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Field Test Evaluation of Conservation Retrofits of Low-Income, Single-Family Buildings in Wisconsin: Audit Field Test Implementation and Results

Lance N. McCold
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ENERGY DIVISION

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Building Energy Retrofit Research Program

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Reports in This Series

General Title: FIELD TEST EVALUATION OF CONSERVATION RETROFITS OF LOW-INCOME, SINGLE-FAMILY BUILDINGS IN WISCONSIN

ORNL/CON-228/P1. Summary Report

ORNL/CON-228/P2. Audit Field Test Implementation and Results

ORNL/CON-228/P3. Combined Building Shell and Heating System Retrofit Audit

ORNL/CON-228/P4. Occupant Behavior and House Thermal Characteristics in Fifteen Energy Conservation Retrofitted Houses

ORNL/CON-228/P5. Blower-Door-Directed Infiltration Reduction Procedure, Field Test Implementation and Results

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ABSTRACT

This report describes the field test of a retrofit audit. The field test was performed during the winter of 1985-86 in four South Central Wisconsin counties. The purpose of the field test was to measure the energy savings and cost effectiveness of the audit-directed retrofit program for optimizing the program's benefit-to-cost ratio. The audit-directed retrofit program is described briefly in this report and in more detail by another report in this series (ORNL/CON-228/P3). The purpose of this report is to describe the methods and results of the field test.

Average energy savings of the 20 retrofitted houses are likely (0.90 probability) to lie between 152 and 262 therms/year/house. The most likely value of the average savings is 207 therms/year/house. These savings are significantly ($p < .05$) smaller than the audit-predicted savings (286 therms/year/house).

Measured savings of individual houses were significantly different than predicted savings for half of the houses. Each house received at least one retrofit. Thirteen of the 20 retrofitted houses received a new condensing furnace or blown-in wall insulation; all but two of the houses received one or more minor retrofits. The seven houses which received condensing furnaces saved, on average, about as much as predicted, but three of the seven houses had significantly more or less savings than predicted. The six houses which received wall insulation saved, on average, about half as much as predicted. The remaining houses which received only minor retrofits saved, on average, less than predicted, but the difference was not significant.

Actual retrofit costs were close to expected costs. Overall measured energy savings averaged 15 therms/year per hundred retrofit dollars invested. Houses which received wall insulation or a condensing furnace did slightly better, and the houses which received only minor retrofits did poorly. When estimated program costs were included, average savings dropped to about 13 therms/year/per hundred dollars. The uncertainty associated with the energy savings means that these comparisons of savings and costs also have large uncertainties.

EXECUTIVE SUMMARY

Until recently, DOE-funded low-income weatherization activities were limited to infiltration control, insulation, and adding storm windows, with an expenditure limit of $1,000 per house. Under these conditions, most retrofit programs operated from a fixed priority list such as: control infiltration, insulate water heater, add ceiling insulation to some level, and spend the remainder on storm windows. Each house received about the same treatment, and the same amount was spent on each house.

Revised DOE regulations allow an average expenditure per dwelling of $1,600 and permit an expanded list of retrofits, including:

- heating and cooling system tune-ups, repair, and modification;
- installation of thermostat control systems, heat exchangers, and heat pump water heaters; and
- furnace and boiler replacement.

This expanded retrofit repertoire provided options for more effective energy savings, but it also complicated the process of selecting the best combination of retrofits.

DOE asked ORNL to develop and field test a procedure for selecting the optimum combination of building shell and heating system retrofits for single-family dwellings. No single combination of retrofits, indeed, no single priority list will give optimum results more often than occasionally. The optimum combination of retrofits always depends on the characteristics of the house which is to receive the retrofits. This fact led to the necessity of using a retrofit audit to find the optimum retrofits for individual houses. Another report in this series (ORNL/CON-228/P3) describes the audit developed in response to DOE's request.

This report describes the field test of the audit. The field test was performed during the winter of 1985-86 in four South Central Wisconsin counties. The purpose of the field test was to measure the energy savings and cost effectiveness of of the audit-directed retrofit program (ADRP) for optimizing the program's benefit-to-cost (B/C) ratio. The ADRP is described briefly by Sect. 2 and in more detail by another report in this series (ORNL/CON-228/P3). The purpose of this report is to describe the methods and results of the field test.

GENERAL APPROACH

This study followed the conventional approach of measuring fuel consumption for a range of weather conditions before and after the retrofit. Linear regression analysis was then used to model the relationship between space heating fuel consumption and the average ambient temperature. Long-term average weather conditions were used to calculate normalized annual heating fuel use. The difference between the normalized annual heating fuel consumption (NAHC), before and after the retrofits, is the normalized annual heating fuel savings (NAHS).

External constraints and the desire for timely results led to formulation of a research plan calling for all data to be collected and retrofits to be completed in one heating season. Fuel use data collection on individual houses began during the last half of October and the first half of November in 1985. Most retrofits were performed during the last two weeks of January and the first two weeks of February, 1986. Post-retrofit data collection for each house began shortly after the retrofits were completed; it terminated during the month of May with the last useful observation on most houses occurring around the first of May. The one heating season study also required that an unconventional type of data be collected: submetered heating system fuel consumption measured at weekly intervals. Meters were installed on the heating system of each house to record fuel use (Sect. 3.2).

A control group was included in the study to allow compensation for seasonal or occupant behavior changes in energy use between the early and late parts of the heating season. The control group houses were analyzed as if they had had retrofits by breaking their data into pre- and post-retrofit periods. The control house pre-retrofit periods ended with the last reading preceding January 29. The post-retrofit periods began after the observation that included January 29. The treatment group results were adjusted for the apparent savings of the control group.

The study began with the identification of suitable houses, defined as those meeting the following suitability criteria:

- o Eligible for the WAP: household income is less than 125% of poverty, and the house has not been weatherized by DOE or utility programs in the past five years.
- o Single-family detached house (but no mobile homes).
- o Owner has occupied the house for at least one year and is not planning on extended time away from home during the test period.
- o House is heated by a natural gas furnace or boiler.
- o Secondary heating devices are not used (electric bathroom heaters and occasional fireplace use are acceptable).
- o Occupants are willing to take part in the field test.

The first criterion, eligibility, was selected to make the results relevant to the WAP. The remaining criteria were chosen to maintain the data quality at the highest feasible level. Houses were randomly assigned to either the audit group or control group.

RESULTS

Mean measured savings were 169 therms/year, 86% of the predicted measurable savings. The seven houses which received a new condensing furnace retrofit saved 102% of the predicted measurable savings. The six houses which received wall insulation saved 74% of the predicted measurable savings. The remaining seven houses, which received only minor retrofits, had a slight increase in energy consumption.

For the group, the measured and predicted savings were not significantly different, but this makes the audit appear more accurate than it is. The mean savings of the houses which received wall insulation and those which received only minor retrofits were significantly less than predicted. Further, 10 of the 20 audit group houses had measured savings which were significantly different than their predicted savings.

The WAP administrator who is interested in making his program more effective is faced with the question: how much energy can I expect to save if I adopt the ADRP? For the area of South Central Wisconsin where the study was performed, the answer is that there is a 0.9 probability that average savings will fall between 105 and 309 therms/year/house. This is a broad confidence interval.

The breadth of the confidence interval may make it difficult for the decision maker to act decisively. The breadth of the confidence interval is the combined result of the variability of energy savings among households and the size of the sample. Studies of this kind are costly and larger studies are more costly, so studies with much larger samples are most likely impractical. One good way to get improved confidence in the ADRP is to try it on limited groups and proceed to larger groups if good results are found.

COST EFFECTIVENESS

Overall, the retrofits saved about 15 $\pm$ 4 therms/year per $100 retrofit dollar. The houses which received major retrofits (wall insulation or a new condensing furnace) were more cost effective, about 17 $\pm$ 4 therms/year per $100 retrofit dollar, and the houses which received no major retrofits were not cost effective, 5 $\pm$ 11 therms/year per $100 retrofit dollar. Assuming that $300/house will cover audit and administrative costs, the program saves 13 $\pm$ 3 therms/year per $100 of program (including retrofit) costs.

At $0.68/therm for natural gas in the study area, the program costs are likely to be repaid by energy savings in about 12 years. A 12-year simple payback period is not really a fair measure of the program's cost effectiveness because it has other benefits. Some of these are:

1. Many low-income families receive assistance with their energy bills, either from government programs or from utility companies. Reducing their fuel bills with this program will reduce the subsidy they require from other sources.
2. The values of low-income families' homes are increased by the retrofits.
3. The audits uncover safety problems that can be corrected.
4. Energy saved in low-income households reduce the nation's dependence on foreign energy sources and helps to hold down energy prices by keeping demand lower.
5. Home owners may experience increased comfort.

CONCLUSIONS AND RECOMMENDATIONS

The audit's predictions of energy savings for individual houses were found to be inaccurate. Ten of 10 audit group houses had savings which were significantly different than their predicted energy savings. These discrepancies are most likely the result of the audit's failure to account for one or more factors which affect energy savings. The causes of these discrepancies should be investigated and the audit savings algorithms adjusted accordingly.

The sample of 20 audit group houses suggests that the value of the retrofit energy savings will about equal the cost of the WAP which incorporates the ADRP. There is, however, a rather wide range of uncertainty associated with this result. When considering the cost effectiveness of the WAP, with or without the ADRP, it is important to remember that the program has other benefits.

The new field test method used in this study was, in itself, an experiment. It was developed for this single heating season field test. The fact that it worked and gave good results is an important outcome of the field test. This new method can be usefully applied in other field tests, especially where they need to be performed in a single heating season. The new field test method should be further developed so that more of the necessary steps are automated, and the details of its implementation should be fully documented so others can use it.

1. INTRODUCTION

Until recently, the U.S. Department of Energy (DOE) funded low-income weatherization activities limited to infiltration control, insulation, and adding storm windows, with an expenditure limit of $1,000 per house. Under these conditions, most retrofit programs operated from a fixed priority list such as: control infiltration, insulate water heater, add ceiling insulation to some level, and spend the remainder on storm windows. Each house received about the same treatment, and the same amount was spent on each house.

Revised DOE regulations allow an average expenditure per dwelling of $1,600 and permit an expanded list of retrofits, including:

- heating and cooling system tune-ups, repair, and modification;
- installation of thermostat control systems, heat exchangers, and heat pump water heaters; and
- furnace and boiler replacement.

This expanded retrofit repertoire provided options for more effective energy savings, but it also complicated the process of selecting the best combination of retrofits.

DOE asked Oak Ridge National Laboratory (ORNL) to select or develop and field test a procedure for selecting the optimum combination of building shell and heating system retrofits for single-family dwellings. No single combination of retrofits, indeed, no single priority list will give optimum results more often than occasionally. The optimum combination of retrofits always depends on the characteristics of the house which is to receive the retrofits. This fact led to the necessity of using a retrofit audit to find the optimum retrofits for individual houses. Another report in this series (ORNL/CON-228/P3) describes the audit-directed retrofit program (ADRP) developed in response to DOE's request.

The field test was designed to test the ADRP concept. Energy savings and cost effectiveness of the savings were used as measures of ADRP performance. The field test was performed during the winter of 1985-86 in four South Central Wisconsin counties.

The field test was a cooperative effort of a variety of organizations. Financial support for the field test was supplied by the DOE Office of Buildings and Community Systems (DOE-OBCS), and Weatherization Assistance Program (DOE-WAP), the State of Wisconsin, the Department of Health and Social Services, and by three Wisconsin utilities (Wisconsin Power and Light, Wisconsin Gas, and Madison Gas and Electric).

The Wisconsin Energy Conservation Corporation (WECC) installed the instrumentation, collected data, and coordinated the audits and retrofits. ORNL developed the method for selecting the retrofits, designed the field test, and analyzed the field test data. The Alliance to Save Energy (ASE) provided assistance in the development and implementation of heating system components of the audit, and helped bring the field test participants together. The nature of the cooperative effort is more thoroughly described in another report in this series (ORNL/CON-228/P1).

The purpose of this report is to describe the methods and results of the field test. This report is organized in six sections. Following this introduction, Sect. 2 gives a brief description of the ADRP and a discussion of a modification made to the ADRP during implementation of the field test. Section 3 is a description of the field test approach. The measured energy savings are presented in Sect. 4 for both the group of houses treated by the ADRP and for individual houses. Section 5 is a discussion of the cost effectiveness of the retrofits as applied to these houses and from the perspective of a retrofit program like DOE's WAP. The conclusions which follow from the study results are presented in the final section.

2. AUDIT-DIRECTED RETROFIT PROGRAM

The audit-directed retrofit program (ADRP) consists of two parts. The first is the audit used to predict energy savings for each individual retrofit; it can stand alone as a tool for estimating retrofit energy and money savings for individual houses. The second part is the retrofit selection procedure which uses the results of an audit to select the best retrofits from the retrofit program perspective, not just for a given house. Both these parts of the ADRP are described briefly below. A thorough description is given in another report in this series (ORNL/CON-228/P3).

2.1 THE AUDIT

An audit is a multi-step process, illustrated by Fig. 2.1. The first step is to collect the data on the audited house that will allow estimation of the costs and savings of the retrofits under consideration. This data collection step is the most visible part of the process. Indeed, many homeowners think that the auditor's observations, measurements, and questions are the audit. Although the data collection step is only part of the process, it is a very important step. The audit cannot give accurate results if the data used in it are inaccurate.

A retrofit audit uses characteristics of the house, the climate, and the retrofit to calculate energy savings. For example, energy savings estimates for ceiling insulation are based on the amount of ceiling insulation in the house, the efficiency of the heating system, the heat retardant characteristics (R-value) of the insulation to be added, and the severity of the climate (heating degree days). Similarly, estimates of heating system retrofit energy savings are typically based on the efficiency of the heating system, the characteristics of the retrofit, and the amount of heating fuel used annually.

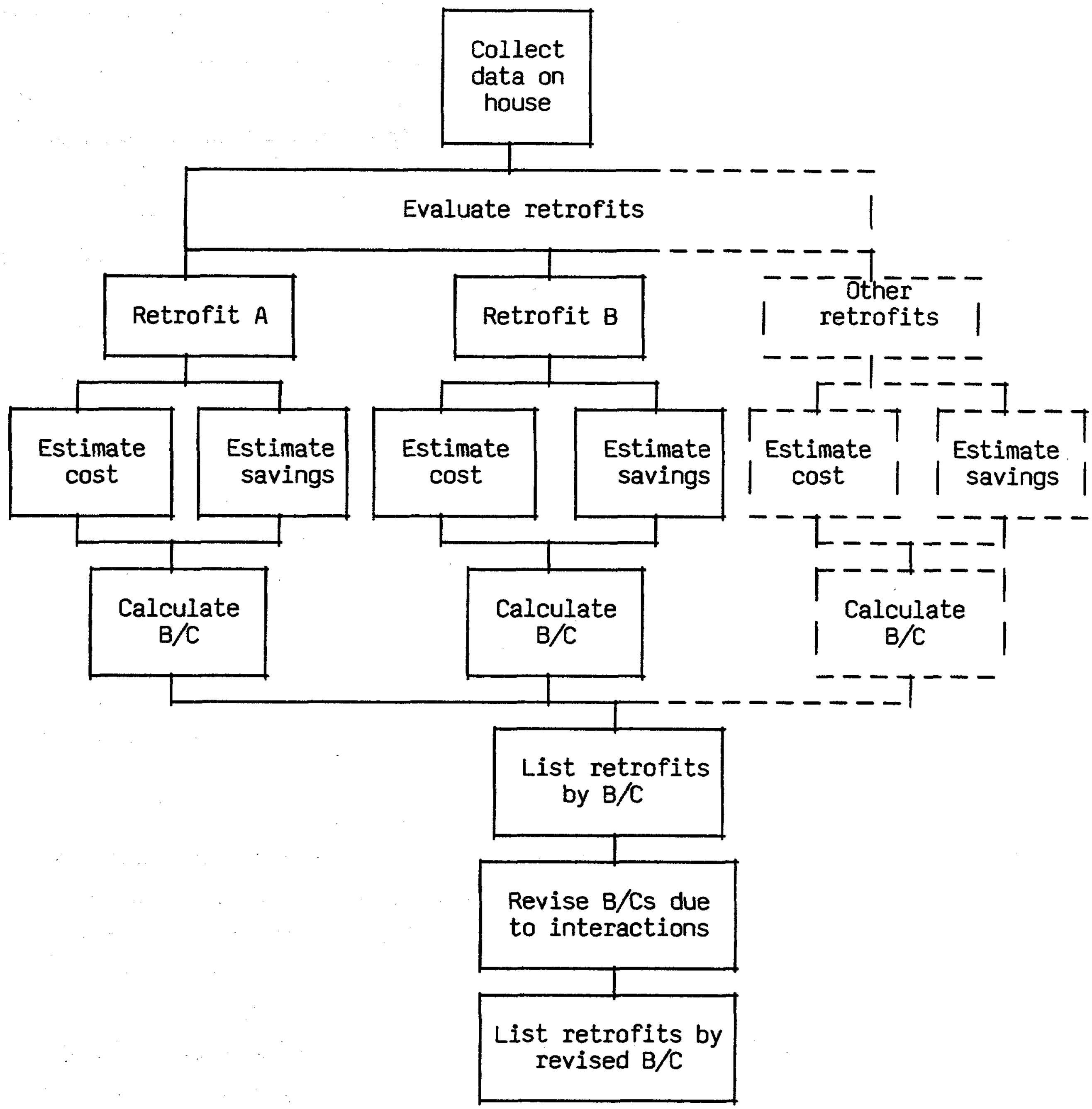

Fig. 2.1. Audit process for an individual house.

This audit, as field tested, takes into consideration six possible heating system retrofits and seven possible building shell retrofits. The heating system retrofits are (1) intermittent ignition devices (IIDs), (2) electro-mechanical full-closure vent dampers (requiring use of an IID), (3) thermally activated vent dampers, (4) secondary condensing heat exchangers, (5) gas power burners, and (6) furnace replacements.

The building shell retrofits are (1) ceiling insulation, (2) wall insulation (blow-in), (3) storm windows, (4) storm doors, (5) sill box insulation, (6) exterior basement wall insulation (R-10), and (7) floor insulation. An eighth shell retrofit, blower-door-guided infiltration reduction, was included for the field test. Reference 1 and another report in this series (ORNL/CON-228/P5) give additional details on the blower door procedure.

As Fig. 2.1 shows, the costs of materials and labor involved in each retrofit need to be estimated. A benefit-to-cost ratio (B/C) is calculated for each retrofit from estimated costs and from savings estimated using audit calculations. A B/C enables retrofits to be ranked according to their cost effectiveness. A B/C greater than 1.0 indicates that the retrofit saves more money (through energy savings) than it costs during its useful life. Conversely, a B/C less than 1.0 will not save as much money as the retrofit cost.

After retrofits have been ranked by B/C, the interactions among retrofits are considered. Retrofit interactions become important when both heating-system and building-shell retrofits are used, as in this audit. Interactions occur when two retrofits work to save the same energy. For instance, ceiling insulation saves energy by reducing the amount of heat needed to keep a house warm, while improving the efficiency of a furnace reduces the amount of fuel needed to deliver the required heat. The interaction between the retrofits causes the energy saved by the combination of retrofits to be less than the sum of the savings each would achieve alone. The method used to account for retrofit interactions is described in Ref. 2. The audit, as field tested, accounted for retrofit interactions.

2.2 RETROFIT SELECTION PROCESS

It is widely recognized that some homes treated under the WAP need retrofits more than others do. The revised DOE regulations that allow weatherization expenses to be averaged across a number of homes give weatherization providers the flexibility to spend retrofit dollars where they are most needed. After the regulations went into effect, the principal remaining impediment to more effective allocation of retrofit dollars was the need for a method of allocating resources among houses. The recommended retrofit selection procedure for a group of houses is: to (1) put all retrofits on a single list ordered by B/C, and (2) select retrofits with the highest B/C until the allocated money is spent.

The WAP rules allow spending up to an average of $1600/house. Although Wisconsin generally spends more than $1600 with funds from varied sources, the $1600 value was chosen for the field test to conform with DOE regulations. Of the $1600, $200 was set aside to cover the cost of publicizing the program, verifying that applicants were qualified for the program and auditing the house. Another $200 was set aside for essential repairs such as replacing broken glass, ventilating attics, and sealing and insulating attic access doors; weatherization providers were specifically instructed not to spend any of this amount on caulking and weatherstripping or on insulating water heaters. An average of $1200 per house remained for actual retrofits selected by the audit.

The $1200 average retrofit expenditure per house allowed $42,000 to be spent on retrofits for the 35 houses,* as directed by the audit. The one planned exception to this procedure was that each furnace or boiler that had no retrofit or was not replaced received a $70 cleaning and tune-up to ensure its

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*Attrition subsequently reduced audit group house numbers to 20. The causes of this attrition are discussed in Sect. 3.2.

continued safe operation. It was thought that servicing unretrofitted heating systems was necessary in order to avoid any potential liability problems as a result of the heating system's being inspected and manipulated during the audit. Heating systems that were retrofitted or replaced received equivalent servicing as a part of the retrofit.

The retrofit selection procedure was applied to the 35 houses to be retrofitted under the ADRP in two phases. Retrofits for a first group of 25 houses were selected on January 14, 1986, and those for the remaining 10 houses were selected on February 6, 1986.

The retrofit selection procedure was modified slightly for the field test to account for an unexpected problem: straight use of the selection procedure would have required use of retrofits with very low B/Cs (less than 0.7) in order to spend an average of $1200/house. The problem can be seen either as the result of trying to spend too much per house or auditing for too few cost-effective retrofits. Two solutions were identified: (1) spend less per house on the average, or (2) modify the selection procedure. It was decided to modify the selection procedure so as to spend $1200/house on retrofits while maintaining the highest possible B/C.

In many of the houses the heating system retrofits had approximately equal B/Cs (e.g., 1.15, 1.20, and 1.25). Performing any one heating system retrofit generally precludes doing another heating system retrofit. In most cases, a relatively inexpensive retrofit, such as an IID, was the heating system retrofit with the highest B/C. Selecting these inexpensive retrofits precluded heating system retrofits with slightly lower B/Cs; thus, shell retrofits with much lower B/Cs would need to be selected to spend the $1200/house.

It was found that selecting an expensive retrofit like a new condensing furnace with an acceptable B/C (e.g., 1.0) was better than choosing an inexpensive retrofit like an IID with a better B/C (e.g., 1.3) because shell retrofits with poor B/Cs (e.g., 0.7) would then not be needed in order to spend the $1200/house average. The selection procedure was modified by selectively replacing low-cost individual heating system retrofits with more expensive ones, while dropping less cost-effective shell retrofits. This process was followed until the average expenditure equaled the $1200/house target. This modified selection procedure had the added benefit of increasing the overall B/C of the whole selection of retrofits, compared to the straight use of the procedure. This variation of the procedure would not have been needed if there had not been a target expenditure level, as only those retrofits with B/Cs greater than some minimum level (e.g., 1.0) would have been selected.

3. FIELD TEST APPROACH

3.1 GENERAL APPROACH

This study followed the conventional approach of measuring heating fuel consumption of individual houses for a range of weather conditions before and after installation of the retrofits. Linear regression analysis was then used to model the relationship between space heating fuel consumption and the average ambient temperature. Long-term average weather conditions were used to calculate normalized annual heating fuel consumption (NAHC). The difference between the NAHC, before and after installation of the retrofits, is the normalized annual heating fuel savings (NAHS).

External constraints and the desire for timely results led to formulation of a research plan calling for all data to be collected and retrofits to be completed in one heating season. In order to collect the maximum quantity of data, an optimum schedule was developed. This schedule had fuel use data collection beginning by October 1, and all retrofits completed during the second and third weeks of January. Fortunately, the regression analysis is resilient enough to accommodate considerable variance from the optimum schedule, and the weather was cooperative.

Fuel use data collection on individual houses began during the last half of October and the first half of November in 1985. Most retrofits were performed during the last two weeks of January and the first two weeks of February, 1986.* Post-retrofit data collection for each house began shortly after the retrofits were completed. Data collection terminated during the month of May. The last useful observation on most houses occurred around the first of May.

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*Two stragglers were not completed until the end of February.

The one heating season study also required that an unconventional type of data be collected: submetered heating system fuel consumption measured at weekly intervals. Meters were installed on the heating system of each house to record fuel use (Sect. 3.2). The submetered heating system data were required because use of utility meter data would have required summer meter readings in order to allow estimation of the base (non-space heating) load. Weekly measurements were necessary because monthly observations would provide an insufficient number of data points for regression analysis.

A comparison group (called the control group) was included in the study to control for factors, other than retrofits, that could influence heating fuel consumption patterns. Some of the possible factors which might influence heating fuel use are: price effects, seasonal variation in occupant behavior, seasonal variation in ground temperatures, and weather parameters which are not related to ambient temperature such as insolation and wind speed. The control group houses were analyzed as if they had had retrofits by breaking their data into pre- and post-retrofit periods. The control house pre-retrofit periods ended with the last reading preceding January 29. The post-retrofit periods began after the observation that included January 29. The treatment group results were adjusted for the apparent savings of the control group.

3.2 HOUSE SELECTION

The study began with the identification of suitable houses, defined as those meeting the following suitability criteria:

- Eligible for the WAP: household income is less than 125% of poverty, and the house has not been weatherized by DOE or utility programs in the past five years.
- Single-family detached house (but no mobile homes).
- Owner has occupied the house for at least one year and is not planning on extended time away from home during the test period.
- House is heated by a natural gas furnace or boiler.

- o Secondary heating devices are not used (electric bathroom heaters and occasional fireplace use are acceptable).
- o Occupants are willing to participate in field test.

The first criterion, eligibility, was selected to make the results relevant to the WAP. The remaining criteria were chosen to maintain the data quality at the highest feasible level.

The audit and control groups each began with 40 tentatively suitable houses. A second treatment group of 26 tentatively suitable houses (the subject of another report in this series, ORNL/CON-228/P5), was established at the same time as the other groups. Tentatively suitable houses were randomly assigned to the audit group, the control group, or the third group. The project schedule made it necessary to begin with tentatively suitable houses, but the 40-house initial group sizes were large enough to allow 25-50% attrition.

The final numbers of houses in the audit and control groups were 20 and 28 houses, respectively. The higher attrition of the audit group can be attributed to two factors. First, tentatively suitable audit group houses were dropped if their income eligibility had not been verified by January (when the retrofits were performed), while tentatively suitable control group houses had until April to demonstrate income eligibility. Consequently, some tentatively suitable audit group houses may have been rejected which would not have been if they had had more time to demonstrate their income eligibility. Also, the audit and retrofit processes uncovered and, in a few cases, caused problems that made houses unsuitable for inclusion in the final audit group. Auditors uncovered the need for emergency weatherization in a few cases. In one case, an auditor accidentally ruined a furnace while attempting to measure its efficiency.

Other kinds of attrition affected both groups about equally. Houses in both groups were dropped because of data quality problems. In addition, a few houses in each group received utility weatherization while the field test was going on.

3.3 ENERGY CONSUMPTION DATA

One of the most important characteristics of the energy consumption data is that they are (approximately) weekly interval data. All meters (furnace run-time meters, utility gas meters, and utility electric meters) were read on weekly schedules by meter readers employed for this project; they went from house to house and recorded the readings on a standard form. When it was not possible to read the meters on schedule, they were read as soon after the desired time as possible. Gas or electric meters that had to be read from inside the house were sometimes missed because the occupant was not at home when the meter reader arrived. Missed readings were not estimated. Observation lengths were allowed to vary so as to correspond to actual meter reading times. The regression analysis (Appendix A) was designed to accommodate variable length observations. The readings were checked for reasonableness as they were transferred to magnetic media.

3.3.1 Heating System Gas Consumption

All the retrofits included in the audit, except the IID,* are intended to reduce space heating energy consumption. The most direct and accurate way to measure the gas consumed by a furnace or boiler is with a standard gas meter on the gas line serving the heating system. Use of a gas meter was impossible for this project because of the cost and the time it would take to have the meters installed. Consequently, a run-time meter (also called an elapsed-time meter) was used to measure furnace gas consumption.

A run-time meter is a clock that records the amount of time a device is on. Instead of a dial with hands marking the hour of the day, a run-time meter has a counter that counts the hours of operation of the device to which it is attached. Cramer type 635G, 24V/60Hz meters were used. Most central gas space

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*The IID replaces the pilot of a furnace or boiler. The pilot contributes very little to space heating, but it or an IID is necessary for gas-heating system operation.

heating systems use a 24V thermostat circuit to control the gas valve. When the thermostat detects a need for heat, it causes the gas valve to open, allowing gas to flow to the furnace or boiler. The run-time meter was wired to the gas valve so that it would measure the amount of time the gas valve was supplying gas to the furnace. The fuel consumption rate of the furnace or boiler was measured so that the hours of run-time could be used to find the quantity of fuel consumed.

The fuel consumption rate of the heating system was measured by timing the fastest dial on the utility gas meter as it made one revolution with the furnace on and all other gas appliances off. A revolution of the fastest dial on the meters encountered, taking 20 to 60 s, represented one or two ft^3 of gas. The time to complete a revolution can be measured to an accuracy of about 0.1 s. If the measurement is done properly and if the utility meter is working correctly, this implies that calibrations are accurate to about 1%. Some heating system timings were recorded to the nearest second; these measurements should be accurate to 2-3%. This method of measuring the heating system firing rate involves a small error because of the gas pilots used by the heating system and other gas appliances.

The furnace pilot usually consumes 1 ft^3 of gas/h, and other pilots are smaller. All the pilots in a house consume 1-3 ft^3 of gas/h, leading to over-estimations of the furnace firing rate of 1-5%.

3.3.2 Utility Meters

Each house had both gas and electric utility meters which were read at approximately weekly intervals when the elapsed-time meters were read. The total house gas and electric data were inexpensive to collect and proved useful in checking the reasonableness of the heating system fuel consumption data. In several cases, the gas meter data showed that a furnace fuel consumption measurement was questionable or erroneous. Section 3.4 discusses the handling of this and other types of data problems.

3.3.3 Weather Data

Ambient temperature is the most important determinant of space heating energy use in houses. This study was designed so that regression analysis of space heating fuel use against ambient temperature could be performed. Weather data were taken from two sources: the National Oceanic and Atmospheric Administration (NOAA) for Truax Field in Madison, and the Wisconsin Automated Agricultural Data Network, operated by the Wisconsin State Climatologist. This data network collects various types of weather data, including the hourly ambient temperatures that were used for this study. The Wisconsin State Climatologist, Douglas R. Clark, supplied hourly ambient temperature data from weather stations in Arlington (south central Columbia County), Janesville (near the center of Rock County), and Prairie du Sac (in Sauk County) near the northwest corner of Dane County and southwest corner of Columbia County. Data from the weather station closest to each house were used in the regression analysis.

The hourly ambient temperatures were averaged for each period corresponding to a fuel consumption observation. These average temperatures were used in the regression analysis.

Estimation of normalized annual energy savings required a normal weather characterization that was congruous with the data and analysis in use. We developed such a weather characterization from 36 years (1949-1984) of hourly temperature observations at Truax Field, supplied by the National Climatic Data Center. The weather data characterization is a frequency distribution of weekly average temperatures for Madison, Wisconsin (Fig. 3.1).

3.3.4 Energy Savings Analysis

The main purpose of this field study was to measure energy savings resulting from retrofits performed as directed by the audit. Unfortunately, retrofit energy savings are not susceptible to direct measurement (as by a ruler or thermometer) but must be inferred from the measurements of fuel use and ambient temperature by statistical techniques.

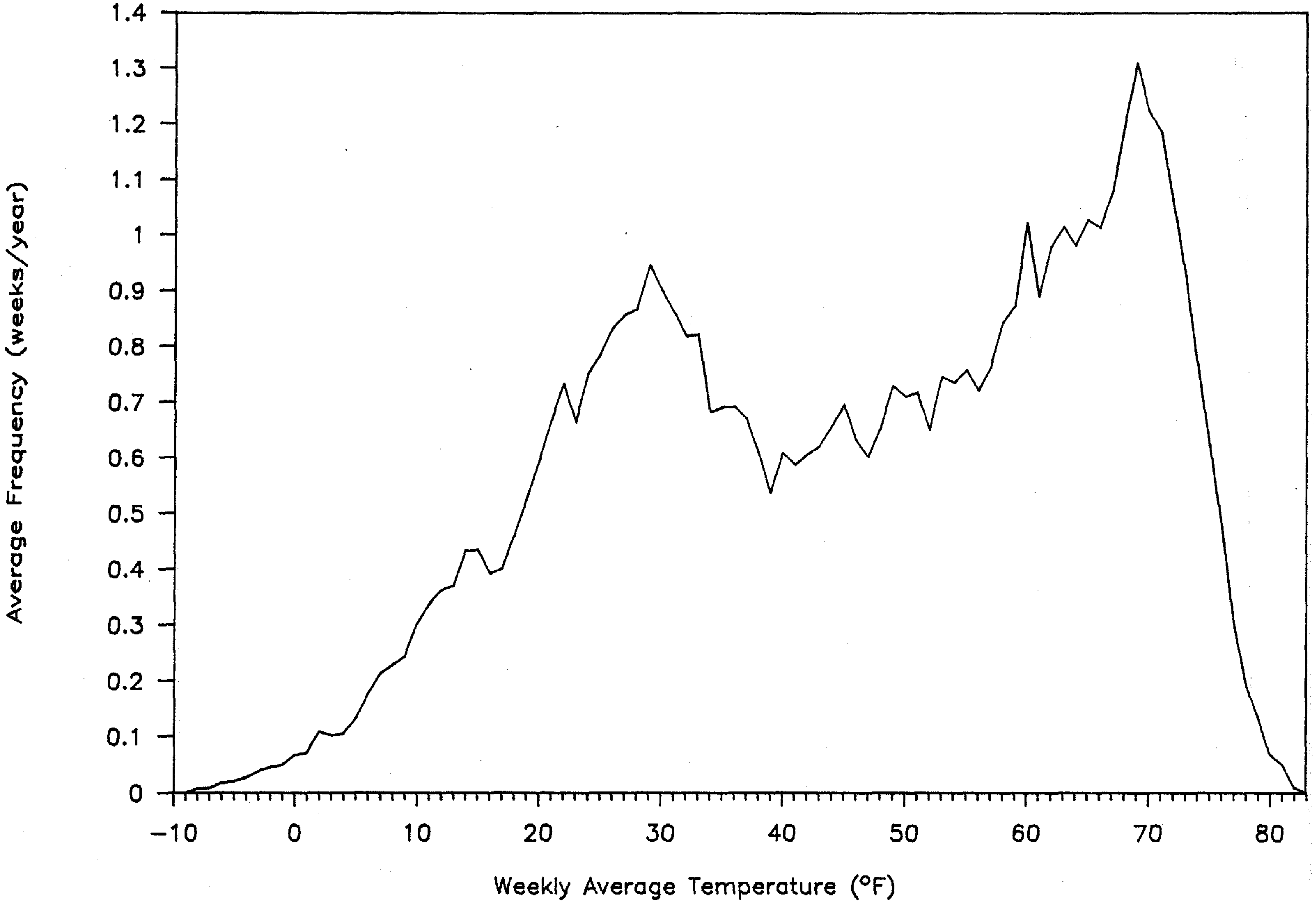

Fig. 3.1. Distribution of weekly 1°F temperature bins for Madison, Wisconsin, based on 36 years of data.

The statistical analysis consists of three principal parts. The first part is calculation of NAHS for each house, performed in three steps: regression analysis of the before- and after-retrofit data, estimation of NAHC before and after the retrofits (using the results of the regression analysis and the long-term weather data), and calculation of the NAHS by subtracting the after-retrofit NAHC from the before-retrofit NAHC. The second part of the statistical analysis is calculation of average savings for the audit and control groups. The final step is adjustment of the audit group savings for the apparent savings of the control group.

All energy savings calculated using statistical techniques are estimates. The uncertainty associated with such estimates is characterized by standard errors, which are reported in the following sections to illustrate the uncertainties associated with the energy savings estimates. Details of the statistical analysis are presented in Appendix A.

3.4 DATA QUALITY

The selection criteria listed in Sect 3.2 were designed to ensure that the houses in the study qualified for the WAP and that their energy savings would be measurable. The requirement that secondary heating devices not be used was specifically intended to ensure that energy savings would be apparent in reduced furnace gas consumption. While this criterion means that the study sample is not representative of all WAP homes, it made little sense to include houses in which energy savings would not be measurable.

The availability of both whole house gas consumption (utility meter) readings and furnace gas consumption (run-time) measurements made it possible to calculate a base load for all observations for which the whole house gas consumption readings were available. Examination of these base loads was the principal data quality check used in the study. A steady base load, generally smaller than the furnace gas consumption, was taken as evidence of good data. Only houses that had anomalous base loads were rejected on data quality grounds. The few houses that had too little whole house gas data to identify useful base load patterns were accepted as good data.

Several houses had isolated base loads that were much higher or lower than normal. In these cases, of which house R24 is a good example, the anomalous observations were eliminated. Figure 3.2a shows a plot of all pre-retrofit observations against ambient temperature. A negative base load is obviously impossible, but it occurs when the measured furnace gas consumption is greater than the measured whole house gas consumption. The fact that the observations with negative base loads (2, 6, 13, and 14) also showed higher-than-normal furnace gas consumption suggests that the furnace gas consumption data are erroneous. Figure 3.2b shows the data and regression for house R24 after eliminating the anomalous observations. Note that the regression (model) fits the data nearly perfectly in Fig. 3.2b but rather poorly in Fig. 3.2a.

House R24 merits further consideration because it illustrates the sensitivity of this method to anomalous observations. The R^2 of the regression with the anomalous points is 0.86, a value that is considered quite good for most purposes. However, the standard error of the NAHC (labeled CSE in Fig. 3.2) is 121 therms/year (9% of the estimated NAHCO). This means that there is a 90% probability that the true value of NAHC is between 1131 and 1557 therms/year. An uncertainty this large means it is unlikely that energy savings smaller than a few hundred therms per year can be discerned. Furthermore, the regression model does not fit many of the observations well, and the base temperature (Tb) at 70°F is uncommonly large. All these problems disappear when the anomalous points are removed. Evidently regressions with R^2 below 0.9 may not be useful when trying to measure small to moderate energy savings.

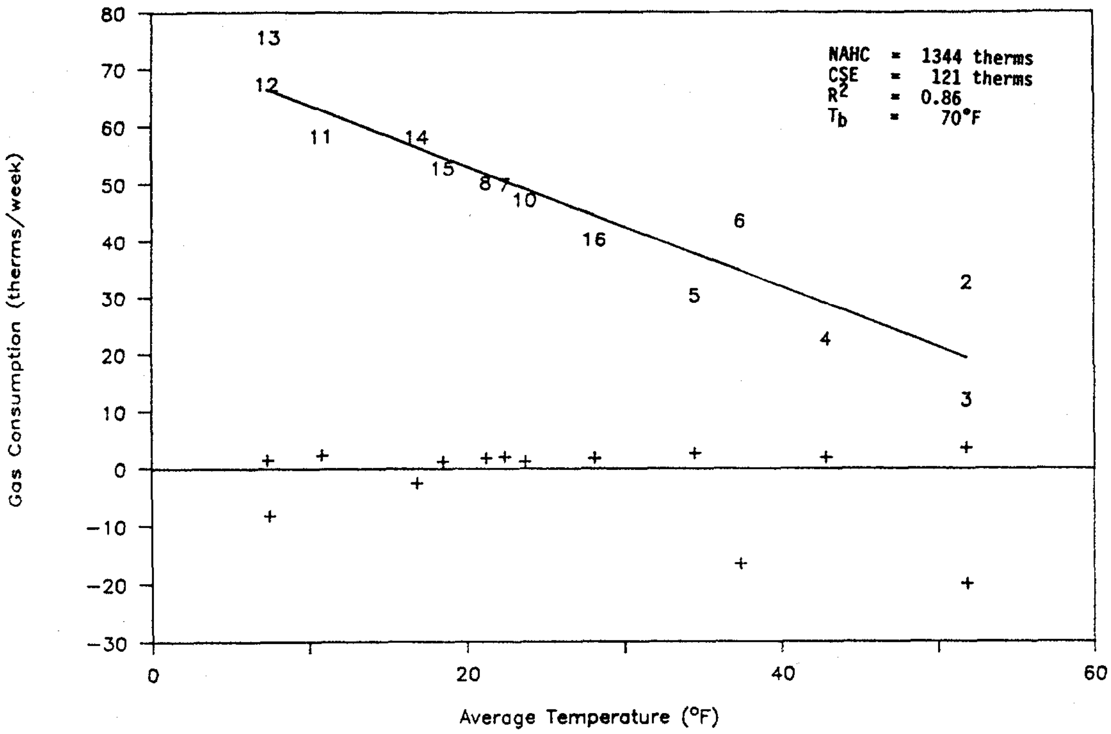

Figure 3.2a. Comparison of house R24 gas consumption observations and regression model, all pre-retrofit observations. Numerals are observation numbers. The diagonal line indicates regression equation values. Plus signs, +, indicate base gas values.

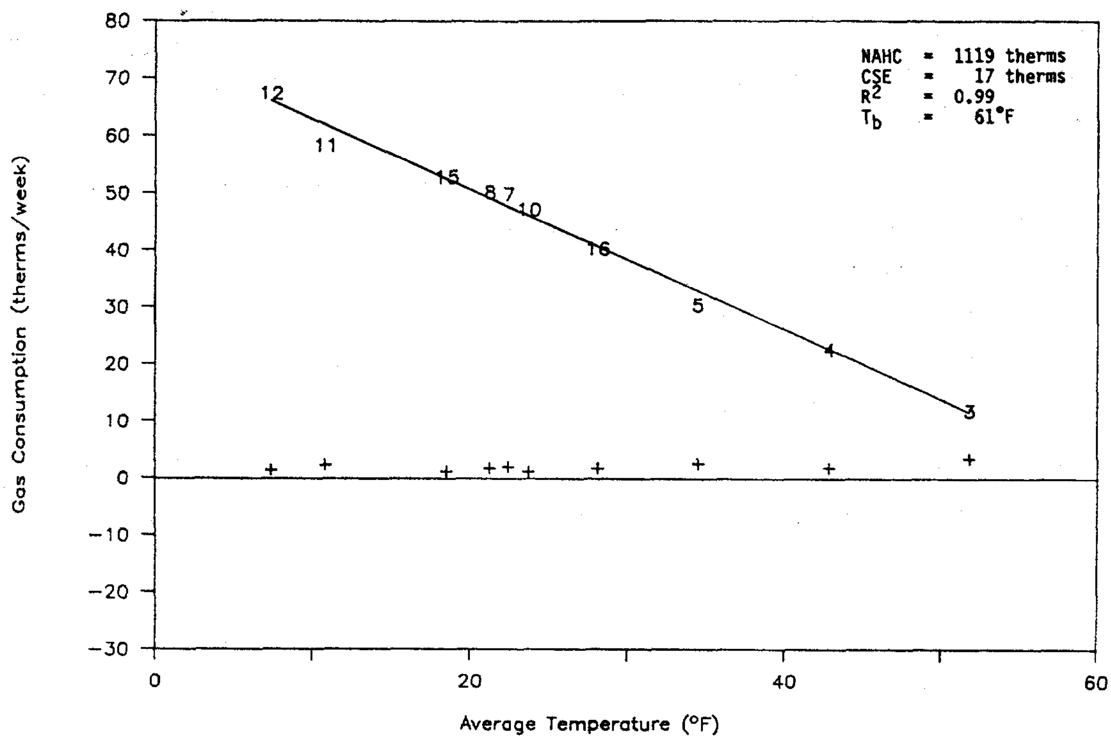

Figure 3.2b. Comparison of house R24 gas consumption observations and regression model, observations with negative base gas values deleted. Numerals are observation numbers. The diagonal line indicates regression equation values. Plus signs, +, indicate base gas values.

Energy savings for each house are based on regression analyses of pre- and post-retrofit data. Figure 3.3 is a histogram of R^2s for all the houses in the control and audit groups. There are two R^2s (pre- and post-retrofit) for each house, so twice as many R^2s as houses are plotted on Fig. 3.3. The shaded bars represent the smaller of each house's two R^2s, and the unshaded bars represent the larger. Clearly, most of the R^2s are very high. This means that, for most houses, ambient temperature variations are the primary causes of variations in heating fuel use.

Figure 3.3 shows how many houses would be dropped if houses with R^2s below some minimum level were excluded from the group. For instance, if the minimum acceptable R^2 were 0.90, 10 of the 48 houses (2 audit group and 8 control group) would be dropped. A comparison of the shaded and unshaded bars shows that a low R^2 is not usually a characteristic of a house. Only one of the ten houses with its lower regression R^2 below 0.90 had its higher regression R^2 below 0.90.

This review shows that the data are of generally high quality. It also suggests that some observations will be more reliable than others. In order to account for uncertain estimates suggested by an occasional low R^2, the savings estimate for each house is accompanied by a standard error of the estimate. The standard error associated with each house contributes to the standard error of the average group savings.

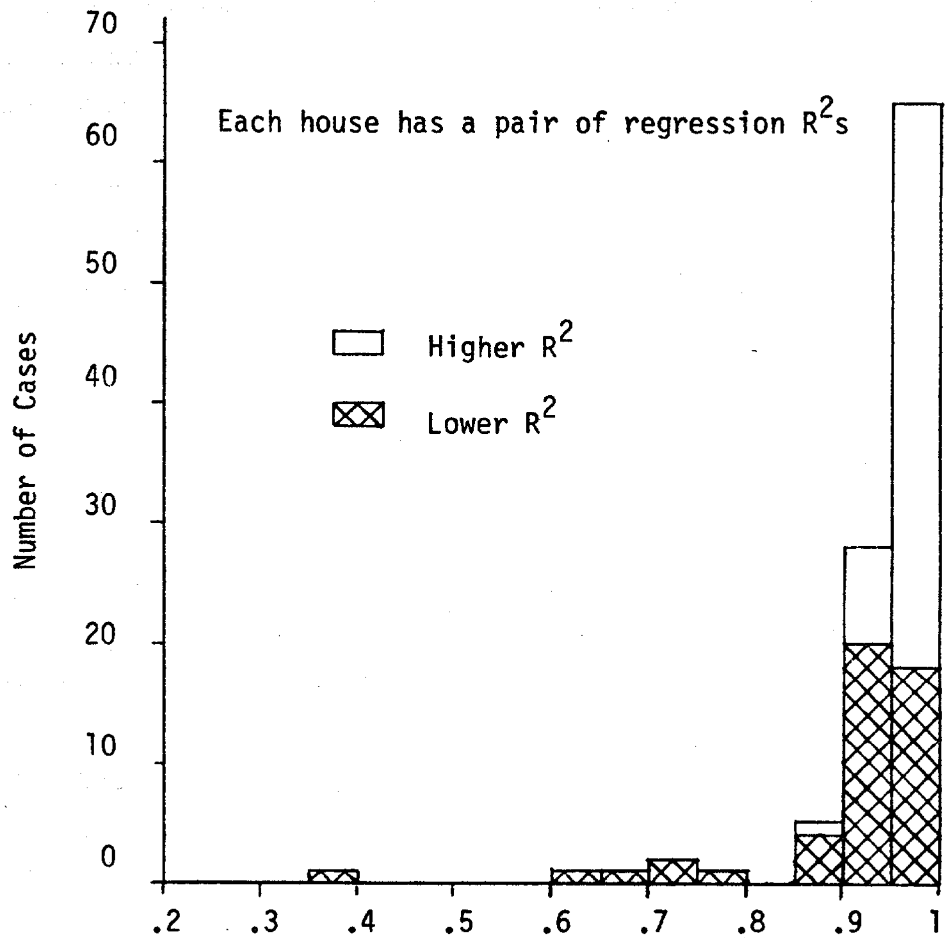

Fig. 3.3. Distribution of regression R^2s for audit and control group houses. Lower R^2s are denoted by cross hatching.

4. ENERGY SAVINGS

The principal objective of this field test was to determine how much energy could be saved by ADRP-selected retrofits and at what cost.* This section presents the energy savings results; Sect. 5 concerns cost effectiveness.

The performance of individual retrofits is also of considerable interest. Over half of the audited houses received one major retrofit and a number of minor retrofits. The major retrofits (usually wall insulation or furnace replacement) account for the vast majority of expected energy savings for individual houses. Minor retrofits have small expected savings and small costs. Average savings are discussed first, then savings associated with individual retrofits.

4.1 AVERAGE SAVINGS

The control group is discussed first because it is a background against which to view the savings realized by the audit group. Energy savings of the audit group are presented first as measured, then adjusted for the apparent savings of the control group.

4.1.1 Control Group

The results of the statistical analysis of the control group are shown in Table 4.1. In most ways, the pre- and post-retrofit characteristics of the control group are the same. The average normalized annual space heating consumption (NAHC) is about 915 therms/year. The standard error of the mean is about 70 in both cases, so there is only about one chance in ten that the true mean value of the NAHC is <790 or >1040 therms/year.

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*Comparison of ADRP performance with Wisconsin's retrofit selection method's performance was not a purpose of this study. A recent study had characterized the performance of Wisconsin's weatherization program, therefore, a new study was not deemed necessary.[3]

For both the pre- and post-retrofit data, the standard error of the mean is principally due to the dispersion of individual NAHC values. Less than 5% of the standard error is attributable to random errors involved in estimating NAHCs.

The control group is far from homogeneous. Individual NAHCs span a range from about 300 therms/year to over 1800 therms/year. The distribution of NAHCs is somewhat skewed toward lower NAHCs. This pattern is to be expected because low-income families often occupy smaller houses.

Table 4.1. Control group statistics.[a]
(therms/year/house)

	Pre-retrofit NAHC	Post-retrofit NAHC	NAHS
Mean	913	918	-5
Standard error of mean	76	70	35
Variance contributions			
Individual measurements	631	40	671
Difference between houses	5165	4861	584
Total	5796	4901	1255
Sample standard deviation	381	376	128
Minimum	347	223	-240
First quartile	656	684	-74
Median	861	883	-5
Third quartile	1085	1081	31
Maximum	1855	1852	422

[a]For 28 control houses t(0.05) is 1.70.

The average normalized annual space heating energy savings (NAHS) is -5 therms/year, but this apparent increase in consumption is not distinguishable from zero. The standard error of the mean is 35 therms/year, so there is a 90% chance that the true mean value NAHS for the control group is between -64 and 55 therms/year. Describing this range of uncertainty (confidence interval) in another way, if the "true" mean NAHS were zero, an apparent energy use change of 60 therms/year or more would result one out of ten times that a 28-house sample is taken from the population of eligible houses in the study area. These statistics indicate that only mean retrofit savings somewhat larger than 60 therms/year can be measured. If retrofit savings less than ~60 therms/year are of interest, a lower level of confidence must be accepted or the number of houses in the sample must be substantially increased.

4.1.2 Audit Group

As outlined earlier, the audit group energy savings are to be adjusted for the apparent energy savings of the control group. The audit group statistics before adjusting for the control group, as well as the adjusted audit group savings, are described here.

The audit group mean pre-retrofit NAHC (see Table 4.2) at 1033 therms/year is 120 therms/year larger than the control group average pre-retrofit NAHC. This difference is not significant ($p > 0.40$), so there is no reason to doubt that the houses come from the same population.

The post-retrofit NAHCs of the audit group are more homogeneous than the pre-retrofit NAHCs. This is an expected result of using the ADRP to select retrofits. Houses that use more energy naturally tend to receive more retrofits and therefore show larger energy savings, while houses that use less energy tend to show little or no reduction in energy consumption. Thus, their energy consumptions become more nearly the same. As is true of the control group, standard errors of the mean NAHCs are dominated by the dispersion of individual NAHCs; errors introduced by the measurement contribute only a small part of the variance.

Table 4.2. Audit group statistics.
(therms/year/house)

	Pre-Retrofit NAHC	Post-Retrofit NAHC	NAHS
Mean	1033	869	164
Standard error of mean	68	43	47
Variance contribution:			
individual measurements	302	44	346
difference between house	4334	1795	1881
Total	4636	1839	2227
Standard deviation	294	189	194
Minimum	459	526	-162
First quartile	793	746	37
Median	1123	873	101
Third quartile	1246	1016	304
Maximum	1669	1259	604

Note: For 20 houses t(.05) is 1.73.

The audit group mean NAHS is 164 therms/year (Table 4.2). Individual savings range from -162 to 604 therms/year. The mean is larger than the median (101 therms/year/house) because a large portion of the energy savings is concentrated in relatively few houses. Again, this is the expected pattern because the ADRP was designed to concentrate retrofits where energy savings would be less expensive (that is, in houses that would most benefit from the retrofits included in the audit).

Table 4.3 shows the mean normalized annual space heating energy savings of the audit group as compared with the control group. The best estimate of the (control group adjusted) mean annual savings realized by the audit group is 169 therms. However, there are two intervals of uncertainty (confidence intervals) associated with this number. These confidence intervals relate to two questions about the mean savings: (1) how accurate is the savings estimate, and (2) how large would the mean (normalized annual) savings be if the ADRP were applied to the whole population of WAP-eligible homes in the study area?

Comparison of predicted and measured average savings gives useful information about the accuracy of the audit. Before making those comparisons, it is important to note the difference between actual savings and our measurement of the savings. Most everyday measurements (e.g., distance, time, or temperature) are more than accurate enough for the purpose at hand. Errors involved in the measurements are negligibly small, so the measured value is taken to be equal to the actual value. The method used here to measure savings is much less accurate than these more familiar measurements. It is important to estimate standard errors and confidence intervals because with an understanding of the accuracy of the observations, they indicate how accurate the measurement is.

Figure 4.1 (and Table 4.3) shows that the mean measured savings are 83% (without the control group adjustment) of the predicted (measurable*) savings. Figure 4.1 also shows that there is enough uncertainty in the mean measured

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*Does not include pilot gas savings due to use of IIDs.

Table 4.3. Audit group mean savings summary.
(therms/year/house)

	Audit[b] group	Control[b] group	Adjusted control group (difference)	Predicted measurable savings
Mean	164	-5	169	197
Measurement standard error of mean	19	26	32	a
Sample standard error of mean	47	35	59	31
Variance contributions				
Individual measurements	346	671	1017	a
Difference between houses	1881	584	2465	981
Total	2227	1255	3482	981

[a]Estimates of uncertainty are not available for the predicted savings of individual retrofits, so this source of variance could not be estimated.

[b]Audit group consists of 20 houses. Control group consists of 28 houses.

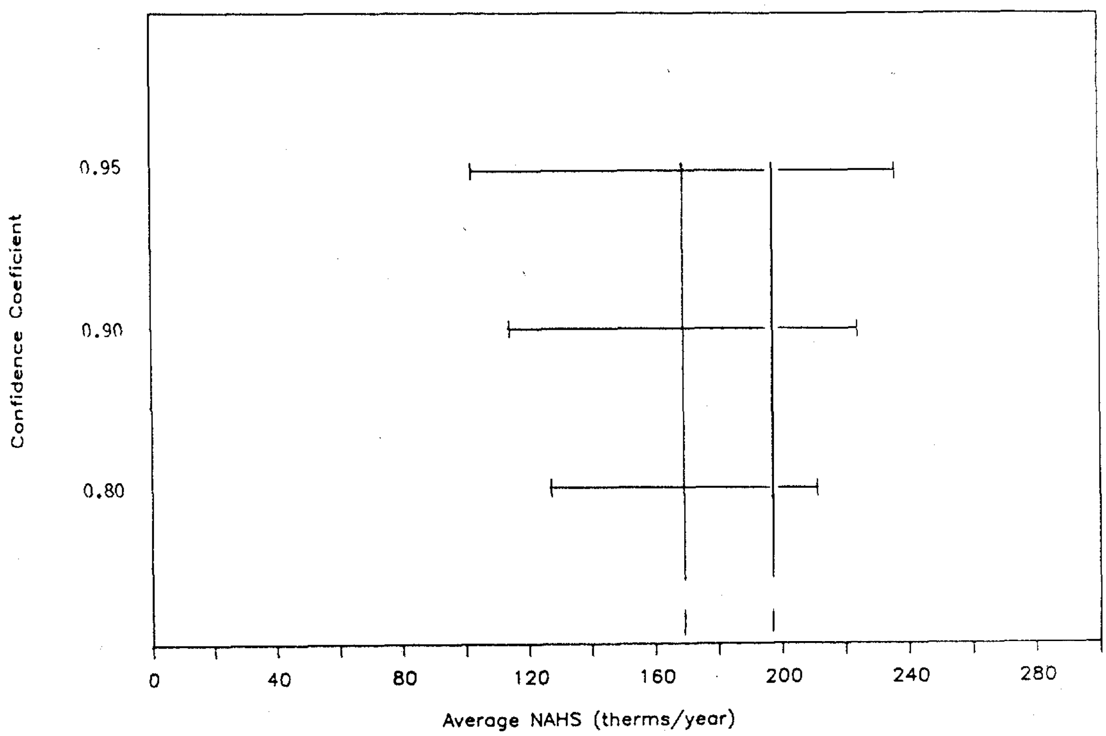

Fig. 4.1. Confidence intervals of measured average savings of 20 audit group houses.

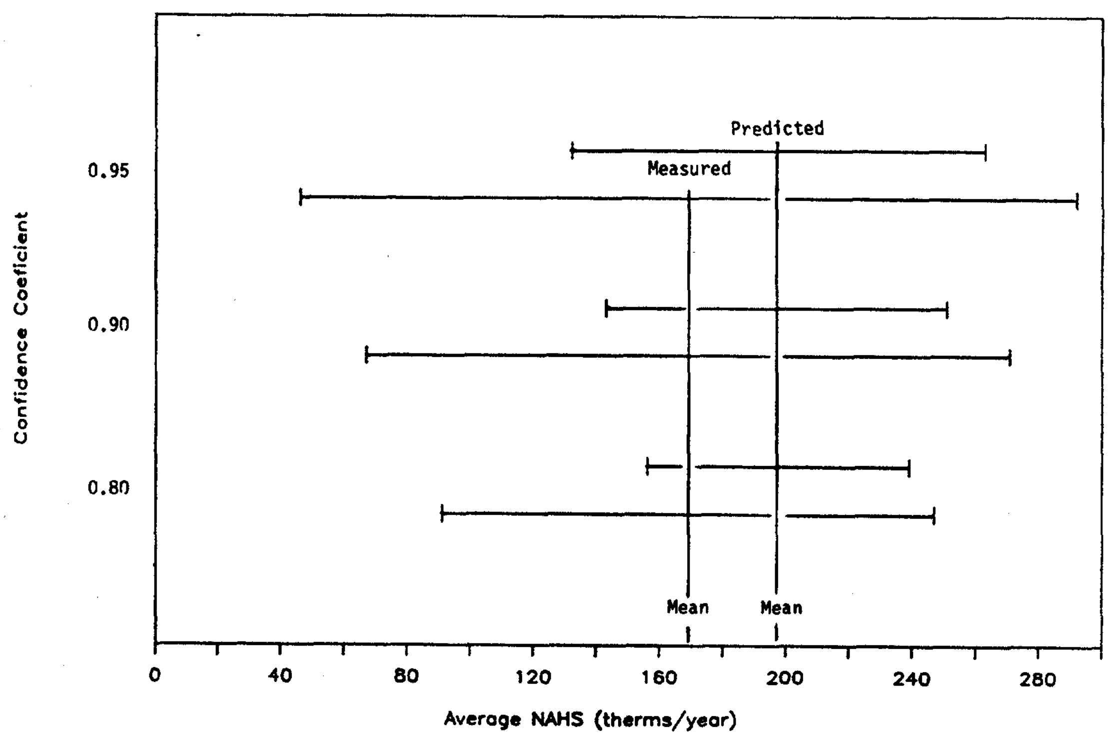

Fig. 4.2. Confidence intervals of measured and predicted average savings for WAP-eligible homes in the South Central Wisconsin study area.

savings that the actual mean savings may be as large as predicted. Indeed, there is about a 25% chance that the actual mean savings were larger than predicted.

Figure 4.2 shows the confidence intervals associated with the question, "how large would the average (normalized annual) savings be if the ADRP were applied to the whole population of WAP-eligible homes in the study area?" Figure 4.2 shows confidence intervals on measured savings which are nearly twice as large as Fig. 4.1 for equal levels of confidence. These larger confidence intervals are the result of the uncertainty introduced by the variation in energy savings observed between one house and another. The answer to the question is: if the ADRP were applied to the whole population of WAP-eligible homes in the study area, there is a 90% probability that the average savings would lie between 67 and 271 therms/year.

Figure 4.2 also displays confidence intervals for the audit prediction. These confidence intervals are entirely attributable to variation of predicted energy savings from one house to another. The similarity of the sizes of these confidence intervals to the corresponding ones for measured savings suggest that more precise estimates of individual house savings would not greatly help refine the estimate of what the ADRP would save if applied to the population from which the sample was drawn. A more precise estimate would require a larger sample.

4.1.3 Unmeasured Savings

Gas savings resulting from elimination of the furnace pilot were not measured, although this is considered an important source of savings. Pilots were eliminated in 15 of the 20 audit group houses when new furnaces were installed or when vent dampers and intermittent ignition devices were installed on existing furnaces. The resultant gas savings were not measured, because the run-time meters measure the gas used by the furnace only while it is operating, while the pilot operates year round. Therefore, most pilot gas savings occur in the summer, fall, and spring.

The ADRP used a reliable but conservative method to estimate the savings which result from eliminating the pilot. Also, the pilot is a very simple gas-consuming device, so there is little room for error. Consequently, we can add the predicted pilot gas savings to the measured and predicted savings with negligible loss of accuracy.

4.1.4 Reportable Average Savings

Table 4.4 presents the average energy savings which should be reported for application of the ADRP to low-income homes in South Central Wisconsin. Table 4.4 incorporates both the measured savings and the pilot gas savings which were not measurable with the instrumentation used in this study. The average audit group savings should be reported as 207 $\pm$ 59 therms/year/house or as lying within the 90% confidence interval of 105 to 309 therms/year/house. The predicted savings should be presented in the same manner.

4.1.5 Discussion of the Results

It is important to remember that these results are relevant to WAP eligible homes in South Central Wisconsin. The characteristics of the housing stock have a profound influence on energy savings. Another part of the state which had a housing stock of poorer condition would be expected to have larger energy savings. Likewise, other parts of the country with different climates will have savings which are larger or smaller than those reported here. The method used here is, however, applicable to other regions, climates, and house types.

These results should be compared with the results of other evaluations very cautiously. The audit component of the ADRP was designed to test the concept of such an audit, not to establish the ultimate capabilities of the ADRP approach. The performance of the ADRP should improve as more retrofits are added (e.g., domestic hot water retrofits). Further, the ADRP was designed to save energy cost effectively, not to save energy at any cost. Consequently, retrofits which save much energy but which are relatively expensive were not done. Storm windows are the best example of this.

Table 4.4. Reportable average audit group savings.[a]

	Average Predicted Savings (therms/yr)	(%[b])	Average Measured Savings (therms/yr)
Measurable savings	197	16	169
Pilot gas savings	38	4	38
Total	235	19[c]	207
Standard error of mean	31		59
90% confidence interval	143-251	<10 - >29	105-309

[a]Audit group consists of 20 houses.

[b]Space heating energy savings as a percent of pre-retrofit space heating energy consumption. Percent space heating energy savings is based on average pre-retrofit space heating energy consumption of 1071 therms/yr. Composed of 1033 therms/yr preserved average pre-retrofit consumption (Table 4.2) and estimated average pre-retrofit pilot gas consumption of 38 therms/yr.

[c]Does not add due to rounding.

[d]This confidence interval is calculated as though average pre-retrofit space heating energy consumption were known to be the value in note b. Since the pre-retrofit NAHC above is an estimate, the confidence interval is larger than indicated.

The large confidence intervals associated with the savings estimates may make it difficult to act decisively on the basis of the results of this study. The simplest way to produce more precise estimates is to use a larger sample, however, there are usually practical constraints on how large a sample can be used. The sample size must be quadrupled in order to halve the size of the standard error.

An examination of the variances displayed on Table 4.3 suggests two other approaches. One approach is to reduce the variances associated with individual measurements. These variances are the sum of the individual regression variances. A more stringent data quality criterion, such as a minimum regression R^2 of 0.9, would be expected to reduce the variance from this source by eliminating from the sample some of the houses with larger standard errors. This process, with a minimum R^2 of 0.85, was tested on the control houses. The criterion eliminated four houses and reduced the variance contributions of the individual measurements by more than one-half.* The criterion was not adopted because of its after-the-fact nature and because eliminating this source of variance would not greatly reduce the standard error of the mean for the reportable savings (Table 4.4).

The largest source of variance is the contribution due to dispersion of the audit group NAHSs. As discussed previously, this dispersion of NAHSs was the expected result of the ADRP. It should also be noted that the variance calculated for the audit predictions (last column of Table 4.3) and the variance from the dispersion of measured audit group NAHS (first column) are nearly the same. The only way to substantially reduce this component of variance is to study a more homogeneous group. For instance, this source of variance might be nearly

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*The variance caused by the dispersion of control group NAHSs was reduced almost as much as the variance caused by individual measurements, suggesting that much of the variance of the control group savings is due to measurement errors, not actual changes in energy consumption patterns between the pre- and post-retrofit period. It also suggests we may be double counting contributions to the variance of the control group. If so, the error is small. Eliminating either source of variance would reduce the standard error of the mean savings by less than 10%.

eliminated if a sample of houses was selected from all those that were predicted to have savings of 200 to 400 therms/year when wall insulation was installed. Of course, this kind of sample would not be representative of the entire population of WAP houses in the area.

In summary, the least expensive way to improve the accuracy of the estimate of average NAHS is to impose more stringent data quality criteria. Unfortunately, this approach leads to modest (20%) reductions in the contributions to variance of the control group. The other approaches require larger samples and are therefore more expensive. However, they offer prospects for more substantial reductions in the standard error of the mean.

4.2 INDIVIDUAL HOUSE SAVINGS

It is useful to consider the energy savings of individual houses, although such consideration is beyond the original scope of this study. Both predicted and measured energy use of each of the 20 audit group houses are displayed in Table 4.5, which also shows the major and minor retrofits that were installed. Major retrofits are those with predicted annual energy savings of 100 therms or more, while predicted annual energy savings of minor retrofits are less than 100 therms.

Table 4.5 shows that the audit group houses fall into three groups: those which received condensing furnaces, those which received wall insulation, and those which received no major retrofits. Examining the average savings of these groups of houses gives a useful perspective on the accuracy of the audit. Table 4.6 displays the total savings (measured and predicted) of these three groups. The houses with no major retrofits accounted for less than 5% of the predicted savings and achieved almost none. Apparently one or more of the minor retrofits are less effective than expected.

Table 4.5. Comparison of measurable predicted and measured savings for each house in the audit group.[a]

House No.	Annual savings[b] (therms) Predicted	Measured	Std. error	Retrofits[a] Major	Minor
C01	211	423	126	CF	S
D02	50	-61	37		VD,ID
D06	222	87	47	CF	S
D08	27	103	45		I,CT
D14	372	197	53	W	I,VD,ID
D18	270	451	62	W	S,VD,ID,C
D19	5	47	43		I
D27	266	303	74	CF	E
D30	90	27	55		VD,C,I,ID
D31	0	67	71		CT
D35	12	-67	34		I,CT
D36	177	305	240	CF	
G13	60	-162	58		VD,ID
R00	207	79	21	W	I
R24	360	247	35	W	S,I,ID
R42	448	604	50	CF, E	C
R44	158	99	102	W	I,C,ID
R46	417	385	105	CF, E	S
R56	284	-37	62	CF	I
R58	310	174	64	W	E,S,VD,I,ID

[a]Retrofits are identified by the following codes:

CF - replace furnace with a condensing furnace
CT - clean and tune furnace
ID - install intermittent ignition device
VD - install vent damper
C - insulate ceiling
E - install insulation on exterior of basement wall
I - perform infiltration reduction work
S - insulate sill box
W - insulate walls

Major retrofits are those with predicted annual savings >100 therms.
Minor retrofits are those with predicted annual savings <100 therms.

[b]Neither predicted nor measured savings presented here include expected savings due to intermittent ignition devices.

Table 4.6. Total savings of audit houses grouped by major retrofit.[a]
(therms/year)

Major retrofit	No. of houses	Predicted	Measured[b]	Standard error[c]	Pilot Gas savings
Condensing furnace	7	2025	2071	314	343
Wall insulation	6	1677	1248	151	294
No major retrofits	7	244	-44	133	126
Total	20	3946	3275		763

[a]These savings do not incorporate adjustment for control group savings. Pilot gas savings were not measured, and are not included in "predicted" column. They are listed here for completeness.

[b]The savings as a fraction of pre-retrofit space heating energy consumption (NAHC) is of interest. NAHCs of the groups were about 8700 therms/yr for seven condensing furnace houses, about 6200 therms/yr for six well-insulated houses, and about 6000 therms/yr for seven houses which received only minor retrofits. By treating these estimated pre-retrofit, group-total NAHCs as exact numbers, the perent savings and standard errors of the groups can be calculated: 24% ± 7%, 20% ± 5%, and -1% ± 4%, respectively

[c]The standard errors presented here are based on individual measurement errors. These are the appropriate standard errors to use when comparing predicted and measured savings. Standard errors which include savings variations between houses are approximately twice as large as those listed here.

As a group, the houses that received condensing furnaces saved as much energy as expected, suggesting that a condensing furnace retrofit would give reliable performance in a retrofit program. Houses with wall insulation saved 74% of the amount that they were expected to save. On average, wall insulation savings were overpredicted; however, accounting for over one-third of the total measured savings, wall insulation made a substantial contribution to the total savings.

Figure 4.3 shows the comparison of predicted and measured energy savings; the estimated (measured) savings for each house are denoted by the code for the major retrofits installed in that house. The lines extending above and below the savings estimates on Fig. 4.3 mark the extent of the 90% confidence interval. That is, the true value of savings for each house has a 90% chance of lying between the ends of the line. If the confidence interval (the space between the ends of the line) includes the diagonal line, where measured savings equal predicted savings, then the measured and predicted savings are not significantly different and the predictions could well have been correct. Those houses with confidence intervals not taking in the diagonal line have measured savings that are significantly different from the predicted savings. For these houses, the predicted savings were probably incorrect (less than one chance in ten of being correct).

The confidence intervals are important because they suggest whether the differences between the predictions and measurements are due to errors in the predictions or in the measurements. The 90% confidence interval means that one time in ten the confidence interval will fail to take in the predicted value due to random chance alone. Overall, 10 of the 20 audit group houses show measured savings that are inconsistent with the audit predictions. Based on random chance alone, two inconsistent measurements would be expected; therefore, audit predictions are probably the cause of many of the discrepancies.

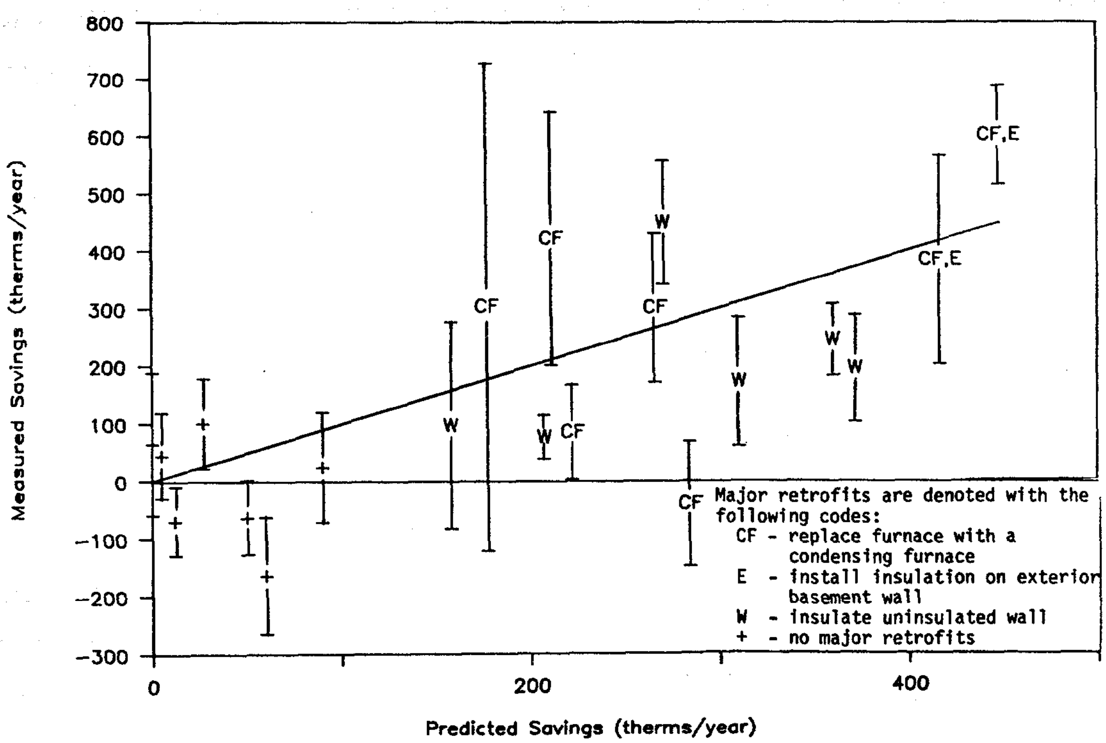

Fig. 4.3. Measured and predicted energy savings of individual houses. Vertical lines indicate the 90% confidence intervals of measured savings. (Houses may have received one or more minor retrofits.)

Inconsistencies between measurements and predictions are fairly evenly distributed among the houses with different major retrofits. Four (67%) of the six wall insulation houses showed measured savings that were inconsistent with the predicted savings, indicating a problem with the audit's predictions of wall insulation energy savings. Three (43%) of the seven houses with no major retrofits showed savings that were inconsistent with the predictions. Houses receiving a condensing furnace did no better; three (43%) of the seven showed measured savings inconsistent with the predicted savings. The audit is apparently not accurate in predicting energy savings of individual houses.

5. COST EFFECTIVENESS

The ADRP was designed as a tool for selecting cost-effective retrofits on house-by-house and program bases. The principal objective of the field test described in this report was to determine how much energy ADRP selected retrofits could save and at what cost. This section presents comparisons of costs and energy savings.

5.1 RETROFIT COSTS

As might be expected, actual retrofit costs were often different from estimated costs. Some retrofits could not be performed, and others cost more or less than expected. Heating system retrofit costs were generally very close to the expected values because they were contracted at fixed prices. Shell retrofits showed more variation because of incorrect estimations of the difficulty or the amount of materials required. Where the actual cost is much less than the estimated cost, the usual reason is that a recommended retrofit turned out to be impossible or unneeded.

Infiltration reduction work was recommended for only 10 of the 20 audit group houses. The average recommended infiltration reduction expenditure for these ten was $113, while actual expenditures averaged $213 per house for these ten. This discrepancy is the result of weatherization crews' resistance to the audit's relatively low infiltration expenditure recommendations. Over the whole audit group, infiltration reduction costs averaged $107 spent and $56 recommended.

The amount budgeted per house for repairs was $200, but actual repair costs were much less. Of the 20 houses, 5 received repairs for a total cost of $732. Thus, the average repair cost for all 20 houses was $37. Table 5.1 shows estimated and actual retrofit costs for each of the 20 houses. Repair costs are

Table 5.1. Expenditures on retrofits of audit group houses.

House No.	Expenditures ($) Estimated	Actual	Retrofits[a] Major	Minor
C01	1675	1738	CF	S
D06	1701	1752	CF	S
D27	2028	2227	CF	C
D36	1650	1650	CF	
R42	2443	3416	CF,E	C
R46	1537	1762	CF,E	S
R56	1795	2210	CF	I
D14	1931	2007	W	I,VD,ID
D18	1195	1656	W	VD,S,ID
R00	1064	664	W	I
R24	1847	1513	W	I,C,ID
R44	816	1218	W	I,C,ID
R58	1570	1726	W	E,S,VD,ID
D02	450	450		VD,ID
D08	207	219		I,CT
D19	469	90		I
D30	1794	1111		VD,C,I,ID
D31	70	70		CT
D35	206	129		I,CT
G13	450	450		VD,ID
TOTAL	24,898	26,058		

[a]Retrofits are identified by the following codes:

CF - replace furnace with a condensing furnace
CT - clean and tune furnace
ID - install intermittent ignition device
VD - install vent damper
C - insulate ceiling
E - install insulation on exterior basement wall
I - perform infiltration reduction work
S - insulate sill box
W - insulate walls

Major retrofits are those with predicted annual savings >100 therms.
Minor retrofits are those with predicted annual savings <100 therms.

not included in the retrofit costs on Table 5.1. Many actual costs were close to estimated costs. The larger discrepancies were caused by retrofits which were selected but could not be installed, or by retrofits, such as insulation, which was needed in larger than anticipated quantities. The heating system retrofits were performed under fixed price contracts so higher-than-predicted costs did not occur.

5.2 RETROFIT COST EFFECTIVENESS

Table 5.2 shows a comparison of actual retrofit costs and measured energy savings. All the savings include estimated annual pilot gas savings. These values do not include adjustment for the control group savings. Overall, the retrofits save about 15 therms/year for every $100 spent (about 9.5 year simple payback period at $.68/therm). The houses with major retrofits (a condensing furnace or wall insulation) did somewhat better at 16 to 18 therms/year/$100 spent (8-9 year simple payback period). The houses that received no major retrofits did rather poorly.

Table 5.2. Comparison of retrofit costs and energy savings.

Major retrofit	Average retrofit cost ($/house)	Average energy savings[a] (therms/year/house)	Annual energy savings per hundred retrofit dollars[a] (therms/year/$100)
All houses	1303	202 ± 47	15.5 ± 3.6
Condensing furnace	2108	345 ± 87	16.4 ± 4.1
Wall insulation	1464	257 ± 56	17.6 ± 3.8
No major retrofit	360	12 ± 38	3.3 ± 10.6

[a]Energy savings include expected pilot gas savings. Numbers following "±" are standard errors. Adjustment for control group is not included.

Evidently, one or more of the minor retrofits are not cost effective. Vent dampers account for over 60% of the predicted measurable energy savings of the houses with minor retrofits. Infiltration reduction work accounts for another

23% of the predicted savings. Poor performance by one or both of these retrofits is likely to be the cause of lower-than-expected energy savings. Average savings per retrofit dollar of all groups of houses would likely have been higher if minor retrofits had not been installed.

Infiltration-reduction work and vent damper installation were performed on houses receiving wall insulation. If either or both of these retrofits are not cost effective, the overall cost effectiveness of the wall insulation houses could have been improved by not doing them.*

5.3 PROGRAM COST EFFECTIVENESS

The retrofits are not the only cost of a weatherization program, and energy savings are not the only benefits. Examining all the costs and benefits of the WAP is beyond the scope of this study. However, some of the costs can be estimated, and the other benefits can be listed.

Audit costs were estimated to be $200/house at the beginning of the field test. An additional $200/house was set aside to be spent as needed for repairs. Average repair costs were less than $40/house. Actual audit costs were not recorded, but experience using the audit suggests that a practiced auditor could do audits for $100 each if not much travel time is needed and if a computer program is used to perform the savings calculations. There are also administrative costs such as outreach, income verification, and record keeping. Overall, an estimate of $300/house for auditing and administrative costs seems reasonable.

Table 5.3 shows an energy savings and retrofit program cost comparison similar to that in Table 5.2, except that $300 has been added to the retrofit cost of each house. Naturally, the amount of energy saved per dollar of expenditure goes down, but not very much. If energy savings are counted as the only benefit of the program, simple payback periods can be calculated. At $.68/therm, the program repays its costs in energy savings in about 12 years.

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*The assumption here is that the measured savings would not have been much affected while the retrofit cost would have gone down.

Table 5.3. Comparison of retrofit program costs and retrofit energy savings.

Major Retrofit	Average cost per house[a] ($)	Energy savings per house[b,c] (therms/year)	Annual energy savings per hundred program dollars (therms/year/$100)
All retrofits	1603	202 ± 47	12.6 ± 2.9
Condensing furnace	2408	345 ± 87	14.3 ± 3.6
Wall insulation	1764	257 ± 56	14.6 ± 3.2
No major retrofits	660	12 ± 38	1.8 ± 5.8

[a]Includes $300/house for audit and administrative costs.

[b]Energy savings include expected pilot gas savings. They do not include adjustment for control group.

[c]Numbers following ± are standard errors.

A 12-year simple payback period should be acceptable for a program of this type. Twelve years is short enough that the retrofits are likely to save money at least equal to the cost of the program. Besides, there are other benefits to the WAP that need to be considered in evaluating the cost effectiveness of the program:

1. Many low-income families receive assistance with their energy bills, either from government programs or from utilities companies. Reducing their fuel bills with this program will reduce the subsidy they require from other sources.
2. The values of low-income families' homes are increased by the retrofits.
3. The audits uncover safety problems that can be corrected.
4. Energy saved in low-income households reduce the nation's dependence on foreign energy sources and helps to hold down energy prices by keeping demand lower.
5. The home owners may experience increased comfort.

The intent of the ADRP is to see that retrofit dollars are spent on the most cost-effective available retrofits. The poor performance of houses which received only minor retrofits shows that the ADRP has room for improvement. Accurate audit predictions would result in elimination of poorly performing retrofits because the ADRP would not select them. Until improved audit predictions are available, ADRP performance can be improved by eliminating from the audit retrofits which do not perform well.

Since it is not certain, based on this study, which of the minor retrofits are not performing as expected, an alternate approach may be desirable. One such approach is to do no retrofits on houses which cannot benefit from a major retrofit. This alternative would make the average retrofit more cost effective (Table 5.2). However, the usefulness of this approach is not obvious when considering program cost effectiveness. Not performing the relatively ineffective minor retrofits will save the cost of those retrofits but will not save the audit and administrative costs that are already spent by the time a house is determined to need no major retrofits. On the other hand, installing retrofits that do not return their own cost in savings will never repay the audit and administrative costs that have already been spent.

Concern for the audit and administrative costs, whether the house is retrofitted or not suggests another approach, adding additional cost-effective retrofits to the program. This is especially helpful if these are retrofits that can be applied to those houses receiving no major retrofits. Some domestic hot water conserving retrofits are likely to be cost-effective additions. Also, some newer ideas, like radiant barriers in attics, may be cost-effective additions.

A final improvement to consider would be to reduce audit and administrative costs. Obviously, as overhead costs get smaller, the program's cost efficiency approaches that of the retrofits themselves. One approach to minimizing audit costs is to screen houses for potentially receiving major retrofits. For example, houses with wall insulation are not candidates for receiving wall insulation. Similarly, houses with newer furnaces (say less than 10 years old) or with small space heating bills are unlikely to be cost-effective candidates for furnace replacement. This type of screening could be done over the telephone in many cases.

Table 5.4 shows the effects of implementing these approaches to improve program cost effectiveness. Each approach leads to appreciable improvements in program cost effectiveness. The first, not performing retrofits in houses where no major retrofits are needed, may be the easiest to implement. Adding new cost-effective major retrofits is an attractive option. Besides improving program cost effectiveness, it leads to more energy savings and allows savings to be provided to more households. Reducing audit and administrative costs is certainly effective, but it is not clear how practical it is. There are certainly practical limits to how far administrative costs can be reduced.

Table 5.4. Comparison of approaches for improving program cost effectiveness.

Approach	Cost effectiveness (therms/year/$100)
Base case (all houses, Table 5.3).	12.6
Do no retrofits on houses that cannot benefit from major retrofits.	13.3
Replace minor retrofits in "no major retrofit" homes with hypothetical new and cost-effective (15 therms/year/$100) retrofits.	13.6
Reduce audit and administrative costs from $300 to $200/house.	13.4

The improvements can certainly help make the program more cost effective, but there are two important limits to this type of analysis. First, these approaches ignore other benefits of the program. An over-emphasis on energy savings as a measure of program effectiveness might lead to inadvertent reductions in other program benefits. For instance, attempts to minimize audit and administrative costs might lead to ignoring problems related to health and safety.

Secondly, a retrofit program cannot be more cost effective than the individual retrofits that are performed. Table 5.3 clearly shows that retrofits that are not cost effective lower the overall effectiveness of the program. However, even houses receiving the most cost-effective retrofits also received some relatively ineffective retrofits. Avoiding non-cost-effective retrofits and increasing the use of cost-effective retrofits offers the best hope of dramatically improving program cost effectiveness. The base prospect for avoiding retrofits which are not cost effective is to have more accurate audit techniques, and more accurate audit techniques will only come as the result of additional research.

6. CONCLUSIONS AND RECOMMENDATIONS

The results of the field test point to conclusions and recommendations about the field test method, the audit's accuracy, the performance of some major retrofits, and the cost effectiveness of the ADRP as a component of the WAP.

Overall, the mean measured savings were 83% of the mean predicted savings, but the statistical uncertainty associated with the measured savings is quite large (see Sect. 4.1.2). On average, measured savings of condensing furnaces were very close to predictions. Houses which received wall insulation achieved mean measured savings only of 74% as large as predicted; a statistically significant difference. The seven houses which had no major retrofits had mean consumption which was slightly larger after retrofit than before; the mean measured savings were significantly smaller than predicted.

While the audit appears to be reasonably accurate for major retrofits from a program perspective, the audit is not very accurate from the individual house perspective. Of the 20 audit group houses, ten had measured savings which were significantly higher or lower than predicted. Three of the seven houses which received condensing furnaces had significant discrepancies between predicted and measured savings. Four of the six houses which received wall insulation had measured savings which were significantly different than predicted. These discrepancies are most likely the result of the audit's failure to account for one or more factors which affect energy savings. The causes of these discrepancies should be investigated and the audit savings algorithms adjusted accordingly.

Condensing furnaces and wall insulation appear to be cost-effective retrofits, while one or more minor retrofits appear not to be cost effective. The most likely ineffective retrofits are vent dampers and infiltration-reduction work. Eliminating ineffective retrofits would lead to a more cost-effective retrofit program. Likewise, adding additional cost-effective retrofits (e.g., domestic hot water heating retrofits) could further improve the cost effectiveness of the retrofit program.

The sample of 20 audit group houses suggests that the value of the retrofit energy savings will about equal the cost of the WAP which incorporates the ADRP. There is, however, a rather wide range of uncertainty associated with this result. When considering the cost effectiveness of the WAP, with or without the ADRP, it is important to remember that the program has other benefits, including: (1) reducing the need for subsidies to low-income families, (2) increasing home values, (3) uncovering safety problems in low-income homes, and (4) reducing the nation's dependence on imported fuels. The ADRP can and should be improved so that it leads to even more cost-effective energy savings.

The new field test method used in this study was, in itself, an experiment. It was developed for this single heating season field test. The fact that it worked and gave good results is an important outcome of the field test. This new method can be usefully applied in other field tests, especially where they need to be performed in a single heating season. The new field test method should be further developed so that more of the necessary steps are automated, and the details of its implementation should be fully documented so others can use it.

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APPENDIX A

STATISTICAL ANALYSIS

STATISTICAL ANALYSIS

A central part of this field study was to measure energy savings resulting from retrofits performed as directed by the ADRP. Energy savings are not directly measurable (as by a ruler or thermometer), but must be inferred from the measurements described in the body of this report and the statistical techniques described below.

The statistical analysis consists of two principal parts. The first part is calculation of normalized annual space heating energy savings for each house. This consists of three steps performed for each house: regression analysis of the before- and after-retrofit data, estimation of normalized annual consumption before and after the retrofits, and estimation of the normalized annual savings. The second part is calculation of average savings for the groups. The methods and equations used for these calculations are presented below. The discussion of the statistical analysis below is in reverse order; that is, it begins with calculation of average group savings and works backwards to the regression analysis.

A.1 GROUP AVERAGE SAVINGS

Many experiments begin with a group of nearly identical objects, each of which is given an identical treatment. The average effect of the treatment is then believed to be the best characterization of the effect of the treatment on objects of the type treated. For example, if ten three-year-old houses of the same design in a neighborhood are each given the same retrofit (e.g., storm windows), the average energy savings should be a good estimate of the energy savings expected for any other house of the same type and located in that neighborhood. In addition, the standard error of the mean should be a good measure of the uncertainty associated with the mean (introduced by factors which were not accounted for, such as the occupants' lifestyles and the orientations of the houses).

This experiment is quite different from the example above. The houses were selected from those eligible for the WAP, but they are a diverse lot in terms of structure and occupant behavior. Each of the audit group houses was given the same audit, but each house received a unique retrofit treatment. In this case, the average energy savings is the best characterization of what is likely to happen in another group of houses from the same population, but it is of little value for predicting what would happen to any individual house.

The average savings is important for this study because average savings can be compared to average audit-predicted savings to evaluate audit accuracy and because the average savings is the best estimate of the savings expected from the whole population. (Of course, the climates and housing stocks around the country are different than South Central Wisconsin, so the energy savings found by this study are not expected to be duplicated elsewhere.) The group average heating energy savings (GAHS) is

$$\text{GAHS} = \frac{1}{N} \sum_{i=1}^{N} \text{NAHS}_i \qquad \text{(A.1)}$$

where N is the number of houses in the group (sample), and NAHS is the normalized annual heating energy savings measured for the house.

There are two ways to estimate the standard error of the GAHS, depending on whether the GAHS is used to describe the group of houses in question or used to infer the savings potential of the population from which the sample is drawn. Naturally, inferences about the population are more uncertain than descriptions of the sample. When comparing predicted and measured savings, the standard error of the GAHS is

$$\text{Standard error} = \frac{1}{N} \left[\sum_{i=1}^{N} \text{SSE}_i^2 \right]^{1/2} \qquad \text{(A.2)}$$

where SSE is the standard error of NAHS. When inferring the average savings which would be achieved if the treatment were applied to the population from which the sample was drawn, the standard error would be as follows:

$$\text{Standard error} = \left[\frac{1}{N(N-1)} \sum_{i=1}^{N} (\text{GAHS} - \text{NAHS}_i)^2 + \frac{1}{N^2} \sum_{i=1}^{N} \text{SSE}_i^2 \right]^{1/2} \qquad \text{(A.3)}$$

The values of NAHS and SSE for each house, i, are calculated as described below.

A.2 NORMALIZED ANNUAL SAVINGS

The normalized annual heating energy savings (NAS_i) for each house (i) is estimated from the before- and after-retrofit normalized annual heating energy consumption ($NAHC_{i,b}$ and $NAHC_{i,a}$).

$$NAHS_i = NAHC_{i,b} - NAHC_{i,a} \tag{A.4}$$

The associated savings standard error (SSE_i) for each house is calculated from the before- and after-retrofit consumption standard errors ($CSE_{i,b}$ and $CSE_{i,a}$).

$$SSE_i = [CSE_{i,b}^2 + CSE_{i,a}^2]^{1/2} \tag{A.5}$$

A.3 NORMALIZED ANNUAL CONSUMPTION

The normalized annual heating consumption (NAHC) is a parameter which allows comparisons of energy consumption measurements made during different weather conditions. If a house could be tested under identical conditions before and after a retrofit is performed, the effect of the retrofit could be directly characterized as the difference. The variability of the weather makes measurements under identical conditions essentially impossible. Observations are made from meter readings as described previously. Regression analysis is used to estimate the dependence of space heating fuel consumption on the ambient temperature (Sect. A.4). The NAHC is estimated by using the house's fuel consumption's dependence on ambient temperature (from regression analysis) and a congruous summary of average ambient temperatures.

The regression analysis described in Sect. A.4 gives estimates of weekly fuel consumption as a function of weekly average ambient temperature, F(T), and the associated standard error SE(T). The congruous normal weather characterization is the number of weeks w(T) in a normal year (the average of 36 years was used) during which the weekly average temperature, $\overline{T}$, falls within one-half a degree range about each Fahrenheit temperature. A house's NAHC is estimated by summing the products found by multiplying the number of weeks, w(T), in a normal year with temperature, T, by the house's fuel consumption at the temperature, F(T), for each integral Fahrenheit temperature, T.

$$\mathrm{NAHC} = \sum_{T=T_{min}}^{T_{max}} w(T) \cdot F(T) \tag{A.6}$$

The form of F(T) used here is

$$F(T) = A + B(T - \overline{T}) \ , \tag{A.7}$$

where $\overline{T}$ is the average of all the weekly temperatures for which fuel consumption was measured. T_B is the temperature at (and above) which F(T) equals zero. Using T_B, Eq. A.8 can be rewritten as

$$\mathrm{NAHC} = \sum_{T=T_{min}}^{T_B} w(T) \cdot F(T) \tag{A.8}$$

In addition, two more useful variables can be defined:

$$W_B = \sum_{T=T_{min}}^{T_B} w(T) \tag{A.9}$$

which is the number of weeks in the normal year which have average temperatures less than T_B, and

$$T_{WB} = \frac{1}{W_B} \sum_{T=T_{min}}^{T_B} w(T) \cdot T \tag{A.10}$$

which is the average temperature of all the weeks in a normal year with average temperatures less than T_B. With these definitions, the standard error of the NAHC can be written

$$\mathrm{CSE} = W_B[\mathrm{var}\,A + (T_{WB} - \overline{T})^2\,\mathrm{var}\,B]^{1/2} \ , \tag{A.11}$$

where var A and var B are the variances of A and B. The formulas for var A and var B are given in Sect. A.4.

A.4 WEIGHTED LEAST SQUARES LINEAR REGRESSION

Linear regression is a very well-known method of fitting a line to experimental data. It proceeds by finding the line for which the sum of the squares for the differences (errors) between the line and the data is the least. This method is based on several assumptions, including the assumption that each datum (observation) deserves the same weight as each other datum. The data collected in this field test violate this assumption because the observations encompass unequal periods of time. The equations used to perform a weighted least squares linear regression are presented below. The development of these equations is described in Sect. A.5.

Each observation consists of three kinds of information: f, the space heating fuel consumption during the period; t, the average ambient temperature during the period; and l, the length of the period (weeks). In terms of these variables, equations for A and B can be written

$$A = \frac{1}{L} \sum_{i=1}^{n} f_i \tag{A.12}$$

$$B = \left[\sum_{i=1}^{n} f_i t_i - \overline{T} \sum_{i=1}^{n} f_i \right] \div \sum_{i=1}^{n} l_i (t_i - \overline{T})^2 \tag{A.13}$$

The variable L is the total duration of the observations.

$$L = \sum_{i=1}^{n} l_i \tag{A.14}$$

The variable $\overline{T}$ is the average of the weekly temperatures for which fuel consumption was measured.

$$\overline{T} = \frac{1}{L} \sum_{i=1}^{n} t_i l_i \qquad \text{(A.15)}$$

The only remaining elements are the equations for var A and var B which are needed for Eq. A.13.

$$\text{var A} = \text{MSE}/L \ , \qquad \text{(A.16)}$$

$$\text{var B} = \text{MSE} \div \sum_{i=1}^{n} l_i(t_i - \overline{T})^2 \qquad \text{(A.17)}$$

The new variable, MSE, Eq. A.18, is the mean square error, that is, the mean of the square of the difference between actual fuel consumption observations and predictions based on F(T).

$$\text{MSE} = \frac{1}{n-2} \sum_{i=1}^{n} l_i[(f_i/l_i) - F(t_i)]^2 \qquad \text{(A.18)}$$

A.5 ADDITIONAL DETAILS

Conventional regression analysis is based on the assumption that all observations have the same variance. Because the observations made for this study are the differences between ending and beginning meter readings for variable duration periods, the observations do not have constant variance. What follows is an explanation of how the observations can be transformed into data with constant variance and regression analyses performed.

The observations consist of triplets of numbers as illustrated in Table A.1.

Table A.1. Symbolic presentation of fuel consumption observation.

Fuel consumption (10^6 Btu)	Average temperature (°F)	Duration period (weeks)
f_1	t_1	l_1
f_2	t_2	l_2
.	.	.
f_n	t_n	l_n

From these data we want to develop an equation for fuel consumption per week, F, as a function of weekly average temperature, T. This equation is assumed to have the form

$$F(T) = A + B(T - \overline{T}) \ , \tag{A.19}$$

where $\overline{T}$ is the time-weighted average temperature of the average temperatures.

$$\overline{T} = \frac{1}{L} \sum_{i=1}^{n} t_i l_i \tag{A.20}$$

where L is the total time encompassed by all the observations.

$$L = \sum_{i=1}^{n} l_i \tag{A.21}$$

The relationship between the observations and the variable F is shown by Eq. A.22.

$$f_i = l_i F(T_i) \ . \tag{A.22}$$

In English this equation says that f_i, the fuel consumption of period i, is equal to l_i, the duration of the period (weeks), multiplied by $F(t_i)$, the fuel consumption of a week with an average temperature, t_i. A convenient variable to use in subsequent discussion is F_i, the average fuel consumption per week for observation i.

$$F_i = f_i / l_i \ . \tag{A.23}$$

Neither F_i nor f_i have constant variance. The transformation from f to the fuel use per week, F_i, eliminates a contribution to the variance of f_i which occurs because fuel consumption increases as the duration of the observation period, l_i (assuming constant average temperature, t_i). The variance of F_i is not constant because longer observation periods have larger variance than shorter periods. If we assume that the variance of one-week observations is S^2, then the variance of an observation which is l_i weeks long is l_iS^2. Hence,

$$\text{var } f_i = l_i S^2 \ , \tag{A.24}$$

and

$$\text{var } F_i = S^2/l_i \ . \tag{A.25}$$

To perform the regression analysis, we start with an equation similar to Eq. A.19.

$$F_i = A + B(t_i - \overline{T}) + e_i \ , \tag{A.26}$$

where e_i is the error of measurement i.

Multiplying both sides of Eq. A.26 by the square root of l_i gives a dependent variable which has constant variance.

$$\sqrt{l_i}\ F_i = \sqrt{l_i}\ A + \sqrt{l_i}\ B(t_i - \overline{T}) + \sqrt{l_i}\ e_i \ . \tag{A.27}$$

Using standard techniques to minimize the square error gives Eqs. A.12 and A.13 for A and B.

The value of S^2 needs to be estimated by calculating the standard error estimate for F(T). The best estimate of S^2 is the mean square error of Eq. A.27 and is given by Eq. A.18.

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