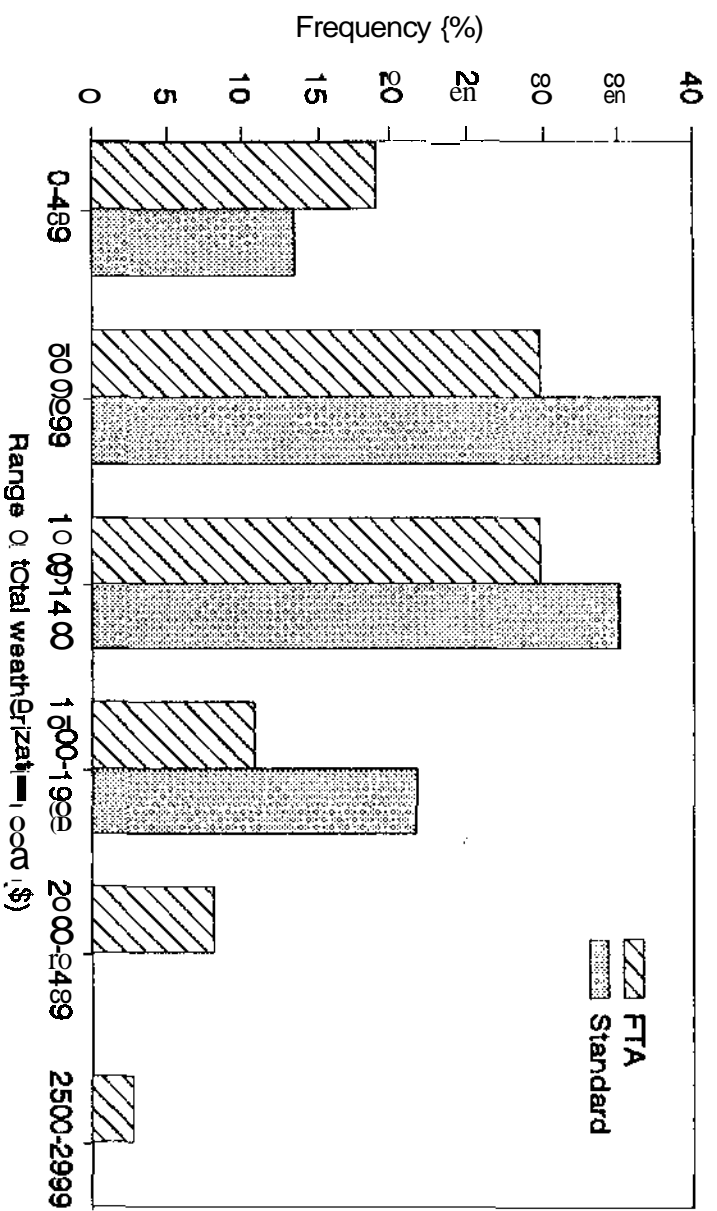


Fig. 10.1 Distribution of weatherization costs by group for sites A and B.

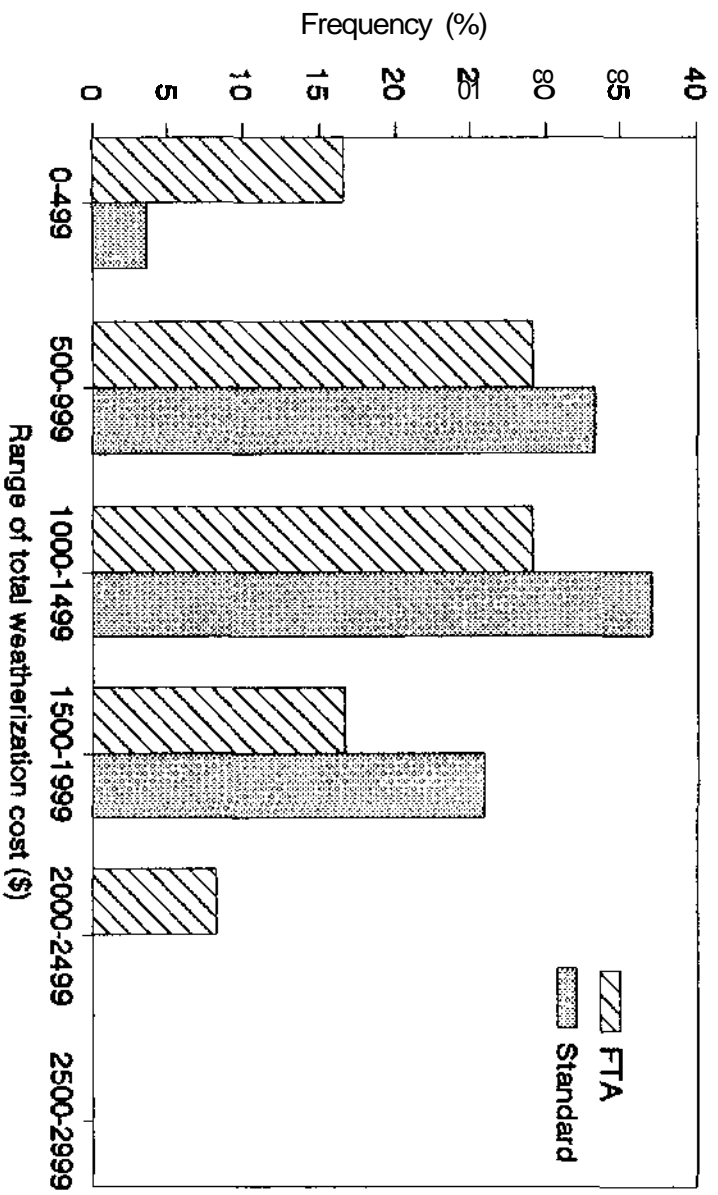
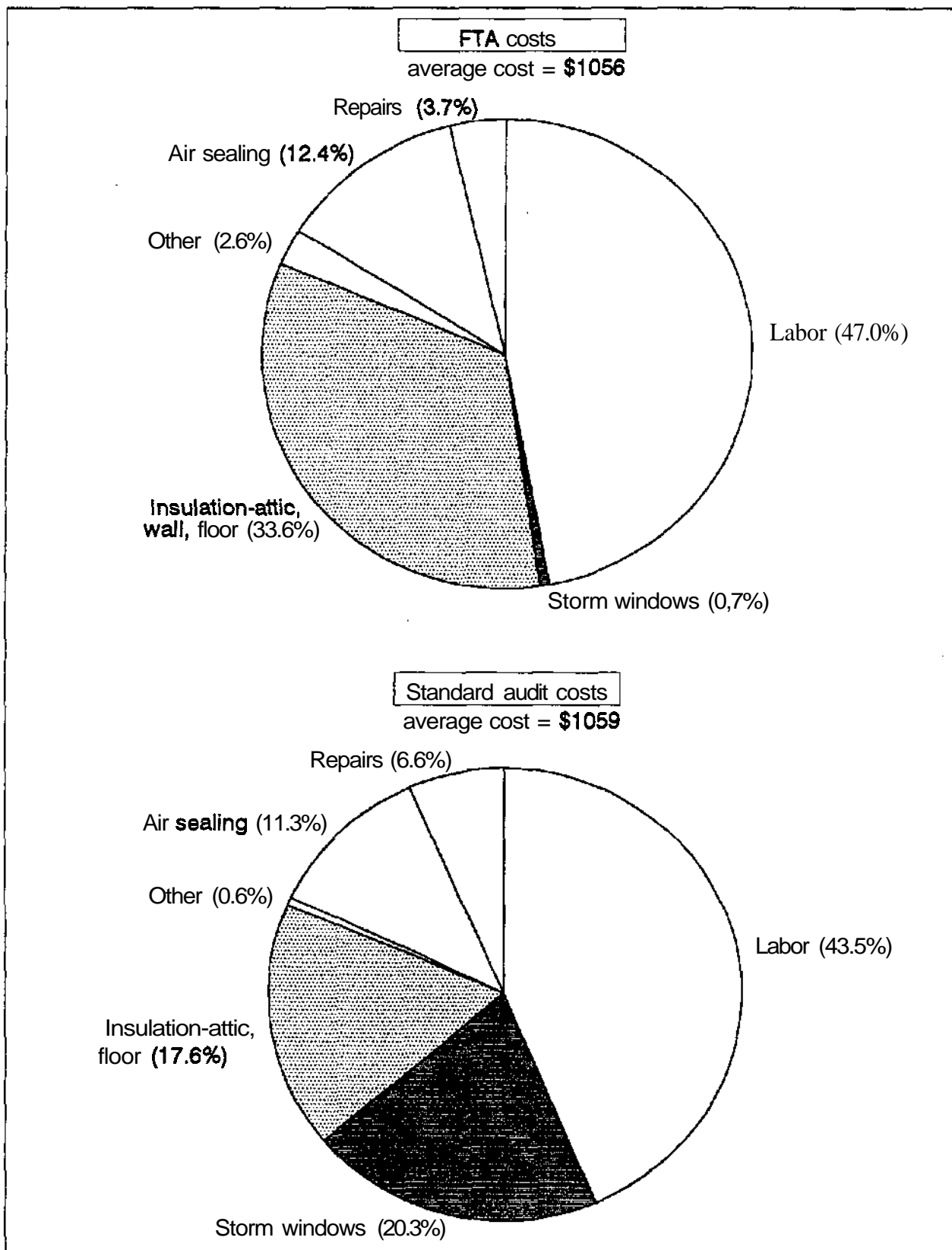


Fig. 10.2 Distribution of weatherization costs by group for sites A and B.



**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,<br>with labor (\$) | House          | Cost for air sealing,<br>with labor (\$) |
| 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                                      |
| <b>Average</b>         | <b>223</b>                               | <b>Average</b> | <b>176</b>                               |



## 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.

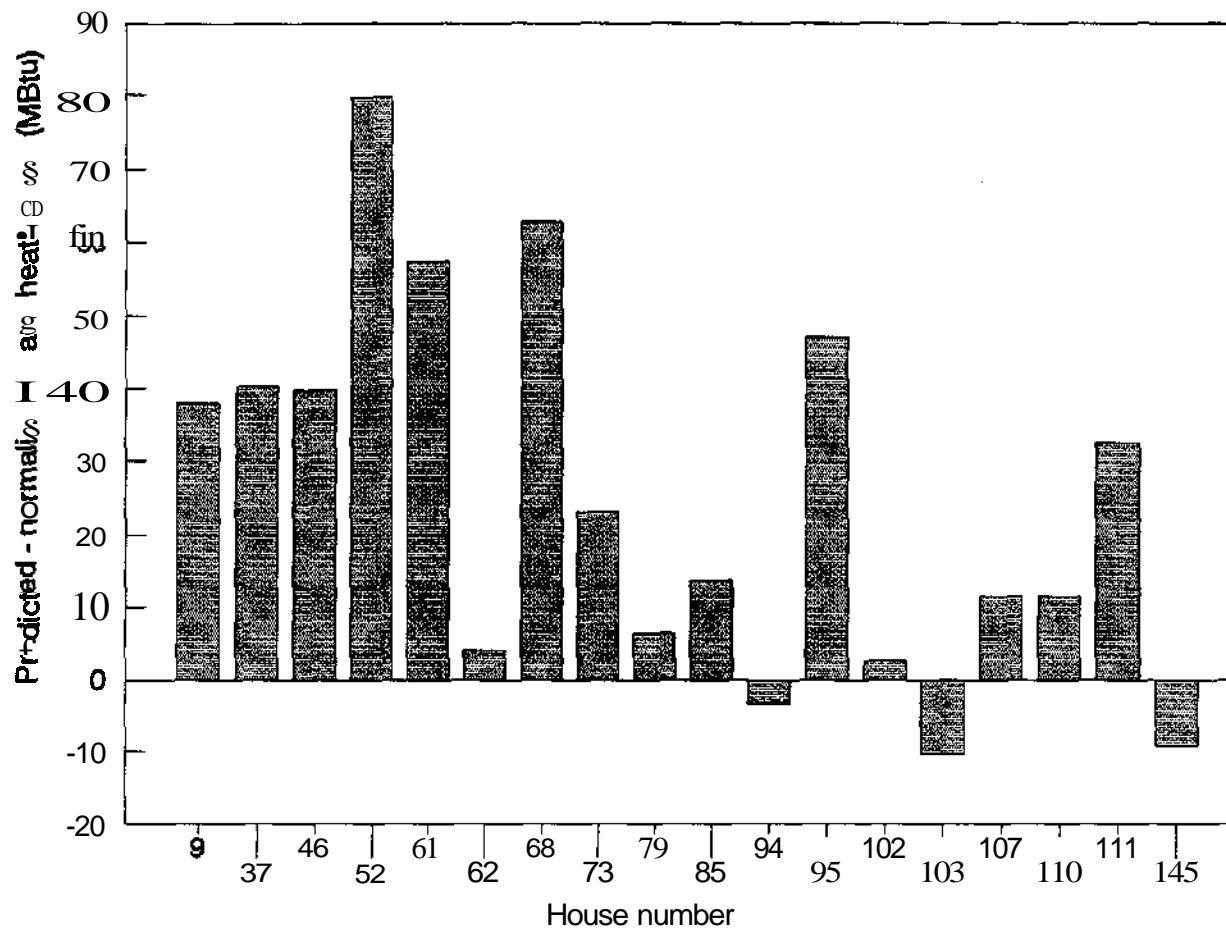
Because larger consumption is often related to larger houses, and larger houses are often only partially heated, the relationship between heated and total floor area was examined. Many houses had significant differences between heated and total floor areas, as can be seen in Fig 11.3. This discrepancy 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 <sup>a</sup> -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                                     |

<sup>a</sup>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

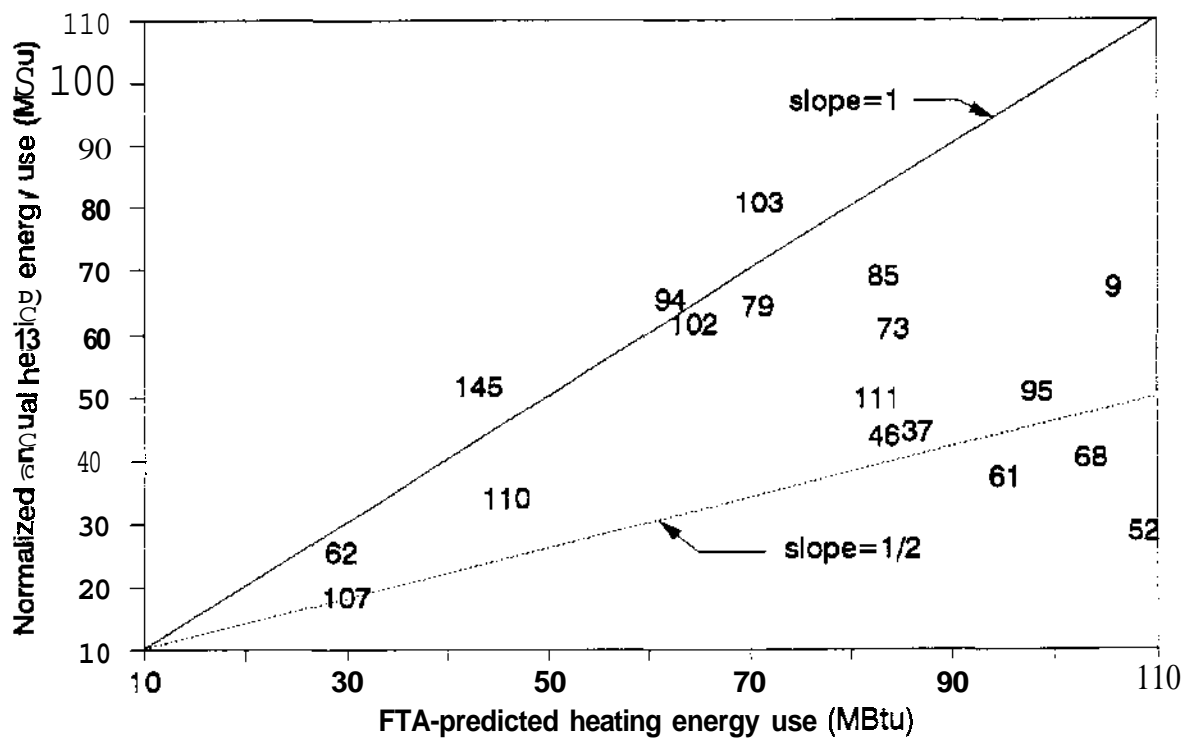


Fig. 11.2. Plot of normalized vs. Field Test audit-predicted pre-weatherization heating energy consumption by house number.

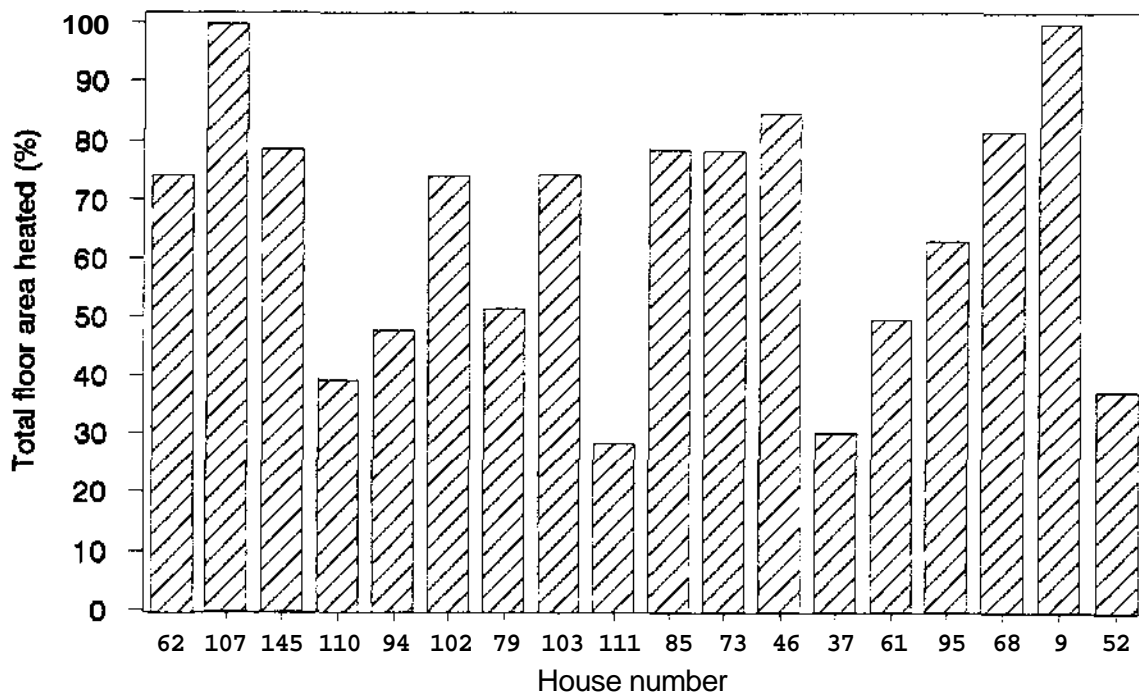
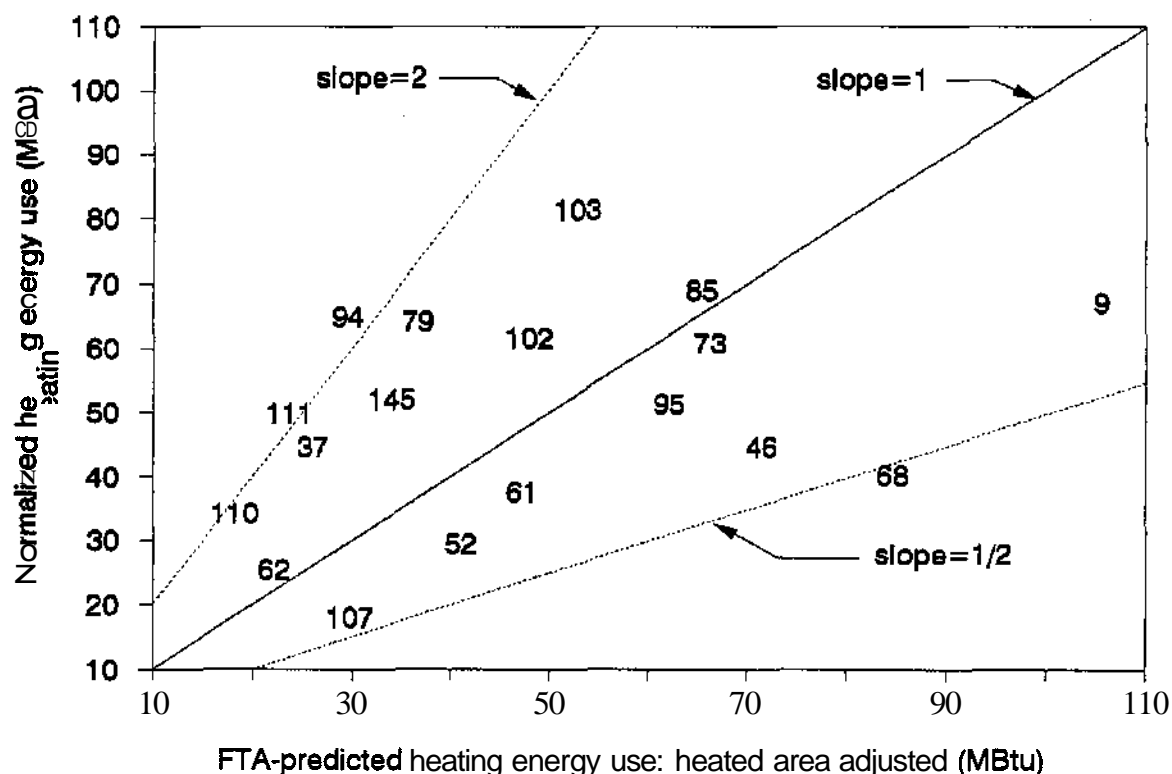


Fig. 11.3. Distribution of the percentage of total floor area heated by house number (ordered left to right by increasing Field Test Audit-predicted pre-weatherization heating energy use).



**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

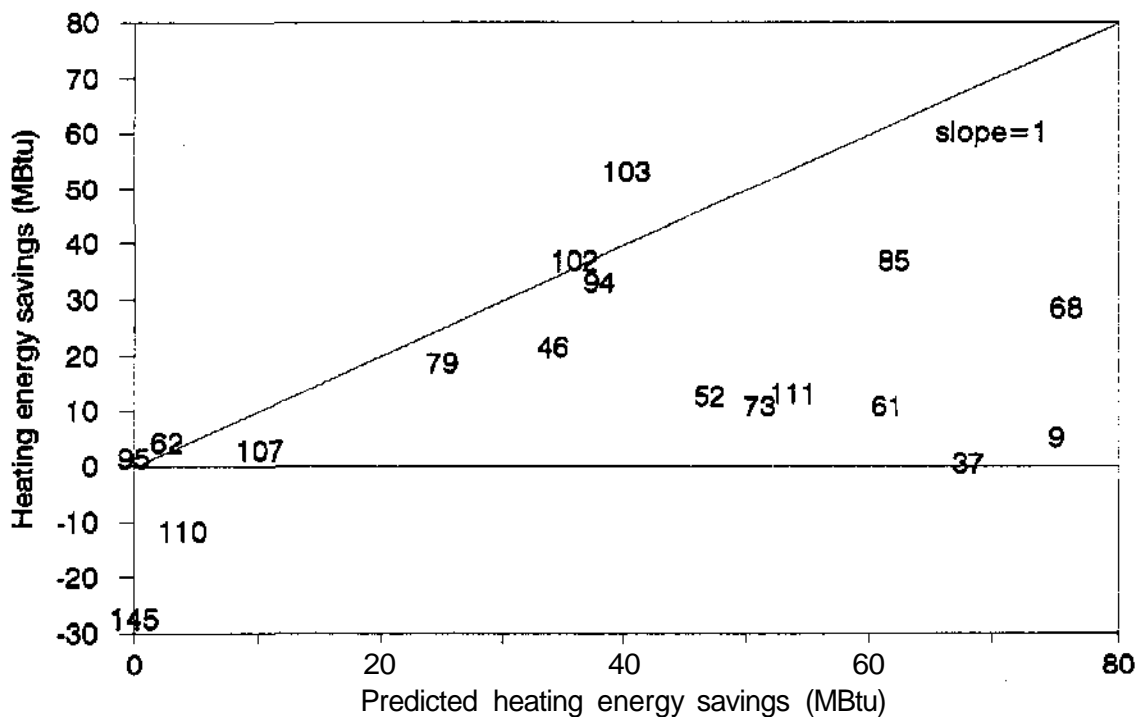


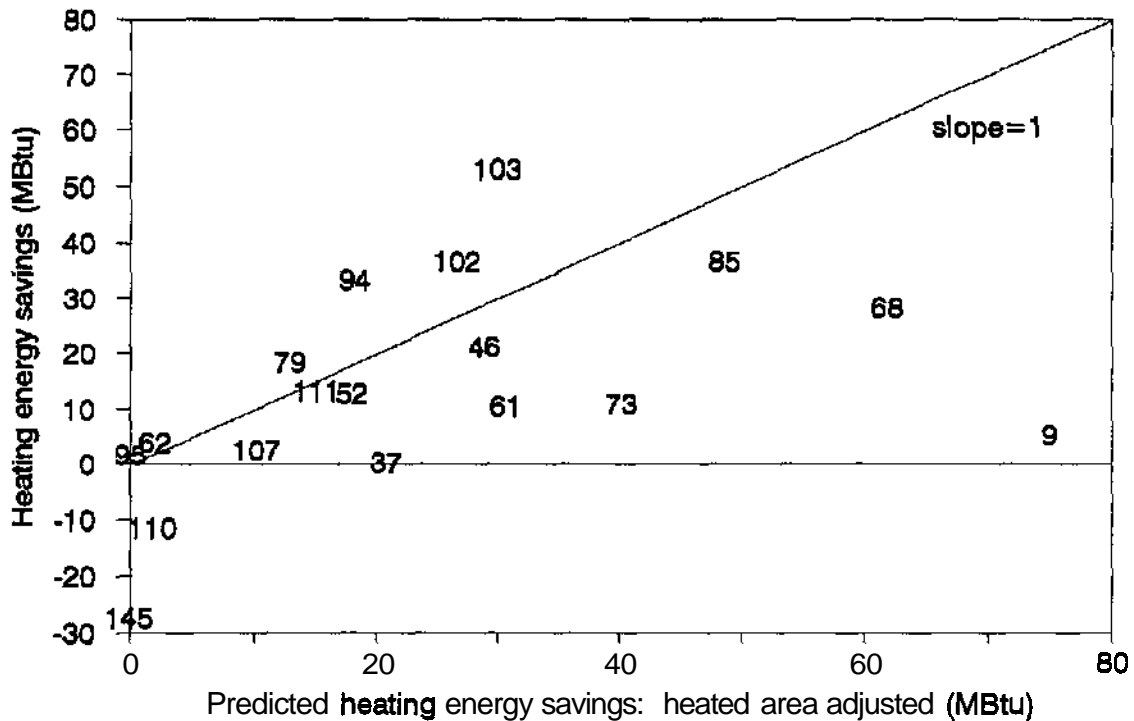
Fig. 11.5. Plot of normalized vs. Field Test Audit-predicted heating energy savings.

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 <sup>a</sup> -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                                      |

<sup>a</sup>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,



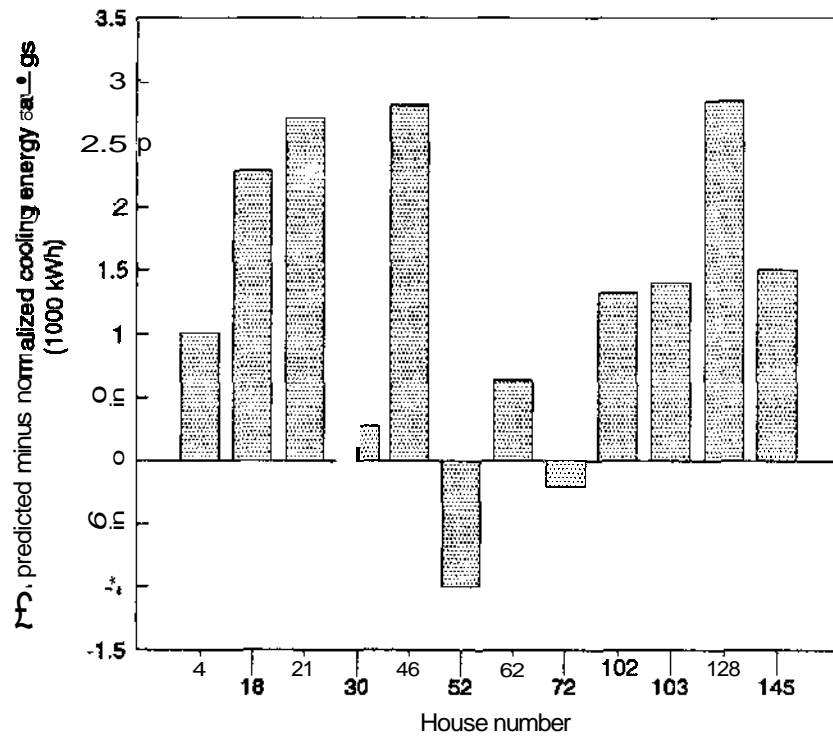


Fig. 11.7. Differences between Field Test Audit-predicted and normalized pre-weatherization cooling energy **consumption**.

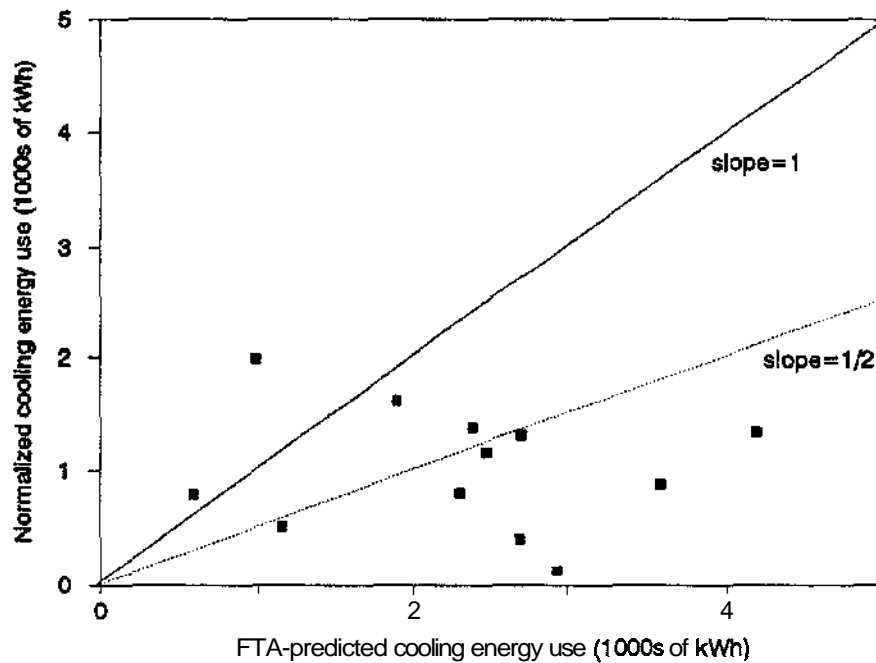
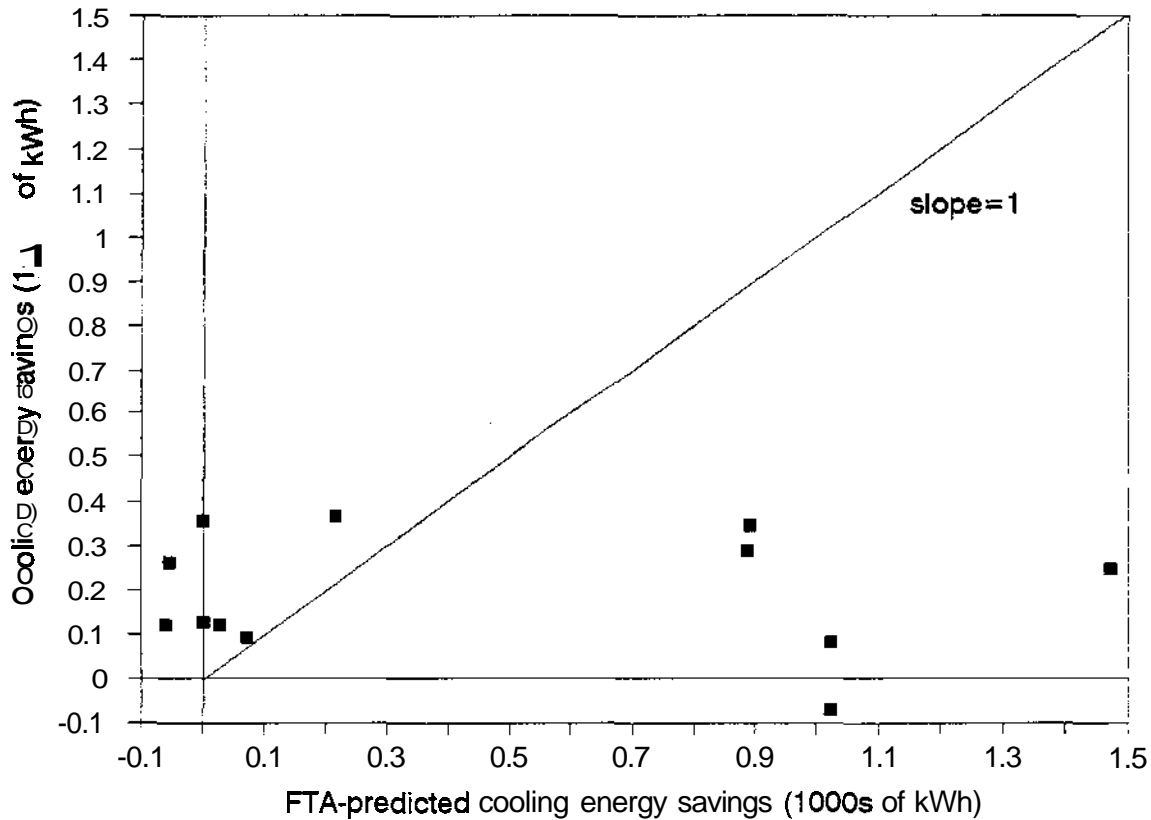


Fig. 11.8. Plot of normalized vs. Field Test Audit-predicted pre-weatherization cooling energy consumption.

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 weathenized 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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