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Field Test Evaluation of Conservation Retrofits of Low-Income Single-Family Buildings in Wisconsin: Summary Report

Mark P. Ternes
Fred D. Boercker
Lance N. McCold
Michael B. Gettings

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ENERGY DIVISION

FIELD TEST EVALUATION OF CONSERVATION RETROFITS OF LOW-INCOME SINGLE-FAMILY BUILDINGS IN WISCONSIN: SUMMARY REPORT

Mark P. Ternes
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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

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ABSTRACT

During the winter of 1985-86, a retrofit field test was performed in 66 occupied, low-income, single-family homes in Madison, Wisconsin. The primary objectives of the field test were to (1) determine the measured energy savings and the relative benefits of a combination of envelope and mechanical equipment retrofits that were selected following a new audit-directed retrofit procedure, (2) determine the energy savings and benefits due to performing infiltration reduction work following a recently developed infiltration reduction procedure, and (3) study general occupant behavior and house thermal characteristics and their possible change following retrofit installation. This report provides an overview of the project and summarizes the findings which will be presented in detail in separate reports.

Major findings from the field test include

(1) The audit-directed retrofit procedure produced an average savings of 207 therms/year/house. The procedure also more than doubled the overall cost-effectiveness of the low-income weatherization assistance program as compared with the priority system formerly used in Wisconsin. Wall insulation and condensing furnaces were the major retrofits (predicted annual energy savings greater than 100 therms/year) most often selected under the procedure. The respective average energy savings of the houses receiving wall insulation and condensing furnaces was 14.6 and 14.3 therms/year for each $100 spent on them under the program.

(2) The blower-door-guided infiltration reduction procedure reduced expenditures for infiltration reduction to about one-fourth of previous program costs (from $570/house to $106/house). The procedure also reduced the average air leakage rate in the treated houses by 16%, whereas, in a previous study, no significant reduction was found following the installation of typical infiltration reduction measures.

(3) Twenty to 60% of the deviation between predicted and measured savings can be attributed to incorrect assumptions regarding the indoor temperature before and after retrofit used in making the predictions. Incorrect assumptions regarding the value of the indoor temperature before retrofit may be more prevalent than incorrect assumptions regarding a constant indoor temperature following retrofit, as the occupants did not generally increase their indoor temperature after retrofit installation (the occupants did not generally display "take back" behavior).

EXECUTIVE SUMMARY

FIELD TEST BACKGROUND AND PURPOSE

During the winter of 1985-86, Oak Ridge National Laboratory (ORNL), the Alliance to Save Energy, and the Wisconsin Energy Conservation Corporation (WECC) performed a field test in 66 occupied, low-income, single-family homes in the area of Madison, Wisconsin. Financial support for this field test was supplied by the U.S. Department of Energy (DOE), Office of Buildings and Community Systems; the DOE Weatherization Assistance Program (WAP); the DOE Low-Income Energy Assistance Program; the State of Wisconsin, Department of Health and Social Services; and three Wisconsin utilities (Wisconsin Power and Light, Wisconsin Gas, and Madison Gas and Electric).

The primary objectives of the field test were to (1) determine the measured energy savings and the relative benefits of a combination of envelope and mechanical equipment retrofits that were selected following a new audit-directed retrofit procedure (ADRP), (2) determine the energy savings and benefits due to performing infiltration reduction work following a recently developed infiltration reduction procedure, and (3) study general occupant behavior and house thermal characteristics and their possible change following retrofit installation. ORNL is preparing, in addition to this summary report, several detailed reports. (A list of these reports is provided at the front of this document.)

FIELD TEST STUDIES

The three field test objectives guided the design of the field test and, in order to provide answers to them, the field test was divided into three significant studies:

(1) ORNL developed an ADRP to improve the selection of building-envelope and heating-system retrofits. The improvement lies in analyzing houses individually to determine which retrofits are most cost-effective for that particular house rather than adhering to a fixed priority list approach typical of most weatherization assistance programs. Further, the ADRP includes a rational process for deciding the amount of money to spend on each house in a group of houses. Because houses receive different retrofits and various amounts of money are spent on each house, the ADRP can significantly enhance program energy savings per dollar of retrofit investment. The primary objective of this study was to determine the benefits and performance of the ADRP and to measure the energy savings of combined heating-system and building-envelope retrofits.

(2) WECC developed an infiltration reduction procedure that uses a blower door to improve the infiltration reduction work performed under weatherization programs. Weatherization programs have previously focused on caulking and weatherstripping doors and windows. Under the infiltration reduction procedure, the air leakage rate of the house is determined using a calibrated blower door, allowing expenditure levels and air leakage rate reduction goals for each house to be set. Major leaks in the house are sealed while the blower door is in place to help locate the leaks and to track the air leakage rate during retrofit. The homes are sealed until the air leakage reduction goal or the expenditure level is reached. The primary objectives of this study were to assist in the development of the procedure and to investigate its cost-effectiveness.

(3) Two explanations have been proposed to explain why measured energy savings of retrofit programs are less than predicted and why large scatter is observed in the measured energy savings of similar homes modified with similar retrofits: (a) actions taken

by the occupants following retrofit, such as increasing the thermostat setpoint, may reduce savings, and (b) the actual temperatures in the house may be lower than the value assumed in estimating the retrofit savings. This study was performed to address these and other related issues by determining (a) if the indoor temperature of the house changes following retrofit installation, (b) if the expected deviation between predicted and monitored energy savings could be reduced by including indoor temperature in the analysis, and (c) general occupant behavior and house thermal characteristics and their possible change following retrofit installation.

FINDINGS

Audit-Directed Retrofit Procedure

The ADRP was found to be a successful tool for cost-effectively selecting building-envelope and heating-system retrofits in weatherization programs, offering significant advantages compared to a fixed priority list approach. Replacing inefficient furnaces with higher-efficiency units and installing wall insulation were found to be effective retrofits well worth considering in weatherization programs. Specific results and conclusions obtained from the audit portion of the field test were

(1) The ADRP, which used an expanded list of building-envelope and heating-system retrofits, more than doubled the overall cost-effectiveness of Wisconsin's low-income WAP as compared with the priority system formerly used in Wisconsin in 1982. The annual energy savings achieved by the program per hundred program dollars increased from 4.8 therms/year/$100 in 1982 to 12.6 therms/year/$100.

(2) Condensing furnace replacement and wall insulation are major retrofits (predicted annual savings greater than 100 therms/year) that appear to be cost-effective. Minor retrofits (such as vent dampers and infiltration reduction) do not appear to be. The average energy savings of the houses receiving wall insulation was 14.6 therms/year for each $100 spent on them under the program, about the same as the houses receiving a condensing furnace. The average energy savings of the houses receiving no major retrofits was only 18 therms/year per hundred program dollars.

(3) The average savings of the houses was 207 therms/year, or 19% of the average pre-retrofit space heating consumption of the houses. Individual house savings was quite variable, ranging from -162 to 604 therms/year. On average, the houses receiving a major retrofit saved the most energy: 345 therms/year and 257 therms/year for the houses receiving a condensing furnace and wall insulation, respectively, as compared to an average of 12 therms/year for houses receiving only minor retrofits. The variability of the individual house savings and the concentration of the savings in the houses receiving a major retrofit can largely be attributed to the ADRP which was designed to concentrate retrofits in houses that would most benefit from the retrofits.

(4) The annual heating energy savings for the entire group of retrofitted houses was approximately 83% of that predicted. On average, the audit accurately predicted the savings for condensing furnaces, but overpredicted the savings for wall insulation (by about 25%) and the minor retrofits. The energy savings for individual houses was not predicted accurately by the audit.

(5) The retrofits selected by the ADRP were quite different from the retrofits employed in the traditional weatherization program: only four of 20 houses retrofitted following the ADRP received ceiling insulation and none received storm windows. Condensing furnaces and wall insulation were major retrofits most often selected by the ADRP in the 20 test homes.

Blower-Door-Guided Infiltration Reduction Procedure

The blower-door-guided infiltration reduction procedure was found to be a useful tool to reduce expenditures for infiltration reduction while ensuring that significant air leakage rate reductions are obtained. However, the infiltration reduction work that was performed did not produce, on average, measurabale energy savings in the test houses. Specific results and conclusions obtained from the "blower door" portion of the field test were

(1) The blower-door-guided infiltration reduction procedure reduced expenditures (labor plus material) for infiltration reduction to about one-fourth of that previously required by Wisconsin's WAP (from $570/house to $106/house).

(2) The infiltration reduction procedure reduced the average air leakage rate in the treated houses by 16%, whereas, in a previous study, no significant reduction was found following the installation of typical infiltration reduction measures.

(3) The air leakage rate reductions were, on average, largest in the houses recommended by the procedure to receive infiltration reduction measures (work was performed on additional houses that was not recommended by the procedure). Because the reductions of individual houses were quite variable, the potential reduction of a house depends on more than the initial air leakage rate.

(4) The infiltration reduction procedure applied to a group of houses provided an effective guide to the average amount of infiltration reduction that can be achieved and the expense necessary to accomplish the reduction.

(5) Although air leakage rates were reduced using the infiltration reduction procedure, a reduction in the average energy consumption of the treated houses was not observed from an analysis of metered energy use data.

Occupant Behavior and House Thermal Characteristics Study

Indoor temperature changes attributable to the installation of conservation measures were not generally observed. However, consideration of the indoor temperature in the analysis can explain a large portion of the deviation between predicted and measured savings. Specific results and conclusions obtained from the occupant behavior and house thermal characteristics study were

(1) Twenty to 60% of the deviation between predicted and measured savings can be attributed to incorrect assumptions regarding the indoor temperature before and after retrofit used in making the predictions. Incorrect assumptions regarding the value of the indoor temperature before retrofit may be more prevalent than incorrect assumptions regarding a constant indoor temperature following retrofit, as the occupants did not generally increase their indoor temperature after retrofit installation (the occupants did not generally display "take back" behavior).

(2) A single indoor temperature was found to adequately represent the average house temperature in many homes.

(3) Indoor temperature and thermostat setpoint are distinct parameters such that inferences concerning one cannot be made from the other; thus, both need to be monitored if both are to be studied in an experiment.

(4) Occupant's perceptions of their house's thermal characteristics and comfort, and their change following retrofit installation, were found to be inconsistent with measured data; thus, responses to occupant questionnaires may not provide sufficiently accurate data to be generally useful in audits or analyses to supplement or interpret results.

1. INTRODUCTION

1.1 BACKGROUND

A retrofit field test involving 66 occupied, low-income, single-family homes in the area of Madison, Wisconsin was performed during the winter of 1985-86. The primary objectives of the field test were to (1) determine the measured energy savings and the relative benefits of a combination of envelope and mechanical equipment retrofits that were selected following a new audit-directed retrofit procedure (ADRP); (2) determine the energy savings and benefits due to performing infiltration reduction work following a recently developed infiltration reduction procedure; and (3) study general occupant behavior and house thermal characteristics and their possible change following retrofit installation.

1.2 PURPOSE

Oak Ridge National Laboratory (ORNL) is preparing, in addition to this summary report, several detailed reports on the results of this project. (A list of these reports is provided at the front of this document.) The purpose of this summary report is to provide a concise and timely listing of the major findings and to provide an overview of the entire project which otherwise might be lost in the detail of individual reports. The general purposes of this report are to

1. provide an overview of the field test performed in Wisconsin, identifying the various studies that were performed, the background that led to the need for the studies, and the various forthcoming reports;
2. provide a summary of the major findings, omitting much of the technical detail; and
3. discuss implications of these findings for future and similar building energy retrofit programs.

The questions of concern to each of the major participants in the study and the role each performed are identified in Sect. 2. In Sect. 3, a detailed overview of the field test and specific objectives of each study are presented. The major findings are summarized in Sect. 4. Implications of the field test findings for future single-family retrofit programs are discussed in Sect. 5.

2. PARTICIPANTS IN THE WISCONSIN FIELD STUDY

2.1 PARTICIPANTS AND THEIR ROLES

The field test was a cooperative effort among several organizations, as shown in Fig. 2.1. The most important requirement was that all participants function as a team, each performing the required tasks on a very tight schedule so that the entire project could be completed within less than one year. The major tasks that had to be performed were

1. Select or develop an audit technique that could recommend the most cost-effective combination of retrofits for each house and for the entire retrofit program.

2. Develop an infiltration reduction procedure using a blower door to optimize the amount of infiltration work performed in a house.

3. Design analysis methods capable of evaluating the effectiveness of the audit technique and infiltration reduction procedure, using a single winter's data, and capable of studying the relations between retrofit installations, occupant behavior, and house thermal characteristics.

4. Devise methods of field metering that are inexpensive and non-intrusive for the occupants, but capable of yielding the required data.

5. Implement the field test plan and collect the necessary data.

6. Analyze the data and report results.

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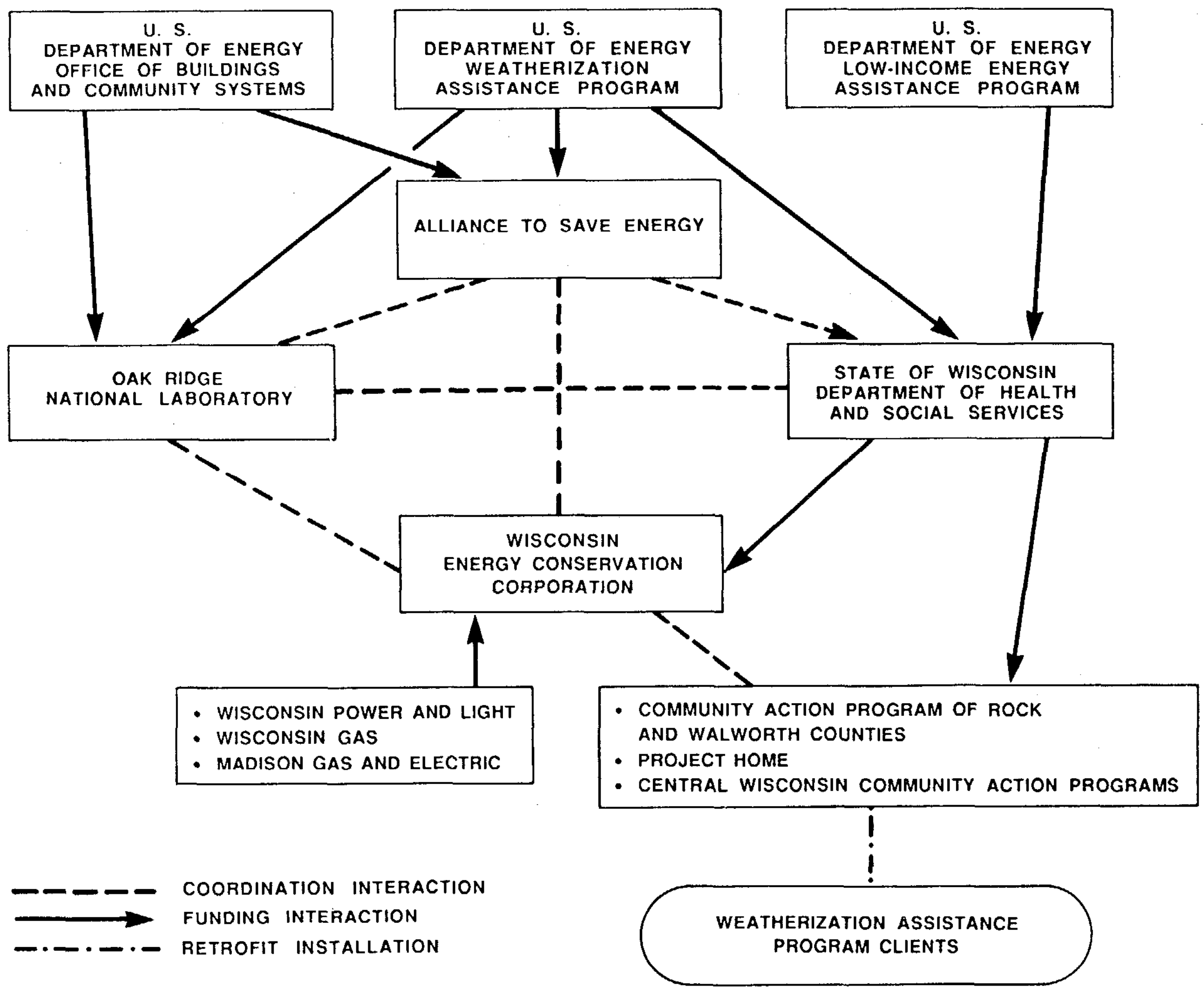

Fig. 2.1. Schematic of the field test organization showing the lines of interaction between the participants.

Financial support for this field test was supplied by the U.S. Department of Energy (DOE), Office of Buildings and Community Systems (DOE-OBCS); the DOE Weatherization Assistance Program (DOE-WAP); the DOE Low-Income Energy Assistance Program (DOE-LIEAP); the State of Wisconsin, Department of Health and Social Services (DHSS); and three Wisconsin utilities (Wisconsin Power and Light, Wisconsin Gas, and Madison Gas and Electric).

The DOE offices provided funding to ORNL and the Alliance to Save Energy (ASE) to develop and test a method for selecting optimal combinations of retrofits. ASE helped initiate the project and assisted in the planning and management of the project; ASE's efforts were instrumental in getting the State of Wisconsin DHSS to join in the field test. ORNL was funded to assist in the technical aspects of the evaluative study. ORNL developed the audit and the field test plan with input from ASE, DHSS, and the Wisconsin Energy Conservation Corporation (WECC) and also had responsibility for analyzing the data and reporting results. DHSS funded WECC to develop a unique infiltration reduction procedure and to implement the field test, which included selecting the homes to retrofit and meter, purchasing and installing meters, collecting weekly meter readings, training auditors, performing audit calculations, and coordinating the retrofit activities. DHSS also provided some of its WAP and LIEAP funds to be used for weatherization of homes in the field test. The three utilities provided funds for the purchase and installation of meters used in the field test. Although each of the groups involved in the field test had an interest in providing maximum energy conservation to low-income homes at reasonable cost, each had a different role in the overall process. Consequently, each had somewhat different concerns that needed to be addressed in the evaluation of the weatherization program, and each had different questions that needed to be answered by the field test study. The remainder of this section discusses briefly some of the questions of concern to each of the major participants in the Wisconsin field test.

2.2 DOE OBJECTIVES FOR THE STUDY

The Single-Family Retrofit Research Program of the DOE-OBCS, Building Services Division,[1] needed quality field data on the performance of energy conservation retrofits in occupied homes to decrease the uncertainty of savings predictions. The DOE-OBCS program also desired to work closely with those implementing conservation programs in order to include the most effective retrofit measures and to facilitate transfer of results to practice. This project represents the initial cooperative, cost-shared field monitoring project that was important to establish roles and procedures, test monitoring and analysis methods, and provide initial data on retrofit issues of interest to OBCS, which included

1. What are the energy savings and cost savings of combined shell and mechanical retrofits?
2. Why do specific energy conservation retrofits save less energy than predicted?
3. To what extent does occupant behavior account for some of the lost energy savings? Is there evidence that occupants convert some potential savings into greater comfort (higher thermostat settings), thus "taking back" savings?
4. To what extent can field test evaluation procedures for single-family buildings be improved and standardized? How may the metering and data analysis be carried out with minimum cost and yet yield credible answers regarding energy savings? Can the entire field test (pre-retrofit metering, retrofit, and post-retrofit metering) be carried out in a single winter?

The WAP of the DOE State and Local Assistance Program is the major source of funding for energy conservation retrofits of low-income housing. This program was created in 1976 by Title IV of Public Law 94-385. WAP's major interests in the Wisconsin field test were to (1) identify any improvements in the method of implementing low-income retrofit programs that would provide greater energy and dollar savings per dollar of WAP investment in retrofits, and (2) learn to what extent occupant behavior is reducing WAP energy savings below the expected levels. Field-tested improvements in the Wisconsin program could be transferred, where applicable, to other states, thus multiplying the savings.

2.3 STATE OF WISCONSIN GOALS

In 1986, Wisconsin spent over $18 million of federal funds to weatherize 7500 low-income homes -- $7.5 million from WAP and $10.5 million from LIEAP, representing 15% of the state's total LIEAP award. In addition, the Utility Weatherization Assistance Program for low-income homes is mandated by the Wisconsin Public Service Commission and involves 11 of the largest gas and electric utilities. This program spent $8 million in 1985 to weatherize 7300 homes.

In 1983, the Wisconsin Department of Administration authorized an evaluative study of the low-income weatherization program to be conducted by WECC, a state-wide, non-profit corporation. Results of the study were reported in October, 1984, in four volumes.[2] The study showed that almost all of the houses weatherized in 1982 were being treated to the same set of retrofits: caulking and weatherstripping, insulating water heater tanks, insulating warm air ducts, insulating the attic, and adding storm windows. Based on analyses of monthly utility bills, average energy savings from these retrofits was estimated to be 80-130 therms/year/house or approximately 6 to 10% of the annual home gas use. Recommendations from the study were to adopt a new and expanded list of retrofit measures, to use blower doors to improve infiltration control work, to insulate walls, and to retrofit or replace furnaces.

As a result of this evaluative study, the State of Wisconsin DHSS had a number of special interests in a field test:

1. Can the energy saved per dollar invested in the Wisconsin low-income retrofit program be improved?
2. Could the use of blower doors significantly improve the effectiveness of infiltration control measures?
3. Could an improved procedure be devised to select retrofits best suited for individual houses?
4. Would additional retrofit options, such as furnace replacement and insulation of walls (both expensive retrofits), prove to be a wise use of retrofit money?

2.4 PRIVATE SECTOR (UTILITY) GOALS

Because of their involvement in the Utility Weatherization Assistance Program, the larger utilities serving Wisconsin had interests in a field test study. Questions of concern to them include

1. Which retrofits are the most cost-effective for low-income homes in Wisconsin?
2. For those retrofits that do not perform as expected, does the fault lie with the quality of the installation of the retrofit or with the method of predicting the savings?

2.5 ASE OBJECTIVE

ASE is a non-profit organization founded in 1977 to promote efficient use of energy. It is supported by contributions from corporations, unions, individuals, and by project-specific grants from public sources. ASE has been interested in enlarging retrofit options to include mechanical retrofits in addition to the conventional building envelope retrofits. Recent revisions in DOE-WAP guidelines allow mechanical retrofits to be included in low-income programs. ASE initiated the idea of a demonstration project as part of a state low-income retrofit program to improve the performance and cost-effectiveness of state and utility weatherization programs through the use of better technology. ASE presented the demonstration project idea to OBCS and to the WAP office of DOE. In order to accommodate some DOE objectives, as well as the ASE objective, the scope of the project was broadened from a demonstration of mechanical system retrofits to a field test evaluative study of a broad range of retrofits. It would include a method to select optimal combinations of mechanical and/or envelope retrofits and an evaluation of the effectiveness of the retrofits selected. However, ASE's primary interest would continue to be "How can better technology be cost-effectively incorporated into low-income energy conservation programs to improve them?"

3. OVERVIEW OF THE WISCONSIN FIELD TEST

In order to provide answers to the variety of questions motivating the field test, the overall program was divided into three separate studies, as indicated in Fig. 3.1. This section describes the objectives of each of the three studies and the experimental design of the entire field test.

3.1 AUDIT-DIRECTED RETROFIT PROCEDURE

The purpose of the DOE-WAP is to improve the energy utilization efficiency of homes of low-income families. Until recently, DOE-funded low-income weatherization activities were limited to infiltration control, insulation, and addition of 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 by installing weatherstripping and caulking, insulate the water heater, add ceiling insulation to some predetermined level, and then install storm windows until the expenditure limit is reached. Under these conditions, each house received about the same treatment, and about the same amount was spent on each house.

Revised DOE regulations increased the average expenditure per dwelling to $1,600 and permitted an expanded list of retrofits to be performed, including

1. heating and cooling system tune-ups, repairs, and modifications;
2. installation of thermostat control systems, heat exchangers, and heat pump water heaters; and
3. furnace and boiler replacements.

This expanded retrofit list provided options for more cost-effective energy savings, but it also complicated the process of selecting the best combination of retrofits for a house or for a given group of

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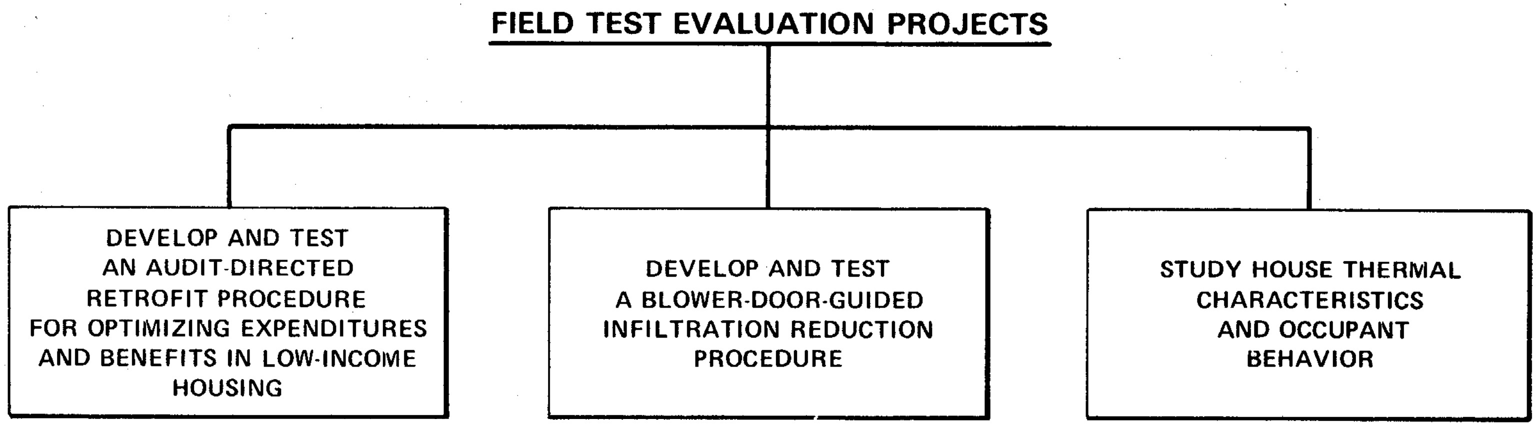

Fig. 3.1. Overview of projects comprising the Field Test Evaluation of Conservation Retrofits of Low-Income, Single-Family Buildings.

houses. With the revised regulations, a set priority list was inadequate to apply to all houses in a geographic area. The optimum combination of retrofits for a given house always depends on the characteristics of the house which is to receive the retrofits.

ORNL was asked by DOE to select or develop a procedure that could be used by home weatherization installers to select retrofits that would optimize conservation program expenditures among low-income, single-family homes. No suitable, public domain audit or analysis program was found, so ORNL developed an audit-directed retrofit procedure (ADRP) which is described in detail in two other reports.[3,4] The chief distinction of the ADRP, as contrasted with the set list of priorities, is that each house is examined individually to determine which retrofits are most cost-effective for that house. An additional distinction of the ADRP is that it includes a rational process for deciding how much money to spend on each house in a group of houses in order to optimize conservation program expenditures for the group. Under this procedure, houses receive different retrofits, and various amounts of money are spent on each house in order to achieve maximum program energy savings per dollar of retrofit investment.

The ADRP was developed to reduce heating energy consumption only. Heating-system retrofits, which were limited to gas furnaces, included: (1) replacing a standing pilot with an intermittent ignition device, (2) installing an electromechanical full-closure vent damper, (3) installing a thermally-activated vent damper, (4) installing a secondary condensing heat exchanger, (5) replacing an atmospheric burner with a gas power burner, and (6) replacing the existing furnace with a high-efficiency furnace. Building-envelope retrofits included (1) ceiling insulation, (2) exterior wall cavity insulation, (3) storm windows, (4) storm doors, (5) floor insulation, (6) exterior basement wall insulation, (7) sill box insulation, and (8) blower-door-guided infiltration reduction.

The ADRP consists of two parts. First, an audit is applied to each house to predict the benefit-to-cost (B/C) ratio for each individual retrofit. Costs of materials and labor involved in each retrofit are estimated by the audit. After retrofit savings are estimated using audit calculations, a B/C ratio is calculated for each retrofit using the estimated costs and savings. Once the retrofits for each individual house are ranked by their B/C ratios, interactions among the retrofits are considered and revised B/C ratios are determined. Retrofit interactions become important when both heating-system and building-envelope retrofits are used. Second, retrofits are selected that optimize the cost effectiveness of the program using the revised B/C ratios. For a group of houses, all the retrofits are ranked by their B/C ratios. Retrofits with the highest B/C ratios are then selected until the allocated money for the group of houses is spent.

The ADRP was used in the Wisconsin Field Test, which is described in detail in Ref. 5. The primary purposes of this portion of the Wisconsin field test were to determine the benefits of the ADRP and to measure the energy savings of combined heating-system and building-envelope retrofits. The prediction capability of the audit and the performance of individual retrofits were also of interest.

3.2 BLOWER-DOOR-GUIDED INFILTRATION REDUCTION PROCEDURE

Infiltration reduction has been an important part of the DOE-WAP and similar programs. Previous infiltration reduction work focused on caulking and weatherstripping doors and windows and was performed without the use of a tool to identify major leakage sites. Questions regarding the effectiveness of this type of infiltration reduction practice have arisen. Indeed, measured energy savings due to this work have been found to be less than expected. One explanation for this is that the common practice of sealing around doors and windows, for example, only seals insignificant leaks, while important leaks are ignored. In addition, infiltration reduction work may be performed in homes that already have low air infiltration rates.

A blower door, shown in Fig. 3.2, either pressurizes or depressurizes a house, allowing the leakiness (or air leakage rate) of the house to be measured. Infiltration reduction techniques using a blower door have also been successfully used by practitioners in the field: the blower door is used to identify the major sources of air leakage (which may be hidden in attic cracks or interior walls) which are then sealed. However, a procedure to incorporate this technique into the WAP had not been developed.

A blower-door-guided infiltration reduction procedure was developed by WECC to (1) solve the problems associated with the conventional approach to reducing air infiltration used in WAPs, (2) incorporate the blower door technique into the WAP, and (3) increase the efficiency and cost-effectiveness of the technique. A detailed description of the procedure and its development is provided in Refs. 6 and 7. The basic approach to the procedure is to have a weatherization crew determine the air leakage rate of the house, using a calibrated blower door, at 50 pascal of depressurization. Expenditure levels and air leakage rate reduction goals for each house are then set based on the measured air leakage rate of that particular house. The expenditure level for labor and materials depends largely on the house air changes per hour at 50 pascal depressurization (ACH50):

$$\text{Expenditure Level} = (\text{ACH50})^2 \times (\text{House Area})/1400,$$

where the expenditure level is in units of dollars and the house area is in units of ft^2. The air leakage rate reduction goals are listed in Table 3.1. Homes whose air leakage rate is 8 ACH50 or less receive

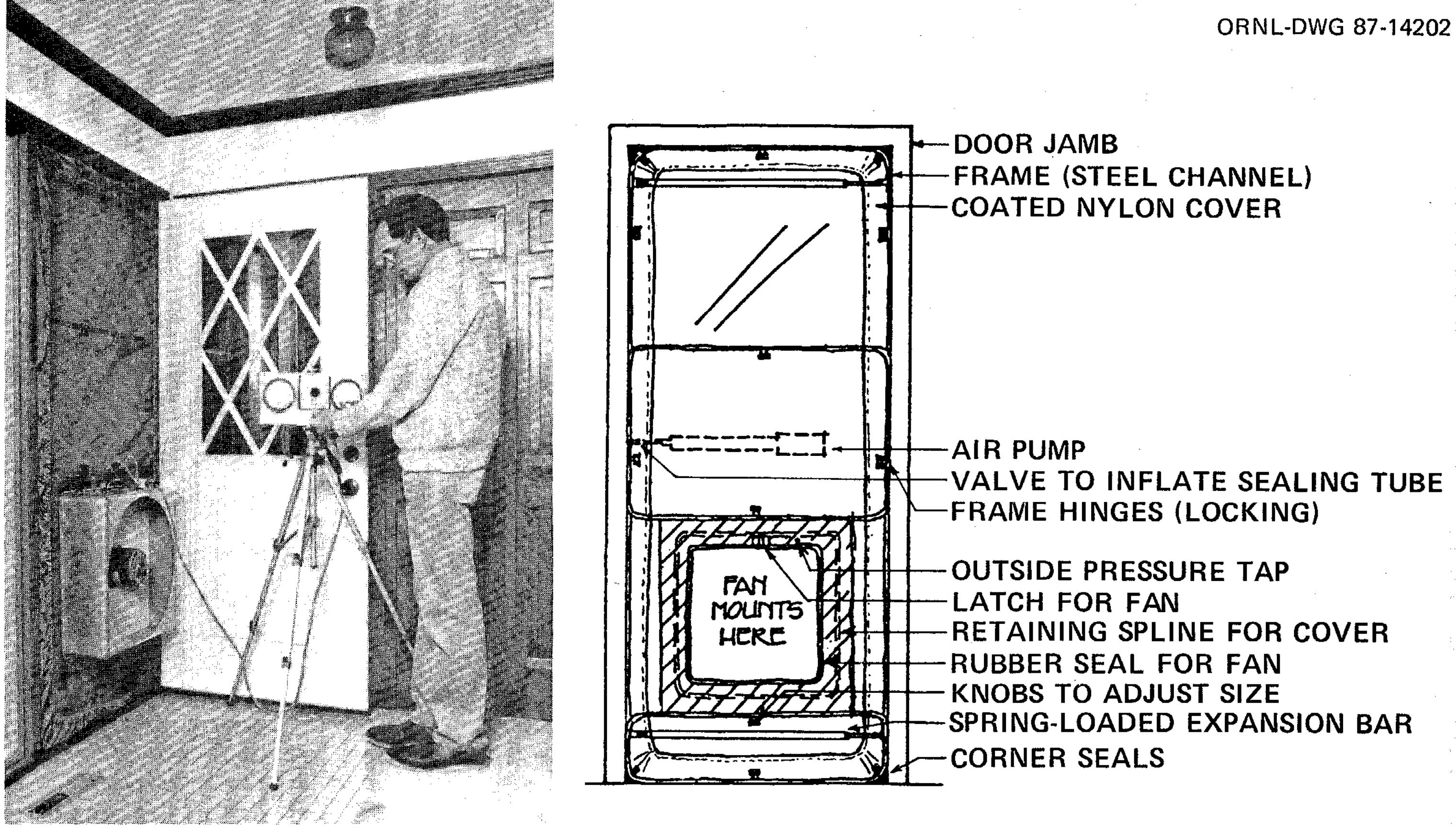

Fig. 3.2. Picture and diagram of a blower door.

Table 3.1. Air leakage rate reduction goals used in the blower-door-guided infiltration reduction procedure

Initial air leakage rate (ACH50)[a]	Reduction goal (ACH50)[a]
8 or less	Seal leaks that affect comfort only
8 to 10	Reduce ACH50 by 1
10 to 12	Reduce ACH50 by 2
13 to 15	Reduce ACH50 by 3
16 to 18	Reduce ACH50 by 4
18 or greater	Reduce ACH50 by 5

[a]ACH50 - house air changes per hour at 50 pascal depressurization.

no treatment (except to seal leaks that directly affect comfort) due to economic considerations and to avoid moisture and indoor air quality problems. Homes that have an air leakage rate greater than 8 ACH50 are assigned reduction goals that vary with the leakiness of the house. Major leaks in the house are sealed while the blower door is in place to help locate the leaks and to track the air leakage rate during retrofit. The homes are sealed until the air leakage rate reduction goal or expenditure level is met. Crews are discouraged from caulking and weatherstripping windows in favor of finding larger leakage areas with the help of the blower door. The crews are equipped with a variety of infiltration control materials to meet most needs.

A detailed description of this project is provided in Ref. 7. The primary objectives of this study were (1) to assist in the development of the blower-door-guided infiltration reduction procedure, (2) to demonstrate techniques of determining the air leakage reduction and subsequent energy savings resulting from the retrofit, and (3) to investigate the cost-effectiveness of the procedure.

3.3 OCCUPANT BEHAVIOR AND HOUSE THERMAL CHARACTERISTICS STUDY

A number of residential weatherization studies have found that the measured energy savings attributed to a retrofit program are less than the predicted savings, and that there is large scatter in the measured energy savings, even for similar houses modified with similar retrofits. Four reasons are often advanced to explain these differences:

1. occupant behavior, especially regarding thermostat settings, may reduce savings;
2. the actual temperatures within the houses may be maintained at a lower level than that assumed in estimating the savings;
3. the weatherization measures may be poorly installed; and
4. the predictive models may systematically overestimate savings.

This study was performed to address the first two points. A detailed description of this project is contained in Ref. 8. Specific purposes were threefold: (1) to determine if the indoor temperature of the home changes following retrofit installation, (2) to determine if the expected deviation between predicted and monitored energy savings could be reduced by including indoor temperature in the analysis, and (3) to study general occupant behavior and house thermal characteristics and their possible change following retrofit installation.

3.4 FIELD TEST EXPERIMENTAL DESIGN

The field test was performed during the winter of 1985-86 in four southern Wisconsin counties in the vicinity of Madison. (See Fig. 3.3.) Initially, over 100 houses, divided evenly into three groups, were to be used in the field test. For several reasons (such as scheduling and attrition), 66 houses, divided into three uneven groups, were actually used in the field test. The houses selected for inclusion in the field test met the following selection criteria:

1. The house must be eligible for the DOE-WAP.
2. The house must be a gas-heated, single-family detached home, excluding mobile homes.
3. The owner must have occupied the house for at least one year and must not have been planning extended time away from home during the 1985-86 winter.
4. Secondary heating devices (e.g., wood stoves) must not be used.
5. The occupants must be willing to participate in the field test.

The ADRP was used to determine which combination of envelope and mechanical system retrofits were installed in a group of 20 homes. An average of $1600/house was selected to be spent on these homes to conform with DOE regulations and to make the study comparable with other studies of Wisconsin's WAP. Of the $1600, $400 was set aside to cover

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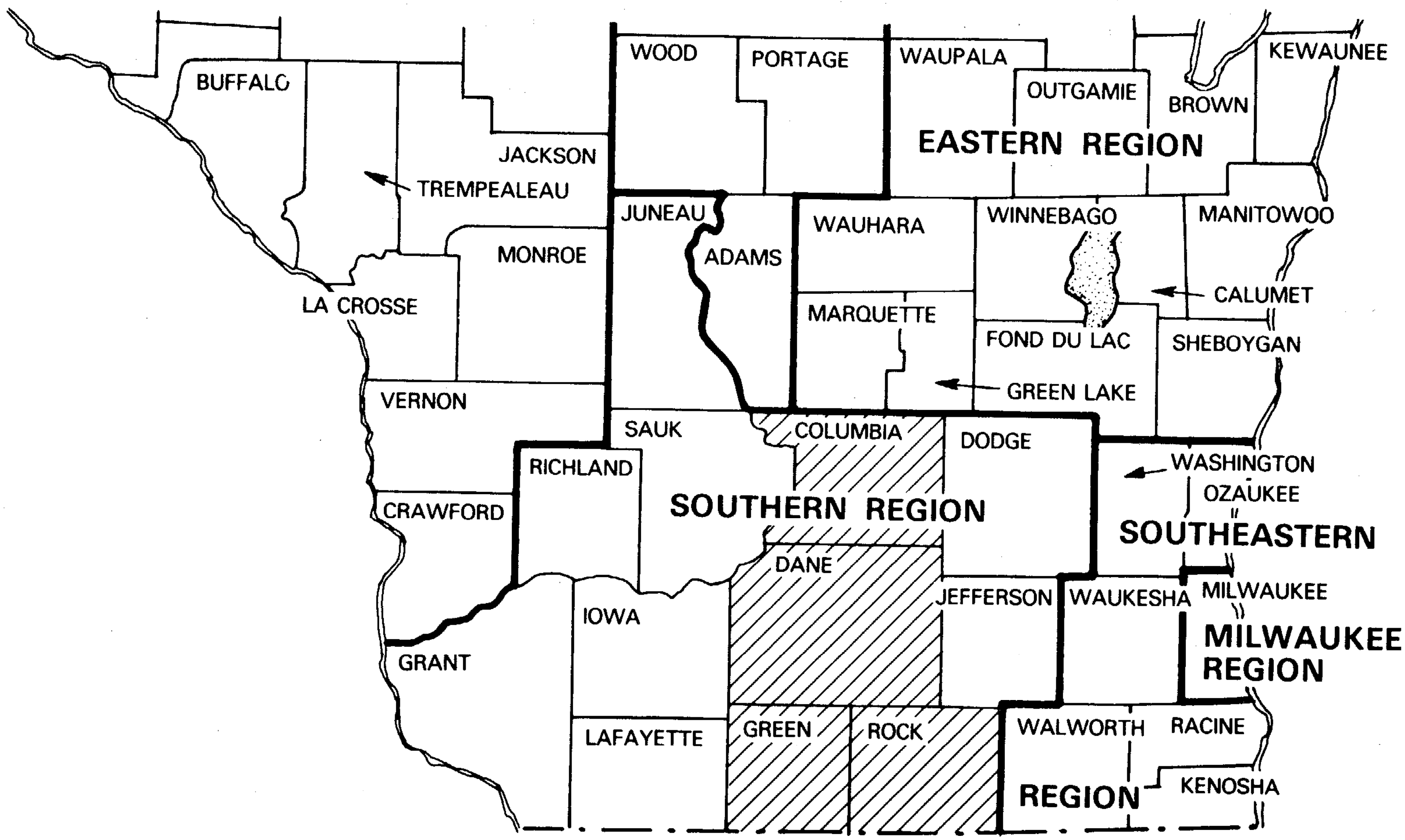

Fig. 3.3. The hatched area shows the location of the low-income, single-family buildings used in the field test.

administration (including auditing) and house repair costs, leaving $1200 to be spent for retrofits. The retrofits were installed by the same local weatherization providers that normally provide these services for the state. The regular auditors were trained in the use of the audit and in heating system efficiency measurements, but specially trained experts were not employed. A second group of 18 homes had air leaks sealed following the blower-door-guided infiltration reduction procedure. The remaining 28 homes served as a control group for the retrofitted houses to allow compensation for house changes and occupant behavior changes between the pre- and post-retrofit periods. Retrofits were not installed in these houses until after the field test was completed.

All houses in the first and third groups were used to study the ADRP, while all houses in the second and third groups were used to study the infiltration reduction procedure. Selected homes from each group were metered more extensively and used in the study of occupant behavior and house thermal characteristics.

Table 3.2 lists the data gathered for each house that was used to calculate pre- and post-retrofit heating system fuel uses, normalized for an average heating season in southern Wisconsin. Three classes of data were collected: (1) data for each house needed to determine the retrofit energy savings, (2) weather data needed to determine the retrofit energy savings, and (3) general data on the houses and occupants needed to implement the ADRP and the infiltration reduction procedure. Three data parameters were monitored weekly for each house: furnace system run-time, house gas consumption, and house electricity consumption. The furnace weekly run-time, combined with a measured fuel consumption rate of the heating system, allowed the weekly heating system fuel consumption to be determined. (The fuel consumptions of the heating system and house are not equal to one another because of other uses of gas within the house, such as for cooking.)

Table 3.2. Information collected for 66 houses in the Wisconsin field test evaluation of conservation retrofits

Data item	Source of information
Whole-house gas use	Utility meter (weekly reading)
Whole-house electricity use	Utility meter (weekly reading)
Furnace gas use	Submetered with run-time meter (weekly reading)
Ambient air temperature	Hourly data from 3 weather stations in the 4 counties; Hourly data from Truax Field in Madison (local airport) for 36-year period
Building characteristics and heating system characteristics	Audit

The house gas and electric utility meter readings were used to verify the reasonableness of the heating season data. In addition to the data identified in Table 3.2, records were kept of the original and of the retrofitted air leakage rates for each of the 20 houses in the audit group and the 18 houses in the infiltration reduction group. These data from the infiltration reduction group were used to estimate energy savings and to evaluate the expenditure levels and air leakage rate reduction goals identified in the infiltration reduction procedure.

The retrofit energy savings of the treated houses were first determined individually. Weekly heating system fuel consumption, measured before and after retrofit installations, spanned a range of weather conditions, allowing fuel consumption to be linearly correlated to the outdoor temperature. The normalized pre- and post-retrofit annual energy consumptions were then determined using the correlations and long-term average outdoor temperatures for the Madison area. The difference between the pre- and post-retrofit annual energy consumptions is the annual energy savings normalized for average Madison outdoor temperatures.

The energy savings of the houses comprising the audited group were then averaged to determine the average benefit of the ADRP. Similarly, the average benefit of the infiltration reduction procedure was determined using the energy savings of the houses comprising the infiltration reduction group. These savings, as calculated, represent the savings due to the respective treatment, as well as to occupant behavior or house changes which may have occurred during the monitoring period. The control group was included in the test in order that other variables that could affect energy use such as occupant behavior or house changes could be accounted for. (Occupant behavior or house changes occurring in the control group are assumed to occur, on average, in the treated groups.) The control group houses were analyzed as if they had been retrofitted, allowing an average energy "savings" to be determined. The average savings of the treated groups were then adjusted by subtracting the control group "savings" from them.

Selected homes from each group were metered more extensively and used in the study of occupant behavior and house thermal characteristics. For this study, ten data parameters were monitored hourly in 15 of the 66 homes used in the field test. These homes were monitored from the two counties closest to Madison (Dane and Rock) to expedite the installation, monitoring, and repair of the data acquisition equipment. The 15 homes included seven homes from the audit group of houses, three from the infiltration reduction or "blower door" group, and five from the control group. The ten monitored data parameters were

1. living room air temperature,
2. kitchen air temperature,
3. master bedroom air temperature,
4. basement air temperature (or spare bedroom air temperature),
5. interior surface temperature of the living room ceiling,
6. interior surface temperature of an exterior wall,
7. air temperature at the thermostat,
8. outdoor temperature,
9. thermostat setpoint, and
10. furnace run-time.

Data were collected approximately every eight seconds, and hourly averages or totals were stored in computer memory. These hourly data were remotely retrieved each week. The majority of the analyses performed using these data were qualitative evaluations of graphical results, although some calculations were also performed.

Monitoring of the data parameters identified in Table 3.2 for each individual house 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 and continued until May. The 15 houses metered more extensively for the occupant behavior and house thermal characteristics study were instrumented between November 21 and December 20, 1985, allowing five to nine weeks of pre-retrofit data to be collected before the audit and infiltration reduction houses were retrofitted. Approximately 14 weeks of post-retrofit data were collected by mid-May.

4. SUMMARY OF FINDINGS FROM THE FIELD TEST

This section will report the major findings resulting from the analysis of the field test data for the three studies. Only the primary findings will be presented. The interested reader is urged to pursue detailed discussions of the findings, including statistical analysis results, for the ADRP in Ref. 5, for the infiltration reduction procedure in Ref. 7, and the occupant behavior and house thermal characteristics study in Ref. 8.

4.1 AUDIT-DIRECTED RETROFIT PROCEDURE

The ADRP was found to be a successful tool for cost-effectively selecting building-envelope and heating system retrofits in weatherization programs, offering significant advantages compared to a fixed priority list approach. Replacing inefficient furnaces with high-efficiency units and installing wall insulation were found to be effective retrofits well worth considering in weatherization programs. Specific results obtained from the audit portion of the field test were

1. The ADRP, together with the expanded list of retrofits, more than doubled the overall cost-effectiveness of Wisconsin's low-income WAP as compared with the priority system formerly used in Wisconsin in 1982. As shown in Table 4.1, the annual energy savings achieved by the program per hundred program dollars increased from 4.8 therms/year/$100 in 1982 to 12.6 therms/year/$100. A portion of the increased efficiency might also be attributed to the increased skill acquired by weatherization installers between 1982 and 1985 through experience and training.

2. Condensing furnace replacement and wall insulation are major retrofits that appear to be cost-effective. Minor retrofits (such as vent dampers and infiltration reduction work) do not appear to be. Major retrofits were defined to be those with predicted annual energy savings greater than 100 therms/yr and minor retrofits to be those with predicted savings less than 100 therms/year. In six of the 20 houses, wall insulation was the only major retrofit installed; with two exceptions, the only major retrofit installed in seven other houses was a condensing furnace replacement. Various other minor retrofits were also installed in these 13 houses, as well as the remaining seven houses. As shown in Table 4.1, the average energy savings of the houses receiving wall insulation was 14.6 therms/year for each $100 spent on them under the program, about the same as the houses receiving a condensing furnace. The average energy savings of the houses receiving no major retrofits was only 1.8 therms/year per one hundred program dollars.

3. Significant savings were achieved, on average, in the 20 houses. As shown in Table 4.2, the average savings of the 20 houses, normalized for long-term weather conditions, was 207 therms/year, or 19% of the average pre-retrofit space heating consumption of the 20 houses (estimated to be 1071/therms/year). This savings includes a calculated value of 38 therms/year for pilot gas savings due to intermittent ignition devices because they could not be measured with the instrumentation used in the study. The average savings also includes an adjustment for control group savings (determined to be -5 therms/year), making it slightly higher than the value listed in Table 4.1 for all the houses.

4. The savings of the individual houses was quite variable and, on average, was largest in the houses receiving a major retrofit. Individual house savings ranged from -162 to 604 therms/year. As

Table 4.1. Comparison of program costs and energy savings: 1983 WECC study[a] vs 1985-86 field test results

	Average amount spent per house[b] ($)	Heating energy savings/house[c] (therms/year)	Annual energy savings per hundred program dollars (therms/year/$100)
1985-86 field test			
Condensing furnace	2,408	345	14.3
Wall insulation	1,764	257	14.6
Minor retrofits	660	12	1.8
All houses	1,603	202	12.6
1983 WECC study	2,250	105	4.8

[a]Ref. 1 (Vol. 3), Wisconsin Energy Conservation Corporation, Low-Income Weatherization Program Study, "Technical Findings," October 31, 1984.

[b]An administrative cost of $300/house is included in the figures for the 1985-86 field test.

[c]The savings for the 1985-86 field test include estimated pilot gas savings, but do not incorporate adjustment for control group savings.

Table 4.2. Reportable average audit group savings

	Energy consumption (therms/year)		Energy savings	
	pre-retrofit	post-retrofit	(therms/year)	%
Control group (mean):				
measurable heating energy use	913	918	-5	
Audit group (mean):				
measurable heating energy use	1033	869	164	16[a]
adjusted heating energy savings[b]			169	
estimated pilot gas energy use	38		38	
Total	1071		207	19[c]

[a]The measurable heating energy savings of the audit group divided by the measurable pre-retrofit heating energy use of the audit group.

[b]The measurable heating energy savings of the audit group adjusted using the measurable heating energy savings of the control group.

[c]The total audit group savings divided by the total pre-retrofit heating energy use of the audit group.

shown in Table 4.1, the average savings for the houses receiving a condensing furnace and wall insulation was 345 therms/year and 257 therms/year, respectively, as compared to an average of 12 therms/year saved by the houses receiving only minor retrofits. The variability of the individual house savings and the concentration of the savings in the houses receiving a major retrofit can largely be attributed to the ADRP, which was designed to concentrate retrofits in houses that would most benefit from the retrofits.

5. The average savings achieved by the 20 houses was closely predicted by the audit. As shown in Fig. 4.1, the annual heating energy savings for the entire group of retrofitted houses was approximately 83% of that predicted.

6. On average, the audit accurately predicted savings for condensing furnaces, but overpredicted the savings for wall insulation and the minor retrofits. As shown in Fig. 4.1, the predicted and measured savings for houses receiving the major retrofit of a condensing furnace agreed very well. However, the savings for houses receiving wall insulation as the major retrofit was only about 74% of that predicted. In addition, little savings was predicted for houses receiving only minor retrofits, and no savings was actually measured.

7. The energy savings for individual houses was not predicted accurately by the audit. A comparison of the measured and predicted savings for each of the 20 houses is presented in Fig. 4.2. 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 a condensing furnace had statistically significant discrepancies between predicted and measured savings. Four of the six houses which received wall

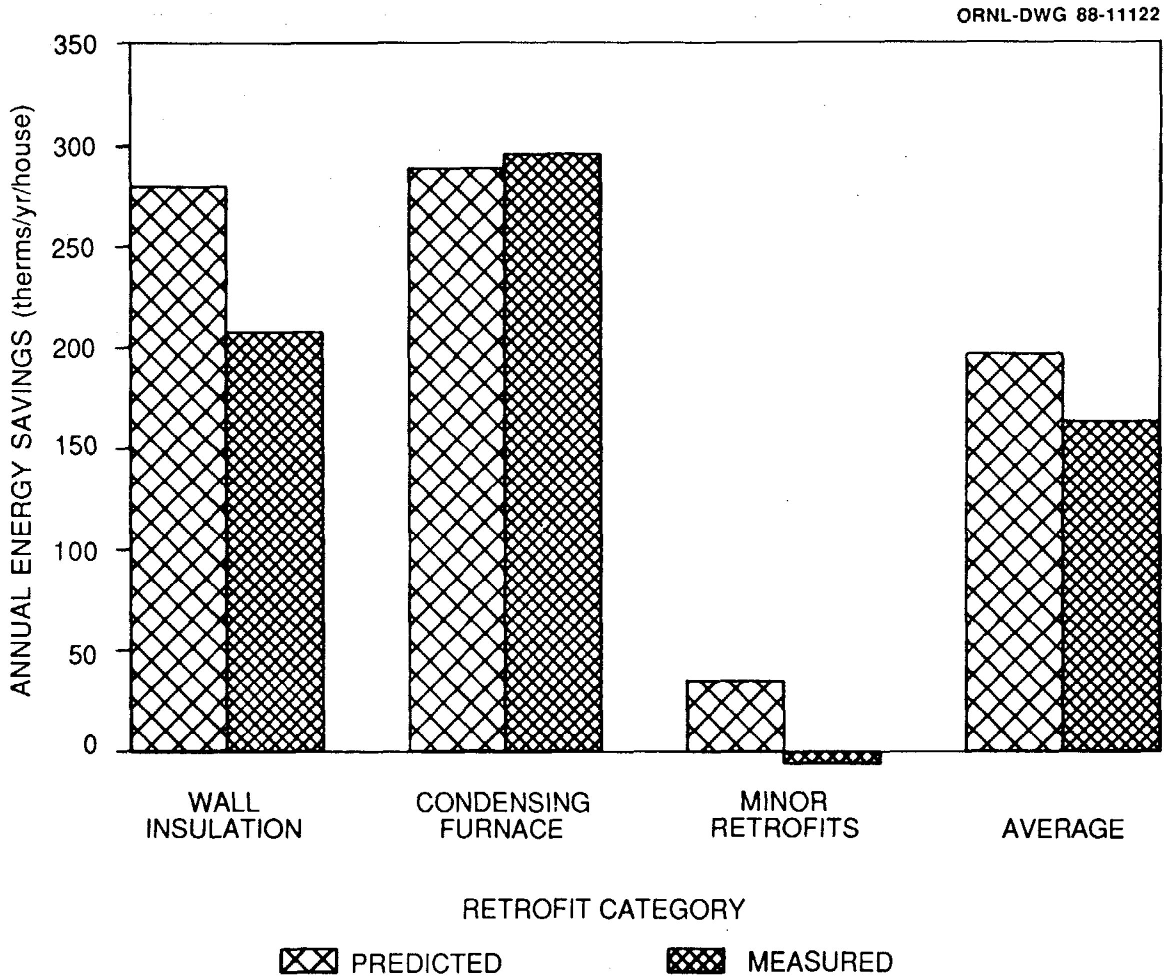

Fig. 4.1. Predicted savings vs measured savings, by predominant retrofit type. (Both the predicted and measured savings do not include pilot gas savings. The measured savings have been adjusted for control group savings.)

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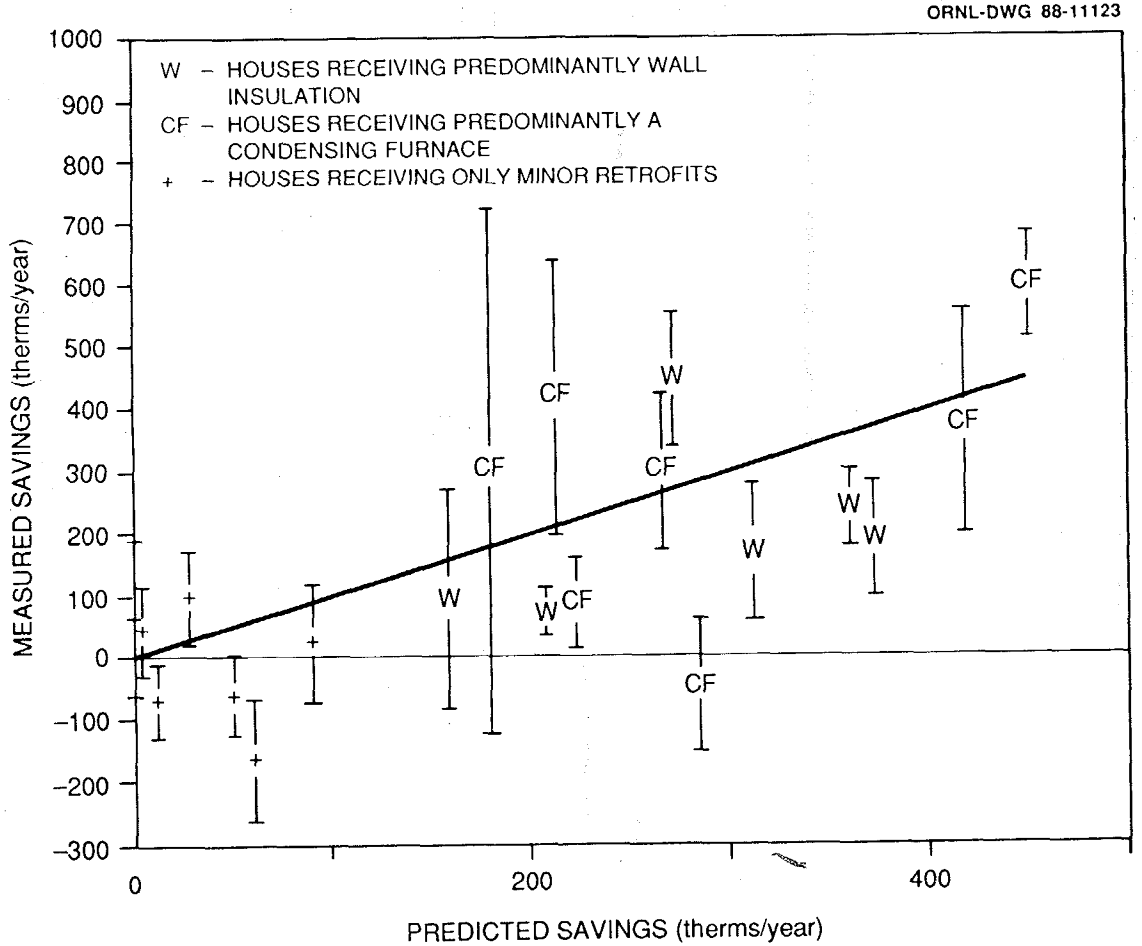

Fig. 4.2. Comparison of predicted and measured savings for individual houses. The vertical lines indicate the 90% confidence intervals of the measured savings. (Both the predicted and measured savings do not include pilot gas savings. The measured savings have not been adjusted for control group savings.)

insulation had measured savings that were statistically different than predicted, with a majority of these having measured savings less than predicted. These discrepancies are likely the result of the audit's failure to account for one or more factors which affect energy savings; a consistent problem may also exist with the wall insulation savings calculations in the audit because of the consistent differences observed.

8. The retrofits selected by the ADRP in the field test were quite different from the retrofits employed in the traditional weatherization program. The traditional program concentrated on ceiling insulation, water heater insulation, infiltration control, and storm windows. In the field test, only four houses received ceiling insulation and none of the 20 houses received storm windows. Water heater insulation was not included in the list of retrofits considered by the audit and, thus, was not installed in the field test.

9. The retrofits included in the expanded list of retrofits were selected for inclusion in the 20 houses at different frequencies by the ADRP. Five retrofits were not installed in any of the houses: secondary condensing heat exchanger, gas power burner, storm windows, storm doors, and floor insulation. The remaining nine retrofits were installed in at least four houses but not more than ten houses.

10. The cost of installing the retrofits in the homes varied depending on the actual retrofits installed. The houses receiving wall insulation as the major retrofit cost $1764/house; the houses receiving a condensing furnace cost $2408/house; and the houses receiving no major retrofits cost $660/house. In each case, these numbers include the costs of various minor retrofits applied to the houses and an administration cost of $300/house.

The administration cost is based upon an average cost of $40/house that occurred in the field test to perform minor house repairs, an estimated cost of $100/house to perform the audit, and an estimated cost of $160/house to perform other administration functions such as outreach, income verification, and record keeping.

11. The overall costs of installing these retrofits were predicted with good accuracy. Total actual costs were less than 5% above total predicted costs, although wider scatter was observed in the cost comparisons of individual houses.

12. The following improvements were identified at the conclusion of the field test that could increase the cost-effectiveness of the ADRP: (a) eliminate the requirement to spend all the money allocated for the group of houses to be retrofitted (such a requirement led to choosing retrofits with B/C ratios less than 1.0 in the field test) or specify that retrofits with a B/C ratio below a minimum value cannot be performed; (b) remove ineffective retrofits from the audit and/or improve the audit predictions and calculations so that ineffective retrofits would not be chosen; (c) reduce or eliminate the installation of minor retrofits by installing retrofits in only those homes that can benefit from a major retrofit or by installing only major retrofits (the savings obtained from minor retrofits are not sufficient to overcome their installation costs plus auditing and administration costs); (d) add additional cost-effective retrofits to the procedure (such as hot water retrofits which were included in the traditional program); and (e) reduce the audit and administration costs.

13. The new test method developed for this project worked well and provided good results. The method principally involved the analysis of weekly submetered heating system fuel consumption

data. The method allowed the field test to be performed in one heating season and included uncertainty analysis which was applied consistently throughout the calculations.

4.2 BLOWER-DOOR-GUIDED INFILTRATION REDUCTION PROCEDURE

The blower-door-guided infiltration reduction procedure was found to be a useful tool to reduce expenditures for infiltration reduction while ensuring that significant air leakage rate reductions are obtained. However, the infiltration reduction work that was performed did not produce, on average, measurable energy savings in the test houses. Specific results from the "blower door" portion of the field test were

1. The blower-door-guided infiltration reduction procedure reduced expenditures (labor plus materials) for infiltration reduction to about one-fourth of that previously required by Wisconsin's WAP. A 1985 study[9] of 50 low-income houses in Wisconsin reported an average infiltration control expenditure of $570/house. The 18 houses in this study were treated for an average of $106/house, which included costs of $13 to $68 to set up the blower door and perform initial testing (the set-up cost depended on travel time and house characteristics). This reduction came about in two ways: (a) the blower door identified houses that already had low infiltration rates, so time and money were not spent providing needless services (see item 3 below), and (b) the procedure limited the expenditures in the individual houses that were retrofitted to values significantly less than that previously spent.

2. The infiltration reduction procedure significantly reduced the average air leakage rate in the treated houses whereas, in the 1985 study,[9] no significant reduction in air leakage rate was

found following the installation of typical infiltration reduction measures. As shown in Table 4.3, the average air leakage rate in the 18 treated houses was reduced from 8.3 to 7.0 ACH50, representing a 16% reduction, despite the fact that the average infiltration rate of the houses was already relatively low.

3. The air leakage rate reductions were, on average, largest in houses recommended for retrofit. Because the reductions of individual houses were quite variable, the potential reduction of a house depends on more than the initial air leakage rate. Of the 18 houses, only seven were recommended to receive infiltration reduction measures (they had an initial air leakage rate greater than 8 ACH50); however, work on seven additional houses was also performed. As shown in Table 4.3, the air leakage rate reductions in the individual homes that were retrofitted ranged from 0.1 to 6.0 ACH50. The average reduction for the seven recommended houses was 2.4 ACH50, while the average reduction for the seven additional retrofitted houses was only 0.9 ACH50. Since no work was performed on the remaining four houses, no reduction occurred in them.

4. The infiltration reduction procedure applied to a group of houses provided an effective guide to the average amount of infiltration reduction that can be achieved and the expense necessary to accomplish the reduction. The average recommended retrofit cost for the 18 houses of the test group was $77, compared with the actual average expenditure of $106. Some of this overexpenditure may be attributed to the cost of performing the initial blower door test, which was not included in the cost estimate. In the seven houses recommended for retrofit, 89% of the targeted air leakage reduction was achieved, and only 76% of the recommended expenditure was required.

Table 4.3. Air leakage rate reductions and retrofit costs

House	Initial air leakage rate (ACH50)	Change in leakage rate: Actual (ACH50)	Change in leakage rate: Actual (%)	Change in leakage rate: Targeted (ACH50)	Cost: Recommended ($)	Cost: Actual ($)
Houses retrofitted as recommended:						
R21	19.5	6.0	31	5.0	256	216
R22	16.8	1.4	8	4.0	291	126
R35	16.2	1.9	12	4.0	129	98
D26	14.7	4.7	32	3.0	218	211
R03	9.2	0.8	9	1.0	94	96
R52	9.0	1.3	14	1.0	88	75
R43	8.6	0.7	8	1.0	49	39
Average	13.4	2.4	18	2.7	161	123
Houses receiving retrofits that were not recommended:						
D04	7.9	3.7	47	0.0	44	301
R07	7.7	0.2	3	0.0	55	50
R01	7.2	1.0	14	0.0	42	60
D41	5.9	0.4	7	0.0	31	186
G27	5.3	0.2	4	0.0	24	88
R06	5.2	0.8	15	0.0	21	92
R39	3.9	0.1	3	0.0	13	92
Average	6.2	0.9	15	0.0	33	124
Houses receiving no retrofits as recommended:						
R31	3.4	0.0	0	0.0	9	63
R04	3.2	0.0	0	0.0	8	13
R27	3.1	0.0	0	0.0	7	25
G01	2.6	0.0	0	0.0	5	68
Average	3.1	0.0	0	0.0	7	42
Overall Average	8.3	1.3	16	1.1	77	106

Note: ACH50 - house air changed per hour at 50 Pascal depressurization.

5. The minimum initial leakage rate of 8 ACH50, below which no retrofit work is advised by the procedure, appears to be an appropriate choice. Although air leakage rate reductions were achieved in houses not recommended for retrofit, these reductions were typically less than those achieved in the recommended houses and required relatively large expenditures per unit of change.

6. Although air leakage rates were reduced using the infiltration reduction procedure, a reduction in the average energy consumption of the treated homes was not observed from an analysis of metered energy use data. Analysis indicated that factors other than the reduction in the air infiltration rate and possible changes in the indoor temperature were influencing the house energy consumptions, making a direct measurement of retrofit savings difficult. Calculation of the expected energy savings using the measured air leakage rate reductions indicated that the average savings would be 37 therms/year for all houses in which infiltration retrofits were performed (or 5% of the average annual heating consumption of the houses).

7. The following improvements were identified at the conclusion of the test that could increase the effectiveness of the procedure: (a) the retrofit crews need to be trained more extensively to ensure stricter adherence to the procedure, and (b) the average cost of establishing the initial leakage rate of the house using a blower door needs to be included in the equation for the recommended expenditure level.

4.3 OCCUPANT BEHAVIOR AND HOUSE THERMAL CHARACTERISTICS STUDY

Indoor temperature changes attributable to the installation of conservation measures were not generally observed. However, consideration of the indoor temperature in the analysis can explain a large portion of the deviation between predicted and measured savings. Specific results from the occupant behavior and house thermal characteristic study were

1. A large portion of the deviation between predicted and measured savings can be attributed to incorrect assumptions used in making the predictions, with other unidentified factors being responsible for the remaining portion of the discrepancy. Knowing the indoor temperature of the houses as well as their measured balance point temperatures (derived from a graphical analysis of heating energy use versus outdoor temperature plots), a value for the measured energy savings of each house was calculated as if the house actually conformed to two main assumptions made in predicting the energy savings (a pre-retrofit balance point temperature of 65°F and a constant indoor temperature). Twenty to 60% of the difference between predicted and measured savings in the houses studied could be accounted for by this type of analysis.

2. Additional results indicate that incorrect assumptions regarding the value of the indoor temperature or balance point may be more prevalent than incorrect assumptions regarding a constant indoor temperature in explaining differences between predicted and measured savings. The indoor temperature in one-third of the 15 homes studied was either warmer or colder than values that might be typically assumed in making energy savings calculations (67 to 73°F). On the other hand, the indoor temperature of the houses was generally steady as the occupants did not typically increase their indoor temperature after retrofit installation (the occupants did not generally display "take back" behavior). Table 4.4 shows that the average change in temperature measured at the thermostat was more than 1°F in only four houses (two of which were only 1.1°F) and that these few houses were evenly distributed among the three groups. Thus, consistent changes in the

Table 4.4. Pre- to post-retrofit thermostat temperature and setpoint changes calculated using daily data

Site no.	House type	Change in temp. at thermostat (°F)	Change in thermostat setpoint (°F)
1	Control	1.1	-0.2
2	Control	2.0	1.4
3	Audit	0.9	-
4	Audit	0.6	-0.9
5	Audit	0.1	-0.6
6	Audit	-0.3	-1.9
7	Audit	-0.2	-0.3
8	Control	0.3	-0.2
9	Blower door	0.6	1.0
10	Blower door	0.7	-1.5
11	Blower door	1.1	1.3
12	Audit	9.0	10.3
13	Audit	-0.7	-1.1
14	Control	-0.9	-0.3
15	Control	0.1	0.0

indoor temperature due to retrofit installation were not observed. In addition, the thermostat management practice used during the post-retrofit period was identical to the practice used during the pre-retrofit period in all 14 houses for which pre- and post-retrofit data were available. This indicated that the management practice was also not affected by a retrofit installation.

3. A single indoor temperature was found to adequately represent the average house temperature in many homes, verifying an assumption made in a monitoring guideline developed by ORNL.[10] The four indoor temperatures monitored in each house were typically within 4°F of each other, indicating that most houses were at a reasonably uniform temperature and might be adequately described by a single temperature measurement (generally, the master bedroom temperature was lower and the kitchen temperature higher). In two-thirds of the houses, the thermostat or living room temperature was found to represent the average house temperature (defined to be the average temperature of the living area, kitchen, and master bedroom weighted using their respective floor area). A typical example is shown in Fig. 4.3.

4. Indoor temperature and thermostat setpoint are distinct parameters such that inferences concerning one cannot be made from the other; thus, both need to be monitored if both are to be studied in an experiment. Average air temperatures at the thermostat were found to be distinctly different from average values of the thermostat setpoint over selected time periods and at different times of the day. However, as indicated in Table 4.4, a change which occurred in one following retrofit installation was not necessarily accompanied by a change in the other.

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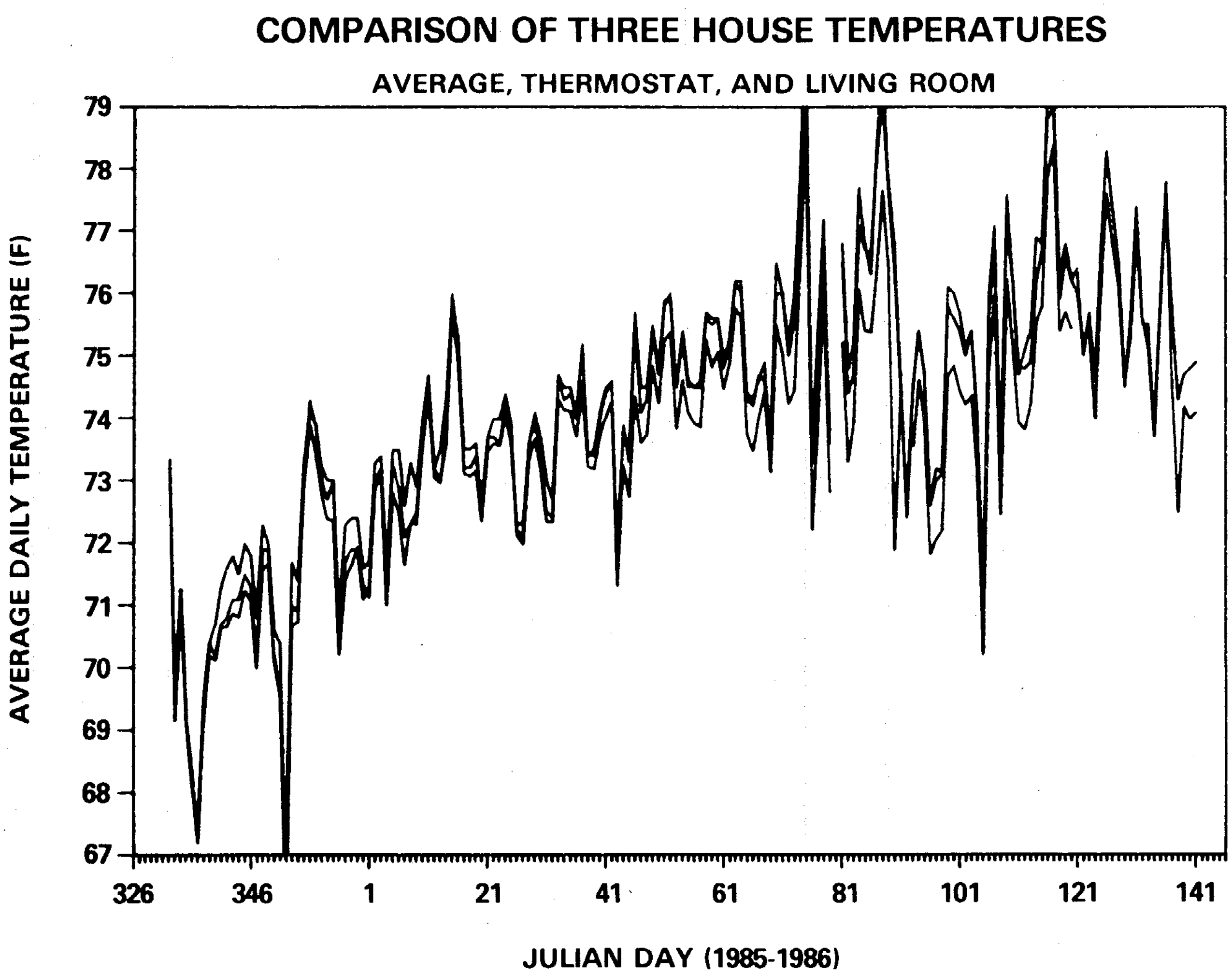

Fig. 4.3. Temperature at the thermostat and in the living room compared with average house temperature.

5. Four different thermostat management practices were observed in the houses: (a) seven households did not adjust their thermostat, (b) four set the thermostat back at night, (c) two set the thermostat back during the day, and (d) one lowered the thermostat at night and during the day, but raised it for a short period in the morning and a slightly longer period in the evening.

6. Occupant's perceptions of their houses' thermal characteristics and comfort, and their change following retrofit installation, were found to be inconsistent with measured data; thus, responses to occupant questionnaires may not provide sufficiently accurate data to be generally useful in audits or analyses to supplement or interpret results. For a given time period, two-thirds of the occupants correctly identified their typical thermostat management practice, but only one-half could accurately provide the average indoor temperature maintained in their house. Furthermore, the occupants could not reliably indicate if a change in indoor temperature or thermostat setpoint had occurred between two time periods. All occupants felt that their comfort had improved following a major retrofit installation, but measured indoor air temperature data did not support their observation. Despite the temperature maintained in the house, the occupants usually wished it could be higher.

5. IMPLICATIONS OF THE FIELD TEST FINDINGS FOR FUTURE SINGLE-FAMILY RETROFIT PROGRAMS

The results reported in the preceding "findings" section are applicable to the four counties in southern Wisconsin and to the kinds of low-income housing stock encountered in the field study. To the extent that the climate or housing stock of some other area differs from that of these four counties, the findings become less and less applicable. The general procedures used in this field test, however, should be useful to managers of most other single-family retrofit programs, regardless of geographic region or house type. The following eight points summarize the implications of the findings of this field test for other similar programs.

1. An audit-directed retrofit procedure, which selects retrofits for houses so as to maximize program benefits, should be seriously considered as an alternative to use of the priority list approach.

2. Heating system retrofits are well worth considering as an addition to the list of retrofit options. The specific mechanical retrofits that should be included for consideration are largely determined by climate. Furnace retrofits and/or replacements are important in northern climates.

3. Although savings due to wall insulation were 74% of that predicted, wall insulation is a useful addition to the envelope retrofit options because of the large energy savings that result.

4. The use of a blower door to evaluate the need to carry out infiltration control work on a house and to locate major leaks efficiently should prove to be a useful technique in most single-family retrofit programs.

5. Monitoring the interior air temperature for a number of houses does offer clues to occupant behaviors that impact the achieved energy savings of retrofits. This process allows better understanding as to how occupants alter energy savings which can lead to improved predictive techniques; it does not change the amount of energy saved. The lack of "take back" behavior in the monitored houses casts doubt on "take back" as the significant cause of the discrepancy between measured and predicted energy savings.

6. Evaluating the performance of a state-run building retrofit program and measuring the impacts of newly-adopted changes in the program procedure should prove to be a cost-effective use of funds. Such evaluative field studies identify what is good in a program and should be retained, and what is not effective and should be dropped. Periodic assessments of retrofit program procedures based upon metered energy consumption data allow for program improvements and provide a firm basis for accounting to public agencies for the wise expenditure of public funds.

7. Low-cost and non-invasive metering techniques are important features of field studies. This project did not devise new hardware, but it did experiment with the use of elapsed-time meters to substitute for a gas meter in measuring furnace fuel use. Low-cost data loggers were also used successfully. Not only do the elapsed-time meters save money, but they also may be installed quickly and inexpensively.

8. With careful planning and with good cooperation among groups, a field test involving both pre-retrofit and post-retrofit metering can be carried out in a single heating season, depending on the research goals of the experiment. Planning and coordination is difficult to achieve, and the time and financial support for these functions should be recognized in scheduling the program.

In summary, the planning and implementation of a field test evaluation of building retrofits require foresight, cooperation, and patience as different groups attempt to coordinate varied inputs to the project. It also requires money. The results, however, are well worth the effort, because the program becomes much more efficient in delivering effective energy conservation retrofits to low-income households.

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