ORNL/CON-228/P5

OAK RIDGE NATIONAL LABORATORY

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Field Test Evaluation of Conservation Retrofits of Low-Income, Single-Family Buildings in Wisconsin: Blower-Door-Directed Infiltration Reduction Procedure, Field Test Implementation and Results

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

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A05 Microfiche A01

ORNL/CON-228/P5

Energy Division

FIELD TEST EVALUATION OF CONSERVATION RETROFITS OF LOW-INCOME, SINGLE-FAMILY BUILDINGS IN WISCONSIN: BLOWER-DOOR-DIRECTED INFILTRATION REDUCTION PROCEDURE, FIELD TEST IMPLEMENTATION AND RESULTS

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Date Published - June 1988

Building Energy Retrofit Research Program

Prepared for the
U.S. Department of Energy
Office of Buildings and Community Systems

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
Operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract No. DE-AC05-84OR21400

Reports in This Series

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ABSTRACT

A blower-door-directed infiltration retrofit procedure was field tested on 18 homes in south central Wisconsin. The procedure, developed by the Wisconsin Energy Conservation Corporation, includes recommended retrofit techniques as well as criteria for estimating the amount of cost-effective work to be performed on a house. A recommended expenditure level and target air leakage reduction, in air changes per hour at 50 pascal (ACH50), are determined from the initial leakage rate measured.

The procedure produced an average 16% reduction in air leakage rate. For the 7 houses recommended for retrofit, 89% of the targeted reductions were accomplished with 76% of the recommended expenditures. The average cost of retrofits per house was reduced by a factor of four compared with previous programs. The average payback period for recommended retrofits was 4.4 years, based on predicted energy savings computed from achieved air leakage reductions. Although exceptions occurred, the procedure's 8 ACH50 minimum initial leakage rate for advising retrofits to be performed appeared a good choice, based on cost-effective air leakage reduction. Houses with initial rates of 7 ACH50 or below consistently required substantially higher costs to achieve significant air leakage reductions.

No statistically significant average annual energy savings was detected as a result of the infiltration retrofits. Average measured savings were -27 therm per year, indicating an increase in energy use, with a 90% confidence interval of 36 therm. Measured savings for individual houses varied widely in both positive and negative directions, indicating that factors not considered affected the results. Large individual confidence intervals indicate a need to increase the accuracy of such measurements as well as understand the factors which may cause such disparity.

Recommendations for the procedure include more extensive training of retrofit crews, checks for minimum air exchange rates to insure air quality, and addition of the basic cost of determining the initial leakage rate to the recommended expenditure level. Recommendations for the field test of the procedure include increasing the number of houses in the sample, more timely examination of metered data to detect anomalies, and the monitoring of indoor air temperature. Though not appropriate in a field test of a procedure, further investigation into the effects of air leakage rate reductions on heating loads needs to be performed.

EXECUTIVE SUMMARY

Infiltration reduction has played a key role in the Department of Energy's Low-Income Weatherization Assistance Program (WAP). Standard infiltration retrofit techniques often include routine caulking or weatherstripping of doors and windows. Frequently, application of these techniques does not produce expected energy savings or results in work on houses not requiring infiltration reduction. The Wisconsin Energy Conservation Corporation (WECC) developed an infiltration retrofit procedure which attempts to increase the efficiency of retrofits not only through the use of a blower door to locate and repair house leaks, but also through prescribing how much infiltration work is cost effective.

This paper describes WECC's infiltration retrofit procedure and a field test of the procedure performed on a sample of south central Wisconsin homes during the winter of 1985-86.

INFILTRATION RETROFIT PROCEDURE

The blower-door-directed infiltration retrofit procedure was developed by WECC based on their experience with blower doors. Retrofit crews examine a house for any evidence of moisture problems, which may indicate that a house is already too tight. A blower door is installed to depressurize the house and an air leakage rate in air changes per hour is measured at an indoor-outdoor pressure differential of 50 pascal (ACH50).

A recommended expenditure level for labor and materials is determined by the equation

$$\text{Expense}[\$] = (\text{ACH50})^2 \times [\text{House Area}(\text{ft}^2)] / 1400.$$

This is normally translated to an approximate number of man-hours through division by an assumed rate, $20/hour for the Wisconsin field study, including labor and materials.

A second criterion is established by setting an air leakage reduction target, in ACH50. For houses with initial air leakage rates of 8 ACH50 and below, no retrofits are recommended, other than those which would affect comfort. For every two or three ACH50 the initial rate is above 8 ACH50, the targeted reduction increases by one ACH50 to a maximum of 5 ACH50 for houses with initial rates above 18 ACH50.

Crews attempt to create a balance between these two guidelines with appropriate deviations for houses showing abnormal characteristics. They are given suggested techniques in locating and repairing the major air leaks in a house. However, the crew decides which measures are implemented. A final air leakage rate is determined after all retrofits have been performed.

THE FIELD TEST

The field test was implemented to evaluate the effectiveness of the infiltration retrofit procedure.

Houses selected for the test had to qualify for WAP assistance in Wisconsin as well as provide opportunity to accurately demonstrate the procedure's potential. Screening criteria included (1) the owner's income was below 125% of the poverty level, (2) the home was single-family detached, excluding mobile homes, not previously retrofitted within the last five years, (3) occupied by current owner for at least one year previous to study with no extended absences during the test, (4) used natural gas heat with minimal secondary heating, and (5) the occupants were willing to participate.

Initially, 40 homes for each of the control and blower door test groups were planned. Scheduling and attrition resulted in only 18 homes available for the test group after the pre-retrofit monitoring period. Of the 18, only 11 remained having acceptable data by the end of the test. Although 40 homes were initially assigned to the control group, only 28 remained by the end of the test. All homes were located in south central Wisconsin.

Homes were metered for whole-house gas and electric use as well as furnace run time. The furnace was calibrated for consumption rate versus run time. Pre-retrofit data collection occurred primarily from October, 1985, into

January, 1986. The retrofits were installed by local weatherization crews during the month of January and early February, 1986. A WECC member accompanied each crew on their first visit to demonstrate procedures and answer questions. Post-retrofit data collection occurred from February into early May, 1986. Weekly meter readings were planned, but varying intervals were common.

The Wisconsin Automated Agricultural Data Network, operated by the Wisconsin State Climatologist, and the National Oceanic and Atmospheric Administration (NOAA) provided hourly ambient temperatures from four locations judged sufficiently close to the test homes to provide accurate estimates at their locations.

RESULTS

The data analyses and results can be divided into four areas: (1) the air leakage rate reductions attained by the retrofits, the retrofit costs, and a predicted dollar savings based on the air leakage reductions, (2) a measured energy savings based on the metered furnace run time and normalized to an average Madison winter, (3) a comparison of predicted and measured energy savings, and (4) average savings of the control and test groups.

The 1.3 ACH50 average reduction in air leakage rate achieved by the retrofits represents a 16% decrease. The average recommended retrofit cost for the 18 houses of the test group was $77, compared with the actual average expenditure of $106 per house. Some of this over-expenditure may be attributed to the cost of performing the blower door tests, necessary whether or not retrofits were implemented. Regardless, even the $124 average cost for the 14 houses actually retrofitted is less than a fourth the $570 average cost reported for earlier implementation of Wisconsin infiltration retrofit procedures.

The retrofit crews performed work on seven more houses than the air leakage reduction target guideline of the procedure recommended. Considering only those houses where this guideline recommended work be performed, the actual expenditures were only 76% of the recommended cost, while accomplishing 89% of the targeted leakage rate reductions. Thus, strictly followed, the procedure predicts fairly well the average air leakage reduction potential and its cost, although individual exceptions were observed.

The predicted heating fuel savings, computed from the air leakage rate reductions actually attained, averaged 37 therms per year for all houses in which infiltration retrofits were performed. This represents five percent of the average annual heating consumption for the houses. Based on the predicted fuel savings, the average payback period for those retrofits recommended by the procedure guidelines was 4.4 years. This value increases to 10.6 years when all homes actually retrofitted are considered. Examining individual results shows a boundary at initial leakage rates between 7.0 and 8.0 ACH50 below which payback periods jump higher. Thus, the procedure's 8 ACH50 minimum initial leakage rate for advising retrofits be performed appears a good choice. Exceptions which occurred demonstrate that for any given house, the leakage rate reduction potential depends on more than a home's initial rate.

Despite the substantial reductions in air leakage rates accomplished, no statistically significant average energy savings were measured. The measured heating energy savings for individual houses, based on furnace run time and normalized to an average Madison winter, vary widely in both positive and negative directions. A substantial number of the savings are negative, producing a -27 therm per year average for all 11 houses having acceptable quality data throughout the test. Considering only the seven of these 11 on which retrofits were actually performed, the average measured savings was -2 therm per year. Negative values signify an increase in energy use following the retrofit.

Confidence intervals provide a statistic upon which to judge the significance of a value relative to its possible error. The 90% confidence interval defines a range above and below a given value in which the actual value has a 90% chance of lying. The 90% confidence interval corresponding to the annual -2 therm average savings for retrofitted houses is 48 therm, implying no significance to the value. However, comparison of the individual measured results with their corresponding confidence intervals indicates that factors other than the precision of the metering devices and the scatter of the data are likely affecting the results.

Factors potentially affecting the measured savings and its statistical significance include solar and internal loads, massive effects of the building components and surrounding earth, seasonal variation in wind speed and direction, and differences in pre- and post-retrofit average interior air temperatures. Some evidence exists for the biasing of the results by the latter factor, although not to a sufficient degree to explain the overall lack of measured savings.

Comparison of the predicted and measured results shows poor agreement, reflecting those difficulties with the latter already mentioned. The predicted results use a degree day calculation with fixed base, or balance point, and the leakage rate reductions found from use of the blower door. An alternate prediction using balance points determined from the measured data shows better correlation with the measured savings. Thus, a significant portion of the original difference between predicted and measured results lies in an incorrect conversion of leakage rate reductions to reductions in furnace loads. Factors previously mentioned as affecting the measured savings also affect this conversion.

The control group of 28 houses had an average energy savings of -5 therm from pre- to post-retrofit periods, with a 90% confidence interval of 44 therm. Thus, the value is indistinguishable from zero, as it should be for the control group having had no retrofits. This compares with the -2 therm change in energy use with 48 therm confidence interval for the retrofitted houses of the test group. Thus, the control and test groups show no statistical difference in energy consumption.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study of the blower-door-directed infiltration retrofit procedure field test are as follows:

1. The procedure provides an effective guide in estimating the average air leakage reduction that can be achieved in a group of houses and the average cost of the work.

The average leakage rate was reduced by 16%, representing 89% of the targeted reduction. These reductions were accomplished for 76% of the recommended cost.

2. The average cost of retrofits per house, $124, is less than a fourth the $570 average cost for a previous program.

3. The air leakage reductions accomplished in this field test produced no measurable, statistically significant energy savings. Factors other than those examined in this study contributed substantial uncertainty to the results which may have masked or biased the expected savings.

4. The minimum initial leakage rate of 8 ACH50, below which no retrofit work is advised by the procedure, appears to be an appropriate choice, based on leakage reductions achieved.

5. Whether significant air leakage reduction can be accomplished in any given house depends on more than the initial rate. Crew training and house characteristics appear important.

6. Additional research is needed to reduce the uncertainty in the energy measurements and to identify the factors which prevent the expected energy savings from being consistently realized.

Recommendations for the procedure and its field test include:

1. More extensive training of the retrofit crews in implementing the procedure and identifying and repairing leakage sites.

2. Inclusion of checks for minimum air exchange rates to guarantee air quality.

3. Consideration of the cost for initial air leakage rate determination in the recommended expenditure level equation.

4. Increase sample size with particular attention to expected attrition of homes.

5. Timely inspection of data to provide early detection of anomalies.

6. Measurement of indoor air temperature and use of indoor-ambient temperature difference in computation of measured savings.

1. INTRODUCTION

Events of the last several decades have increased a general awareness that conventional energy resources may be limited. As energy prices rose in response to this realization, the ability for low-income families to pay for their basic energy needs became a serious concern. Federal and local agencies evolved to provide needed services.

One way of reducing a family's energy expenses is to provide assistance in weatherizing their home to reduce the need for heating and cooling energy. Infiltration reduction has played a key role in the Department of Energy's (DOE's) Low-Income Weatherization Assistance Program (WAP). However, questions regarding the effectiveness of current infiltration retrofit practices have arisen.

Frequently, expected energy savings are not achieved or work is performed on houses not requiring reduction in infiltration. A Wisconsin Energy Conservation Corporation (WECC) study (Hewitt, 1984) revealed that 35% of retrofit funds from Wisconsin's Low-Income Energy Assistance Program (LIEAP) went toward infiltration retrofits. However, many retrofitted homes were still found to have major infiltration problems. A University of Wisconsin study (Kanarek, 1985) of 50 low-income homes showed no significant reduction in air change rates following retrofits which included air infiltration reduction.

Standard infiltration retrofit procedures often include routine caulking or weatherstripping of doors and windows. These areas may not be the major contributors to a home's infiltration problems. Other areas, such as walls, ceilings, attic accesses, fireplaces, or electrical outlets, may also need attention. A blower door is a device which either pressurizes or depressurizes a house to aid in locating leaks and allow a measure of a house's leakiness. Proper use of the blower door greatly facilitates the identification and repair of significant infiltration leaks within a home.

WECC subsequently developed an infiltration retrofit procedure utilizing the blower door. Major house leaks are repaired while the blower door is in place, permitting tracking of the home's air leakage rate during retrofit. The procedure also includes guidelines as to how much infiltration work should be performed, based on the initial leakiness of the house and the funds available for the work.

The DOE Office of Buildings and Community Systems' (OBCS) Building Energy Retrofit Research Program commissioned the Oak Ridge National Laboratory (ORNL) to develop a mechanism by which the entire retrofit procedure could be made more efficient. The need to field test both ORNL's audit program and Wisconsin's blower door infiltration retrofit procedure prompted a joint project to provide evidence as to the effectiveness of these new methods. Funding was supplied by DOE's OBCS, WAP, Wisconsin's Department of Health and Social Services (DHSS), and three Wisconsin utility companies. For additional information of agency responsibilities and interests in the project, see ORNL/CON-228/P1. This report details the investigation of the blower door segment of the project. Information on the whole-house audit may be found in ORNL/CON-228/P2 and ORNL/CON-228/P3.

The primary objectives of the blower door study are to assist in the development of the blower door retrofit procedure, demonstrate techniques of determining the air leakage reduction and subsequent energy savings resulting from the retrofit, and investigate the cost effectiveness of the technique. This report will describe the procedure as implemented in the field test, examine a method of data analysis which quantifies the resulting energy savings and its uncertainty, investigate the cost effectiveness of the technique, and offer further suggestions on how the technique might be improved.

2. INFILTRATION RETROFIT PROCEDURE

The blower-door-directed infiltration retrofit procedure described in this study was developed by WECC based on their experience with blower doors and that of several private contractors and local utilities. It attempts to increase the efficiency of infiltration retrofits not only through the use of a blower door to locate and repair house leaks, but also through prescribing how much infiltration retrofit work is cost effective.

Blower doors were developed in the mid-1970's as a means to quantify the leakiness of a house. A fan is mounted into the envelope of a structure, normally a door (see Fig. 2.1). Varying the speed of the fan varies the indoor-outdoor pressure differential established. Both this pressure differential and the air flow rate through the fan are measured. The air flow rate through the fan must equal the air leakage rate from the house at the pressure differential measured. Division of this volumetric flow rate by the house volume gives the number of air changes per unit of time at the pressure differential. This value, in air changes per hour at 50 pascal depressurization, ACH50, is used in this study to compare air leakage rates before and after the retrofits.

A retrofit crew first walks through a house ensuring that interior doors are open and exterior doors and windows are closed and looking for any indications of moisture problems. High humidity in a house having no abnormal sources of interior water vapor may be an indication that the house is already too tight. Further reduction in infiltration would only worsen the moisture problem. The blower door is installed and readings of the house leakiness in air changes per hour are determined at 50 pascal of depressurization. This measure of leakiness is used by two guidelines in estimating a level of effort for infiltration retrofit work to be performed in the house.

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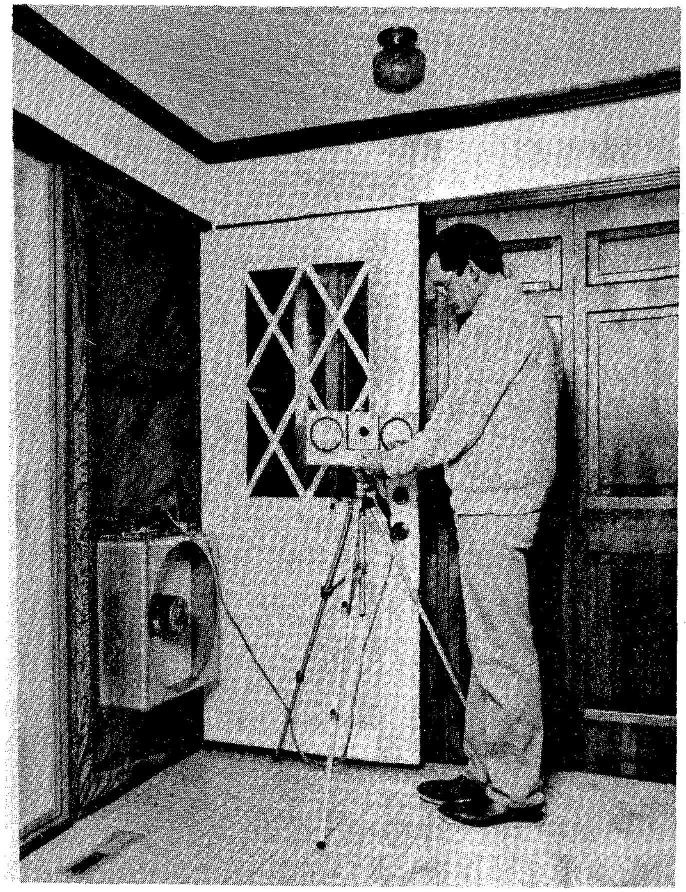

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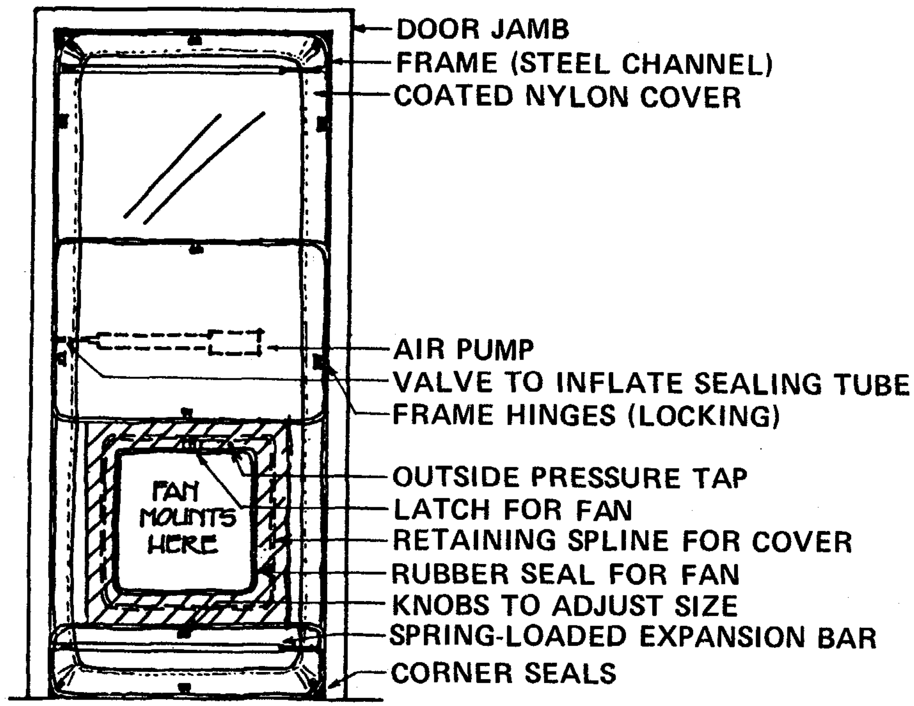

Fig. 2.1. Picture and diagram of a blower door.

A recommended expenditure level for labor and materials is determined by the equation*

$$\text{Expense}(\$) = (\text{ACH50})^2 \times [\text{House Area}(\text{ft}^2)] / 1400.$$

This is normally translated to an approximate number of man-hours through division by an assumed rate, $20/hour for the Wisconsin field study, which includes labor and materials. Figure 2.2 plots this expenditure level against the pre-retrofit ACH50 for three different size houses.

A second guideline is established by setting an air leakage reduction target, in ACH50. Table 2.1 lists the desired reduction in air leakage rate based on the initial level measured by the blower door.

Crews attempt to create a balance between these two guidelines with appropriate alterations for houses showing abnormal characteristics. The guidelines were developed for the "average" house, allowing auditors to characterize the relative ease with which individual houses could be retrofitted. Initial attempts to seal some houses could meet with such little success that further work would be discontinued before reaching either the target leakage reduction or the recommended expenditure level. On the other hand, if air leakage reduction beyond the target could be obtained relatively easily, work beyond the recommended expenditure level might be performed.

Although the retrofit crew decides on the measures to be implemented, the following suggestions were given to assist them:

1. Fix the largest and least expensive leaks first.
2. Use the blower door in conjunction with smoke sticks or feel to detect many leaks.
3. Pressurize the house to 50 pascal, enter attic, closing access afterward, and detect leaks around electrical fixtures or plumbing and stack penetrations.

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*More recent application of the infiltration retrofit procedure in Wisconsin uses a variation of this equation:

$$\text{Expense}[\$] = (\text{ACH50})^2 \times [\text{House Volume}(\text{ft}^3)] / 20{,}000 + \text{Setup Costs}.$$

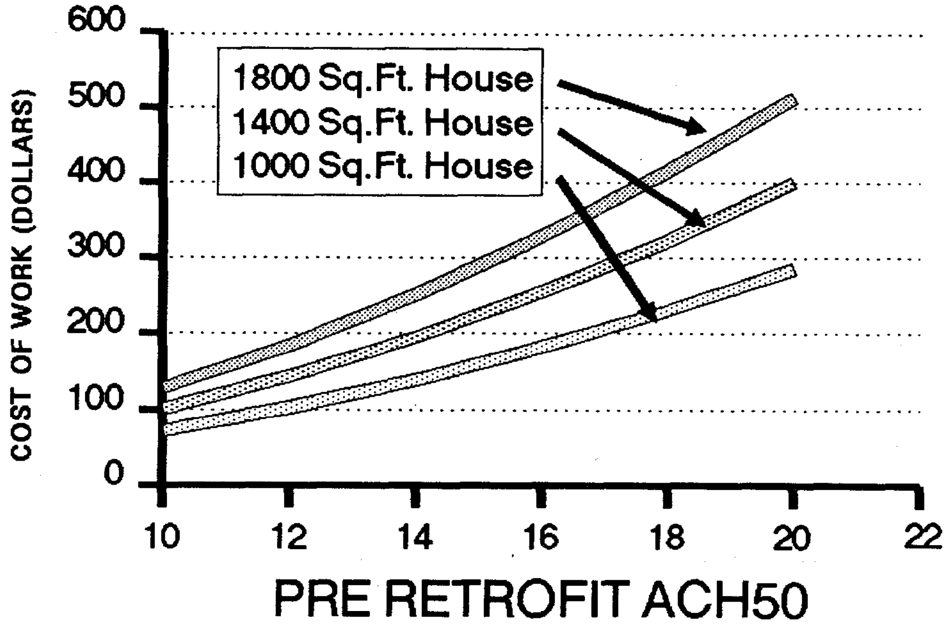

Fig. 2.2. Recommended expenditure levels, Guideline 1.

Table 2.1. ACH50 reduction targets, Guideline 2.

Pre-Retrofit ACH50	ACH50 Reduction Target
8 or less	Seal leaks that affect comfort
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

4. An individual room may be checked for leaks by depressurizing the house, then feeling for drafts through the room's door left open only a crack, while other room doors are shut (except any leading to the blower door).
5. Weatherstripping windows and replacing window lock sets is generally less effective than weatherstripping door and attic access areas.
6. Leaks may be fixed with caulk, polyethylene, tape, foil-faced fiberglass, or other stuffage.
7. Generally, leaks should be fixed with blower door off, then checked afterward with blower door operating.

A final air leakage rate is determined after all retrofits have been performed.

3. THE FIELD TEST

The field test was implemented to evaluate the effectiveness of the infiltration retrofit procedure. Houses selected for the test had to ensure eligibility in the WAP program in Wisconsin as well as provide the opportunity to accurately demonstrate the procedure's potential. Sufficient data needed to be collected to allow measures of effectiveness to be determined without adding unreasonable cost to the project.

3.1 HOUSE SELECTION

Houses selected for the field test of the retrofit procedure were required to meet the following eligibility criteria:

1. The house was eligible for the Weatherization Assistance Program, i.e., the owner's income was less than 125% of poverty level and the home was not retrofitted by DOE or local utility within the last five years.

2. The home was single family, detached, excluding mobile homes.

3. The owner had occupied the home for at least one year previously and had not expected an extended absence during the test.

4. The home utilized natural gas heat with minimal secondary heating devices.

5. The occupants were willing to participate.

The first criterion was to ensure the study was relevant to the WAP program. The remaining conditions were implemented to help guarantee the quality of the data collected in its ability to reflect actual energy savings.

Initially, 40 homes for each of the control and blower test groups were planned. However, scheduling permitted sufficient homes to allow only 28 to be assigned to the test group. Attrition, due to eligibility requirements, reduced this number to 18 after the pre-retrofit monitoring period. Of the 18, only 11 remained having acceptable data by the end of the test. Forty homes were initially assigned to the control group, but attrition resulted in 28 acceptable homes in this group by the end of the test. All homes were located in South Central Wisconsin. (See Appendix A for additional location and attrition information.) Homes in each group were chosen randomly from the entire set of eligible homes.

3.2 INSTRUMENTATION AND DATA COLLECTION

Homes were metered for whole-house gas and electric use as well as furnace run time. The furnace was calibrated for consumption rate versus run time by recording the time required for the gas utility meter to show a specified gas usage while the furnace was on and all other gas appliances off. Even though all other gas appliances were turned off when the calibration occurred, their pilot lights remained on, contributing some error. Estimates of the accuracy of obtaining the heating energy consumption rate in this manner are to within 3-5%.

The instrumentation was installed at the beginning of the pre-retrofit metering period, mostly by WECC personnel. Pre-retrofit data collection occurred primarily from October, 1985, into January, 1986. The retrofits were installed during the month of January and early February, 1986. Post-retrofit data collection occurred from February into early May, 1986. Weekly meter readings were planned, but varying intervals were common.

Following the pre-retrofit data collection period, local weatherization crews entered each house with no prior knowledge of its condition. A WECC member accompanied each crew on their first visit to demonstrate procedures and answer any questions. This constituted the only instructions given to the crews. Results of the field test indicate that more training may have been necessary. Each crew did have at least one member with former exposure to blower door techniques. Crews performed the prescribed infiltration retrofit procedure, recording the pre- and post-retrofit air leakage rates. Appendix B summarizes the retrofits performed on each house. No correlation between the type of retrofits implemented and the magnitude of leakage rate reduction is apparent.

No single blower door assembly was used in all air change rate measurements. Three manufacturers' equipment was used: Minneapolis Blower Door, Retrotech, and Infiltech. Each have their own characteristic method of determining the pressure differential across the blower and the air flow rate through it. However, all were required to be factory calibrated.

The Wisconsin Automated Agricultural Data Network, operated by the Wisconsin State Climatologist, and the National Oceanic and Atmospheric Administration (NOAA) provided hourly ambient temperatures from four locations judged sufficiently close to the test homes to provide accurate estimates at their locations.

4. DATA ANALYSES

The data analyses described in this section are divided into four areas: (1) leakage rate reductions, retrofit costs, and predicted savings, (2) measured savings, (3) comparison of predicted and measured savings, and (4) average savings of the control and test groups.

The pre- and post-retrofit air leakage rates are used in a simple equation employing the heating degree day method to estimate the fuel cost savings which might result from each retrofit. Appendix C gives greater detail on the method for determining these predicted results. Knowledge of the retrofit costs then allows a determination of a simple payback period. The actual changes in air leakage rates and retrofit costs are also compared with those prescribed by the blower-door-directed infiltration retrofit procedure.

The second area of data analyses employs the metered furnace run times from each house to compute an annual heating savings for an average Madison, Wisconsin winter. Since the pre- and post-retrofit time periods were not the same, the difference in pre- and post-retrofit heating energy use cannot be used directly for an estimate of savings.

The furnace calibrations are used to convert the recorded furnace run times into weekly heating fuel consumptions. Pre- and post-retrofit linear regressions of heating fuel consumption versus outdoor temperature are computed from these weekly fuel consumptions and corresonding weekly average ambient temperatures. Thirty-six year average weather data from Madison, Wisconsin are then used with the regressions to compute annual house fuel consumptions for an average Wisconsin winter. The difference between these pre- and post-retrofit normalized annual heating consumptions, NAHC's, form the basis of determining the effectiveness of the retrofits.

Statistical determination of the confidence intervals resulting from the regressions and normalization of the data is provided to allow comment on the statistical significance of any computed savings. Appendix D contains the equations used to determine the normalized savings and the statistical measures associated with them. Appendix E approximates what effect variations in average indoor setpoint temperature have on the measured savings. Appendix F examines the measured data to determine pre- and post-retrofit house balance points and the relation they have to the measured savings.

A third area of analyses compares the savings predicted by the air leakage rate reductions to those computed from the pre- and post-retrofit metered furnace run times, values described in the first two areas of data analyses discussed above. An alternative method of predicting the savings from the air leakage rate reductions is introduced in Appendix G to provide some insight into the discrepancy between these predicted results and those measured.

In the fourth area of analyses, statistics relating to the infiltration retrofitted houses and control houses as two individual groups are examined. Here, means and deviations from the means are discussed.

5. RESULTS

The following discussion of the results for the infiltration retrofit procedure field test is divided into the four areas of data analyses discussed in the previous section: (1) the air leakage rate reductions accomplished by the retrofits, as measured by the blower door tests, the retrofit costs, and predicted savings based on the air leakage reduction; (2) the measured savings based on the metered furnace run times, normalized to an average Madison winter; (3) a comparison of the predicted and measured savings; and (4) average savings with deviations about the means for the test and control groups of houses.

5.1 AIR LEAKAGE RATE REDUCTIONS AND RETROFIT COSTS

Table 5.1 lists the 18 houses originally eligible for the blower door retrofits. Information relating to the retrofits is listed in the numbered columns and will be discussed below. Column (1) is a house designation whose form has no significance for this report. The three averages given at the bottom of this table are for all 18 houses; those actually retrofitted, the first 14 in the table; and those for which retrofits were recommended by the procedure, the first seven entries.

Column (2) gives the initial measured ACH50. The houses are listed in order of decreasing initial air leakage. Column (3) lists the change in ACH50 achieved by the retrofit and column (4) the percentage reduction. Column (5) lists the targeted air leakage rate reduction as prescribed by the blower-door-directed infiltration retrofit procedure.

Column (6) lists the recommended labor plus materials cost for each house, also from the procedure. In comparison, column (7) gives the actual cost of the visit to the house, including labor and materials. Column (8) lists the cost of the retrofit, labor and materials, per ACH50 reduction, i.e., column (7) divided by column (3).

Table 5.1. Air leakage rate reductions, retrofit costs, and predicted dollar savings.

HOUSE (1)	INIT ACH50 (2)	DELTA ACH50 (3)	% CHANGE (4)	TARG DELTA ACH50 (5)	RECM COST $ (6)	ACTL COST $ (7)	$/ ACH50 (8)	PRED SAVINGS $/YR (9)	YRS PAYBACK (10)
R21	19.5	6.0	31	5.0	256	216	36	78	2.8
R22	16.8	1.4	8	4.0	291	126	90	26	4.8
R35	16.2	1.9	12	4.0	129	98	52	22	4.4
D26	14.7	4.7	32	3.0	218	211	45	57	3.7
R03	9.2	0.8	9	1.0	94	96	119	18	5.4
R52	9.0	1.3	14	1.0	88	75	60	26	2.9
R43	8.6	0.7	8	1.0	49	39	59	5	6.9
D04	7.9	3.7	47	0.0	44	301	80	56	5.4
R07	7.7	0.2	3	0.0	55	50	238	4	14.8
R01	7.2	1.0	14	0.0	42	60	62	19	3.1
D41	5.9	0.4	7	0.0	31	186	477	9	21.7
G27	5.3	0.2	4	0.0	24	88	518	4	21.3
R06	5.2	0.8	15	0.0	21	92	111	16	6.0
R39	3.9	0.1	3	0.0	13	92	1022	2	44.9
R31	3.4	0.0	0	0.0	9	63	-	0	-
R04	3.2	0.0	0	0.0	8	13	-	0	-
R27	3.1	0.0	0	0.0	7	25	-	0	-
G01	2.6	0.0	0	0.0	5	68	-	0	-
AVERAGES									
ALL	8.3	1.3	16	1.1	77	106	-	19	-
RETROF	9.8	1.7	17	1.4	97	124	212	24	10.6
RECM RETROF	13.4	2.4	18	2.7	161	123	66	33	4.4

Column (9) lists the predicted annual savings in heating fuel for the home owner, resulting from the retrofits. The values are based on the air leakage rate reductions actually achieved and assume a 75% efficient furnace and a fuel price of $8/MMBtu. (See Appendix C for the defining equation.) These values are used with the retrofit costs of column (7) to compute the simple payback period of column (10).

ASHRAE (ASHRAE, 1985, p.22.7) lists typical leakage rates as falling between 6 and 10 ACH50, with the tighter Swedish homes averaging as low as 3 ACH50. In comparison, the average pre-retrofit leakage rates for the homes within this study was 8.3 ACH50. Twenty-two percent of the homes had pre-retrofit leakage rates above the ASHRAE typical values and 44% below. Thus, the homes studied provided a wide range of initial leakage rates though somewhat skewed to the lower rates.

A house having too little infiltration or ventilation can have problems with air quality or moisture. The minimum outdoor air supply rate from ASHRAE Ventilation Standard 62-1981 is 5 cfm/person for sedentary activity. Assuming 4 persons per dwelling and a conversion of 1 ACH50 to 0.05 air changes per hour at normal conditions, the minimum leakage rates for all test houses fall well below any measured rates, either before or after the infiltration retrofits. The majority of minimum rates are 1.5 ACH50 or below. Thus, the houses in this study were not in danger of being made too tight as a result of the work performed on them.*

Fourteen of the 18 blower door houses were actually retrofitted, even though the procedure guidelines dictated that only seven needed work performed on them. Only brief descriptions of the work performed on specific houses exists (see Appendix B). There is no account of the reasoning used by the retrofit crews regarding their decisions to perform the work. The retrofit of

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*More recent application of the infiltration retrofit procedure in Wisconsin uses the ASHRAE Ventilation Standard to compute the minimum ventilation rate for a house to ensure that retrofits do not violate the standard.

homes with pre-retrofit air leakage below 8 ACH50 is likely a result of suggestions allowing such work if it could be performed easily. However, in several instances crews appear to have ignored the recommended expenditure level or misjudged the expense of the retrofits. Retrofits for house D04 cost an estimated $301 while guidelines dictated no work be performed. However, the leakage rate was reduced 47%. On the other hand, $186 was spent on house D41 when none was recommended, and only a 7% reduction was accomplished.

Conversely, houses R22 and R35 had the second and third highest initial air leakage rates yet underspent their budgets without arriving at the target reductions. Here, the crew found progression toward the target so slow, they abandoned attempts early. It is questionable whether the crews were actually locating major leaks via the blower door, or simply falling back to former experience of weatherstripping and caulking. It would be expected that major attic bypasses be common in such housing, yet crews only found and sealed such sources of infiltration in one house. It is concluded that whether significant air leakage reduction is possible depends on more than a home's initial rate. The training of the retrofit crew and the house characteristics also undoubtedly play important roles.

The 18 homes in the field test showed an average 16% reduction in air leakage rate. The average recommended cost was $77 per house, while the actual cost was $106 per house. Some of this over-expenditure may be attributed to the cost of performing the blower door tests, necessary whether retrofits were implemented or not. These costs ranged from $13 to $68 per house. If the median of these values, $40, is taken as the minimum recommended expenditure, the average recommended value for all 18 houses increases to $88. The formula for the recommended expenditure level does not take this and other administrative costs into account. Provision for such should be made. If the infiltration retrofit procedure were used in conjunction with a whole house weatherization program, the overhead cost of administration and transportation would be shared with other retrofit procedures. Even with the added cost of the blower door tests, the actual costs per house were less than a fourth of the $570 average cost per retrofit typically spent in Wisconsin (Hewitt, 1984). Thus, the procedure does demonstrate significant improved efficiency over past infiltration retrofit programs.

Considering only those houses where the procedure recommended work be performed (the first seven listed in Table 5.1) the actual expenditures are only 76% of the recommended, while accomplishing 89% of the targeted leakage rate reduction. Thus, on the average, the procedure predicts fairly well the air leakage reduction potential and its cost, even though any one house may vary from its predictions.

On the basis of this study and studies of several other "average" homes, WECC considers $100 per every 1 ACH50 reduction in air leakage reasonable (Schlegel, 1986). Column (8) shows that all but one house with initial air leakage rate greater than 8 ACH50 had their retrofits performed for less than this amount. The average cost per ACH50 reduction for these houses is $66. This is most consistent with what the procedure would predict. For the average size house considered, the procedure predicts an average cost per ACH50 reduction of $60, assuming initial leakage rates from 8 to 19 ACH50. Thus, again, the procedure predicted well the average cost of the retrofits in this study.

Two of the three houses with initial leakage rates between 7.0 and 8.0 ACH50 also had retrofits costing less than $100/ACH50. However, the third house in this grouping required $238/ACH50, having had its leakage rate reduced by only 0.2 ACH50. Evidently, for the type of infiltration retrofit measures used in this study, houses with initial leakage rates in this range form a boundary between houses which may be expected to realize reasonably cost-effective leakage reductions from retrofits and those not seeing such reductions. With the limited sample number present in this study, it is impossible to set this boundary any more precisely.

The predicted savings reported in column 9 of Table 5.1 are small compared with expected annual heating costs for Wisconsin. Six homes have infiltration retrofits with payback periods of five years or less. The average payback period for those retrofits recommended by the procedure is 4.4 years, not totally unacceptable by most measures. This assumes no degradation in the performance of the retrofits with time. The average payback period increases to 10.6 when all homes actually retrofitted are considered. There again appears a boundary at initial leakage rates between 7.0 and 8.0 below which payback periods jump higher. Even here, though, there is an exception with house R06, having initial rate of 5.2 ACH50 and a payback of 6.0 years. The majority of retrofits on houses with initial rates greater than this boundary could be considered as cost effective, based on the predicted results.

In summary: (1) although the sample size for the study was small, the homes studied provided a wide range of initial leakage rates; (2) the leakage rates attained or targeted by the procedure fall well above the minimum rates set by ASHRAE to avoid air quality degradation; (3) the formula for the recommended expenditure level given by the procedure should include the cost of the initial blower door evaluation of leakage rate; (4) on the average, the procedure predicts fairly well the potential for air leakage rate reduction and its cost; (5) whether significant air leakage reduction is possible in any given house depends on more factors than the initial leakage rate; (6) cost-effective retrofits for houses with initial rates less then 7 ACH50 are not likely to occur; (7) the majority of retrofits on houses with initial leakage rates greater than the procedure's minimum 8 ACH50 could be considered cost effective; and (8) using the retrofit procedure, average retrofit costs per house were less than a fourth that typically spent in Wisconsin. Above statements relating the cost effectiveness of the retrofits will be challenged by results computed from metered fuel use.

5.2 NORMALIZED ANNUAL HEATING COST SAVINGS

Table 5.2 lists the houses of the blower-door test group in the same order as in Table 5.1 except that seven entries are missing. These seven were eliminated due to situations arising after the retrofits, which made calculation of accurate savings impossible. See Appendix A for house attrition explanations.

The results of normalizing the pre- and post-retrofit furnace heating energy to the 36-year average Madison weather are shown in columns (2) and (3), the normalized annual heating consumptions (NAHC). The difference in these two quantities, shown in column (4), is a best estimate of the average annual energy saved due to the retrofit, the normalized annual heating savings (NAHS). Negative values of this savings indicate an increased energy use during the post-retrofit period compared with the pre-retrofit period.

The normalized savings vary widely in both positive and negative directions. A substantial number of the savings are negative, producing a -27 therm average for all 11 houses, or an average -2 therm for only those houses retrofitted. Thus, the reductions in air leakage accomplished did not induce consistently measurable reductions in energy consumption.

In order to establish the significance of the savings, some measure of the potential error is necessary. The 90% confidence intervals in column (5) provide this measure. Other measures could have been chosen, but the confidence intervals provide an easily understood physical picture. The actual savings has a 90% probability of lying somewhere between the NAHS reported in column (4) minus the 90% confidence interval and the NAHS plus this interval. The confidence intervals for the averages are not simple averages of the individual intervals. They are statistically valid grouped values, allowing evaluation of the significance of the average savings listed. (See Appendix D for derivations of the confidence intervals used.)

Table 5.2. Normalized annual heating consumptions and savings.

HOUSE (1)	PRE-RETR NAHC (THERMS) (2)	POST-RETR NAHC (THERMS) (3)	NAHS (THERMS) (4)	90% CONFID INTERVAL (THERMS) (5)	PRED SAVINGS (THERMS) (6)	ALT PRED SAVINGS[3] (THERMS) (7)
R21	868	748	120 (141)[1]	90	97	129
R22	837	937	-100 (-72)	70	33	-1
R03	964	791	173 (187)	180	22	216
R43	586	610	-24	88	7	5
D04	410	436	-26	48	70	83
R01	1108	1303	-195	230	24	35
R39	957	920	37	130	3	9
R31	279	395	-116	47	0	0
R04	431	468	-37	34	0	0
R27	591	748	-157	125	0	0
G01	385	356	29	43	0	0
AVERAGES						
ALL	674	701	-27	36[2]	23	43
RETROF	819	821	-2	48	37	68
RECM RETROF	814	772	42	78	40	87

[1] Values in parentheses are adjusted for known changes in indoor air temperature from pre- to post-retrofit periods. (See Appendix E.)

[2] Simple averages of confidence limits are not valid statistics for assessing the uncertainty. Group confidence limits of the measure have been used instead.

[3] The alternate predicted savings use the 36-year average weather data and individual house balance points rather than the 7700 HDD with 0.6 correction factor used in the original predicted results. (See Appendix G.)

Under this criteria, the average -27 therm energy increase is not significant when compared with its 36 therm confidence limit. Examined individually, only the savings in R21 are truly statistically significant. Those of R03 are nearly so. Conversely, the energy increase shown for R22 is also significant. The air leakage reduction of this house, however, was less than a fourth that of R21. The last four houses listed in the table had no infiltration retrofits installed, yet three of the four show statistically significant increases in energy use from the pre- to post-retrofit periods. Two of the four, R31 and R27, have negative normalized annual heating savings representing 42 and 27 percent of their total normalized annual heating consumptions. Thus, elements other than the precision of the metering devices and the scatter of the data are likely affecting the results.

Seasonal variations in many factors could contribute to the unexpected measured savings obtained. Changing wind speed and direction, solar or internal loads, and ground temperature are but a few. Appendix E investigates the effects of greater average indoor air temperature after the retrofit than before, a situation having some experimental confirmation. Adjusted normalized annual heating savings, reported in parentheses in column 4 of Table 5.2, suggest that the magnitude of this effect is not sufficient to account for the overall lack of measured savings.

Appendix F examines the regressions of fuel consumption against ambient temperature to show that the house balance points obtained from this measured data reflect the trends seen in the measured savings. However, in themselves, they cannot explain why such trends exist.

The magnitude of the confidence intervals relative to the savings themselves suggest a need to increase the precision of the estimates. The confidence intervals reflect to what degree the linear regressions fit the relationships between measured fuel use and ambient temperature. Thus, a lack of fit can be caused not only by inaccurate or imprecise data, but also by any actual condition which lessens the linearity of the relationship. Weekly fluctuations in the same factors whose seasonal variations could contribute to the lack of measured savings, would detract from this linearity. Increasing the number of observations per period, by either increasing the frequency for recording data or the duration of the period, would decrease the effect of random error on the confidence interval. However, the error resulting from the nonlinear effects would place a limit on the precision of the regressions.

In summary, measured savings vary widely, showing little consistent correspondence to the leakage rate reductions. Despite broad confidence limits, several statistically significant negative savings indicate that other factors are likely affecting the results. Accounting for changes in indoor air temperature helps reduce the number of these significant negative savings, but cannot eliminate the most pronounced discrepancies. Two of the four houses not retrofitted show energy increases which are 27 and 42 percent of their total annual normalized consumptions. The possibility for undetected equipment error always exists. It is also not impossible that while performing the retrofits or measurements, unknown changes in the house's characteristics occurred which decreased its energy efficiency. In general, however, with the information available, it is impossible to state whether any major cause lies with the procedure or its implementation. Further instrumentation may be necessary to isolate factors which conceal savings derived from infiltration retrofits.

5.3 COMPARISON OF PREDICTED AND MEASURED RESULTS

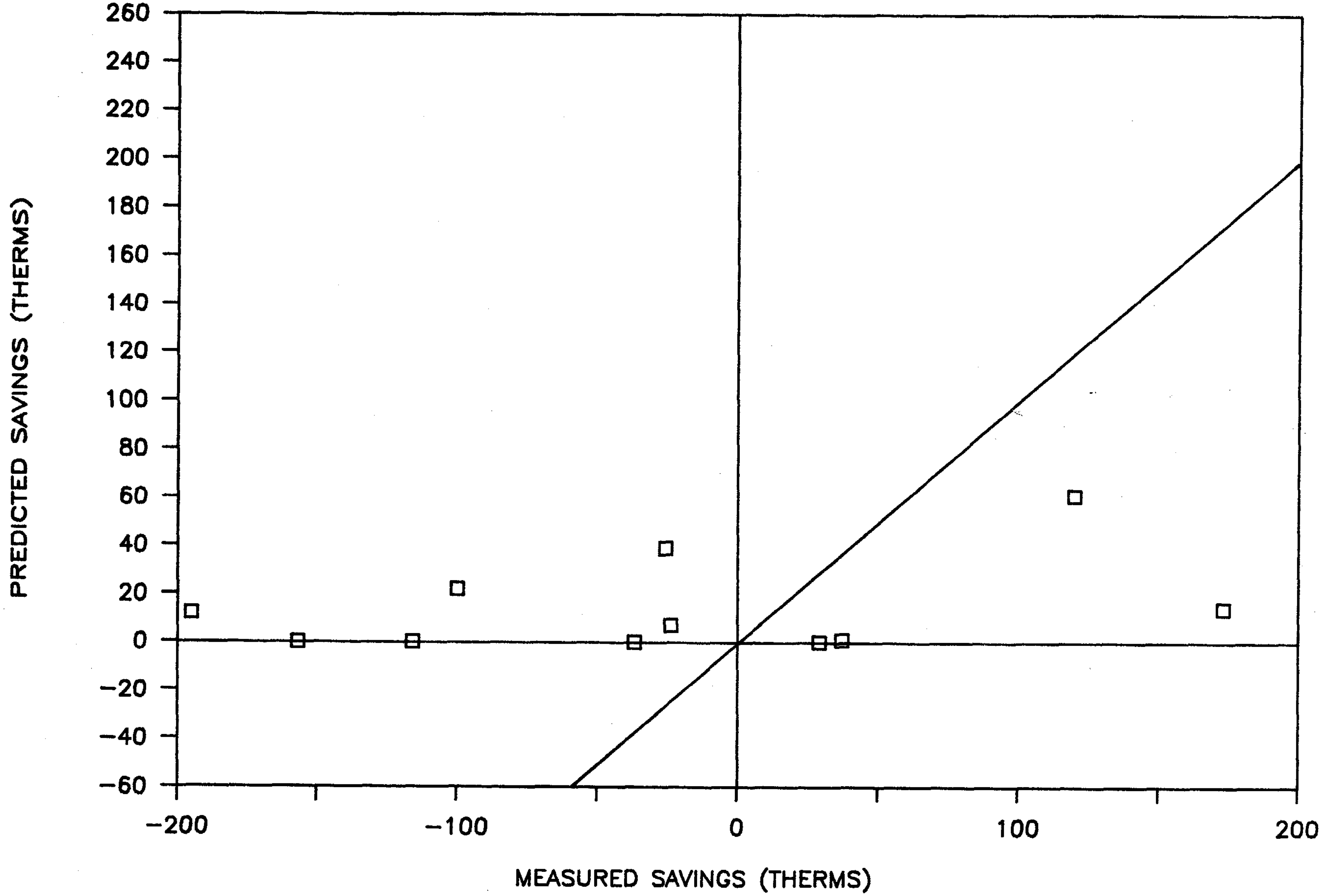
Column (6) of Table 5.2 reports the estimates of the annual heating savings determined from the reported air leakage rate reductions, using the same algorithm which computed the dollar savings of Table 5.1. (See Appendix C.) These values are termed the predicted results, as opposed to measured results computed from the metered furnace consumptions. The 37-therm average predicted savings for all retrofitted houses represents five percent of the average pre-retrofit normalized annual heating consumptions. However, percent savings for individual houses range as high as 17 percent.

Little correlation exits between the predicted savings and the measured results, reported in column (4). Figure 5.1 plots these two results against one another. Equivalence is represented by the diagonal line on the plot. The correlation coefficient between the measured and predicted values is only 0.34.

By their very nature, the predicted results could not reflect the increases in energy consumption seen in the measured results. The house having the greatest predicted savings, R21, has the second greatest measured savings. However, even though R03 has a greater measured savings, its confidence interval is nearly twice that of R21, lending less credence to the value. All but two of the houses actually retrofitted have predicted values falling within the measured values' 90% confidence limits, though in some instances the limits are so broad as to make the comparison somewhat uninformative.

The predicted results use a somewhat different weather base than the measured results, heating degree day methodology versus a 36-year average weather. An examination of the 36-year average weather data yields a base 65°F heating degree day value of 7400, compared with the predicted method's value of 7700. Using this lessor value would yield less than a 4% decrease in the predicted savings, not affecting the comparison with the measured savings significantly.

The predicted method also includes a correction factor, CD, equal to 0.6, which accounts for homes having balance points which are normally less than the 65°F base used. As previously indicated, the balance points derived from the metered furnace consumption and outdoor temperature data reflect the trends seen in the measured savings. Appendix G uses these balance points to derive an alternate predicted annual savings, reported in column 7 of Table 5.2. As expected, the correlation coefficient of these alternate values with the measured savings, .71, is improved over the coefficient using the initial predicted results, .37.


PREDICTED SAVINGS (THERMS)
260
240
220
200
180
160
140
120
100
80
60
40
20
0
−20
−40
−60
−200
−100
0
100
200
MEASURED SAVINGS (THERMS)

Thus, a significant amount of the difference between predicted and measured results lies not in incorrect leakage rate reductions, but in the conversion of this, or any load reduction, to a decrease in furnace heating requirements. Many factors already discussed as directly biasing the results or contributing to the uncertainty of the measured savings (e.g., solar, internals, mass, etc.), also affect this conversion.

Unique to the infiltration load is the factor converting the air leakage rate reductions at 50 pascal to average infiltration reductions under actual weather conditions. Both predicted techniques assume a constant factor of 0.05 ACH infiltration reduction for every 1 ACH50 reduction in air leakage. Wind speed and direction, location of infiltration sites, and possibly even the furnace's air delivery system affect this factor directly. More detailed analyses and instrumentation than is appropriate in a field test would be required to more fully understand the processes involved.

5.4 GROUP STATISTICS

The individual measured results in Table 5.2 can be summarized by looking at the statistics for the group of houses as a whole. These may then be compared with the group statistics for the control houses. Table 5.3 displays the average pre- and post-retrofit consumptions and savings for all houses in the blower-door test and control groups. As seen earlier, the measured mean savings for the blower door houses is negative, indicating an increase in energy use from pre- to post-retrofit periods.

In order to establish the significance of this mean, it must be compared with the 90% confidence interval for the measured results taken together. The value labeled "90% Confidence Interval of Measure" provides this statistic. The values are based on the sum of the variances of the individual houses. The confidence interval for the savings is greater than the magnitude of the mean savings, indicating that the increase in measured energy use seen on the average is not significant. On the other hand, there also exists no evidence of a decrease in average energy use due to the retrofits.

Table 5.3. Grouped statistics for blower door and control house groups.

	BLOWER DOOR HOUSES	CONTROL HOUSES
MEAN CONSUMPTION		
PRE-RETROFIT	674	913
POST-RETROFIT (THERMS)	701	918
MEAN SAVINGS (THERMS)	-27	-5
90% CONFIDENCE INTERVAL OF MEASURE	36	44
TOTAL 90% CONFIDENCE INTERVAL	69	61

In order to compare the results of the blower-door houses with those of the control houses, a confidence interval must be determined which represents the potential scatter of not only the eleven houses retrofitted, but of the effect of these retrofits on all houses similar to those actually used in the study. This is accomplished by computing a 90% confidence interval which includes the contribution from the individual variances, as used above, as well as a contribution of the individual values about their mean. (See Appendix D.) This statistic is designated "Total 90% Confidence Interval" in Table 5.3.

Thus, the comparison of the mean savings for the test group with its total confidence interval, and the mean and interval for the control group indicates that neither show statistically significant savings or energy increases. Both groups have similar confidence intervals, implying that neither had more accurate data acquisition or more similar house characteristics within the group.

Values of the normalized annual savings, as reported in column (4) of Table 5.2, could be adjusted upward by 5 therm to account for the bias seen in the control group average savings. However, this small a change is not significant.

6. CONCLUSIONS AND RECOMMENDATIONS

The primary objective of the blower door retrofit field test was to evaluate the effectiveness of the blower-door-directed infiltration retrofit procedure compared with previous methods and provide estimates of the resulting savings in program cost and residential energy use.

Applied to a group of houses, the procedure appears to provide an effective guide to the average amount of air leakage reduction that can be achieved and the expense necessary to accomplish the reduction. The blower-door-directed infiltration retrofit procedure produced an average 16% reduction in air leakage rate. This is despite an already average pre-retrofit mean rate of 9.8 ACH at 50 pascal depressurization. In comparison, a 1985 study of 50 low-income houses in Wisconsin found no significant difference in infiltration rate after installation of typical weatherization measures including infiltration reduction retrofits (Kanarek, 1985).

Considering only those houses in which retrofit work was recommmeded, the procedure accomplished 89% of its targeted air leakage reduction while using only 76% of its recommended budget. The average retrofit cost per house for all houses retrofitted was $124. This amount is less than one-fourth of the $570 per house required by a previous Wisconsin weatherization program (Hewitt, 1984).

On the basis of cost per reduction of air leakage ($/ACH50), the procedure's 8 ACH50 cutoff point for performing retrofits appears a good choice. Houses with initial rates of 7 ACH50 or below consistently required substantially higher costs.

However, whether significant air leakage reduction is possible in any given house depends on more than the home's initial leakage rate. The training and experience of the retrofit crew undoubtedly also play a key role. It is believed that the crews performing the retrofits for the field test should have had additional exposure to the techniques intended for implementation by the procedure, such as examination and repair of attic bypasses. In addition, there is indication of houses whose air leakage was not amenable to easy detection and reduction regardless of the initial rate.

Reductions in air leakage did not induce consistently measurable reductions in energy consumption. The average annual heating savings, computed from the metered furnace run times, was not statistically significant. The average for all houses was -27 therm with a 90% confidence limit of 36 therm. The negative quantity implies a net energy increase after retrofit implementation. For comparison, the average predicted savings for all houses, computed from the individual air leakage rate reductions, was 23 therm.

Values of the measured heating savings for individual houses varied widely in both positive and negative directions. A significant number of houses showed increases in energy consumption, from pre- to post-retrofit periods, larger than their uncertainty. Thus, factors other than the precision of the measurements are likely affecting the results.

Weekly fluctuations in parameters such as wind speed and direction, solar and internal loads, and indoor setpoint temperature, contribute to the relatively large error bounds for the results. Increasing the number of observations per period would decrease the random error of the results, but not affect systematic error introduced by neglect of physical effects. Seasonal variations in these same factors, as well as ground temperature, could bias the measured energy savings.

Additional analyses appear to indicate that the major cause for the lack of consistent measured savings stems from incorrect conversion of building component loads to furnace energy consumption, including specifically the conversion of air leakage rate at 50 pascal to actual infiltration rate under actual weather conditions. Further research is needed to identify factors masking the effect of reduced air leakage rate on the heating energy consumption.

Specific recommendations for the procedure include more extensive training of the retrofit crews not only to ensure proper operation of the equipment, but also to allow application of the most current retrofit techniques. Crews also need to adhere more closely to minimum leakage rate specifications in order to produce more cost-effective results. Although none of the retrofitted homes approached minimum rates specified by ASHRAE to ensure air quality, checks should be made to guarantee adherence to such standards. Also, some average cost of performing the blower door test, establishing the initial leakage rate, needs to be included in the equation for the recommended expenditure level.

Whether increasing the minimum pre-retrofit leakage rate, below which no work is recommended, would increase the cost effectiveness of the program is yet uncertain. The answer appears to rely too heavily on other factors including crew experience and training, house characteristics which establish ease of air leakage reduction, and factors which determine whether realized leakage reduction actually appears as a reduced load to the furnace.

Recommendations for field testing of the infiltration retrofit procedure include increasing the sample size. The small number of homes in this study made separation of significant results from experimental error difficult. Even further difficulty arises in attempting to apply the results to the low-income housing stock in general. Attrition from an initial target size depends on the criteria of acceptance. Nevertheless, measures need to be taken to ensure a sufficient final sample size. In addition the houses selected need to represent an unbiased sample of the set of houses they represent, for example with regards to location (city versus rural), age, or possibly even styles, etc.

The scatter of the data may possibly be reduced by having data analyzed soon after its collection. As weekly readings are taken, analyses to allow plotting of the new data point with those preceding it, could permit early recognition of trends or instrument errors requiring corrective action.

Interior air temperature should be monitored and regression of furnace consumption made against indoor-ambient temperature differences. Whether further instrumentation is required should be the subject of further research, not to be addressed within the context of a field trial of a retrofit procedure.

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APPENDIX A

TABLE. A.1. HOUSE LOCATION AND ATTRITION

HOUSE	LOCATION (CITY,COUNTY)	WEATHER STATION	CAUSE FOR ATTRITION
R21	JANESVILLE, ROCK	JANESVILLE	
R22	JANESVILLE, ROCK	JANESVILLE	
R35	BELOIT, ROCK	JANESVILLE	PREVIOUSLY WEATHERIZED
D26	MADISON, DANE	TRUAX FIELD	FAULTY INSTRUMENTATION
R03	EDGERTON, ROCK	JANESVILLE	
R52	BELOIT, ROCK	JANESVILLE	FAULTY CALIBRATION
R43	BELOIT, ROCK	JANESVILLE	
D04	STOUGHTHON, DANE	TRUAX FIELD	
R07	JANESVILLE, ROCK	JANESVILLE	FAULTY CALIBRATION
R01	EDGERTON, ROCK	JANESVILLE	
D41	DEERFIELD, DANE	TRUAX FIELD	HIGH BALANCE TEMPERATURE
G27	ALBANY, GREEN	JANESVILLE	FAULTY CALIBRATION
R06	JANESVILLE, ROCK	JANESVILLE	SPURIOUS DATA
R39	BELOIT, ROCK	JANESVILLE	
R31	JANESVILLE, ROCK	JANESVILLE	
R04	MILTON, ROCK	JANESVILLE	
R27	JANESVILE, ROCK	JANESVILLE	
G01	BRODHEAD, GREEN	JANESVILLE	

The above are the 18 houses remaining in the study at the time of the retrofit. Of the 40 planned for the study, only 28 were initially identified. Of these, ten were dropped prior to the retrofits due to ineligibility requirements, five for income over WAP minimum, and five for applications received too late.

EXPLANATION OF CAUSES FOR ATTRITION

The causes for attrition reported refer to the following:

Previously weatherized - It was revealed that the house had previously been weatherized within a the last five years, making it ineligible for the WAP program.

Faulty instrumentation - Undetected instrument failure prevented sufficient data collection to provide proper analyses.

Faulty calibration - A comparison of the furnace consumption to whole house consumption revealed that calibration of the furnace was in error. Recalibration was not able to be carried out.

High balance point - The regression of metered furnace consumption against ambient temperature produced unreasonable balance point temperatures. No apparent cause was found.

Spurious data - Unreasonable data warranted rejection of the house from the study.

APPENDIX B

TABLE B.1. INFILTRATION RELATED RETROFITS PERFORMED

HOUSE	CAULK	WEATHERSTRIP	DOOR SWEEPS	DOOR JAMBS	OTHER
R21	X	X			FOAM, ROPECAULK
R22	X	X			PULLEY SEALS
R35	X	X	X		THRESHOLD
D26	X			X	TAPE
R03	X	X	X		FOAM
R52	X	X	X		
R43	X				
D04	X		X	X	SASH LOCKS, SOCKET SEALS
R07					ATTIC BYPASSES, SEAL HOUSEFAN
R01	X	X			
D41	X			X	SOCKET SEALS, TAPE
G27			X	X	SASH LOCKS
R06	X	X	X		
R39	X	X	X		
R31					
R04					
R27					
G01					

APPENDIX C

COMPUTATION OF PREDICTED RESULTS

The predicted energy and fuel cost savings were computed from the recorded pre- and post-retrofit air infiltration rates, in ACH50, air changes per hour at 50 pascals depressurization. The formulas below use a heating degree day methodology. (See ASHRAE Handbook of Fundamentals, 1985, p.28.4.)

$$\text{ENERGY SAVINGS (THERM)} = \text{DELTA ACH50} * .05\ \text{ACH/ACH50} * \text{HVOL}$$

$$* \text{CAIR} * \text{HDD} * \text{CD} * 24 / \text{FEFF} * 1\ \text{THERM}/10^5\ \text{BTU}$$

where

DELTA ACH50 = Infiltration Reduction, Column (3), Table 5.1.
ACH/ACH50 = Suggested conversion from air infiltration at 50 pascals pressure to infiltration under actual conditions.

and

HVOL	= House Volume (ft^3)		CD	= HDD Correction Factor
CAIR	= Heat Capacity of air			= 0.6 for Madison
	= 0.0183 Btu/ft^3/°F		FEFF	= Furnace Efficiency
HDD	= Heating Degree Days			= 0.75
	Base 65°F			
	= 7700 in Madison			

Assuming a fuel cost of $0.80 / therm, the dollar savings is

$$\$\ \text{SAVINGS} = \text{ENERGY SAVINGS} * \$0.80$$

APPENDIX D

ANALYSES OF METERED DATA

Linear Regression of Furnace Fuel Use With Ambient Temperature

Each home was metered during both pre- and post-retrofit periods for furnace run time and whole house gas and electric usage. The furnace was calibrated for fuel use versus run time, neglecting the small effects of pilot lights. Weekly readings were planned, but variations in duration were common. Hourly ambient temperatures from three sites, supplied by the Wisconsin State Climatologist and the National Oceanic and Atmospheric Administration, were used to compute average ambient temperatures for the measurement periods. Since the periods varied in duration, weighting of the linear regressions, used in normalizing the data to a common weather base, was necessary.

Given the i'th period's fuel usage reading, f_i, corresponding to a period of duration l_i, in weeks, an average period weekly fuel usage can be defined as $F_i = f_i/l_i$. Assuming that all readings corresponding to exactly one week's duration have the same variance, σ^2, the variance of a reading corresponding to the i'th period would be $l_i \sigma^2$. Then, the period's average weekly usage, F_i, has variance

$$\mathrm{var}(F_i) = \mathrm{var}(f_i/l_i) = 1/l_i^2\, \mathrm{var}(f_i) = \sigma^2/l_i \ .$$

Thus,

$$\mathrm{var}(\sqrt{l_i}\ F_i) = l_i\, \mathrm{var}\, F_i = l_i(\sigma^2/l_i) = \sigma^2$$

is constant, independent of the period's duration.

Values for A and B are sought such as to minimize the squared error introduced by approximating the metered energy use by the linear expression

$$F(t_i) = A + B(t_i - \overline{T}) \ ,$$

where $\overline{T}$, the average temperature for all measurement periods, is defined as

$$\overline{T} = [\Sigma\, l_i t_i]/L, \qquad L = \Sigma\, l_i \ .$$

The summations extend over the number of measurement periods in either the pre- or post-retrofit period. The quantity, L, is simply the total number of weeks. The error in the approximation, e_i, is

$$e_i = F_i - F(t_i) = F_i - A - B(t_i - \overline{T}) \ .$$

In order to provide for the unequal time durations of the periods, the equation is multiplied by $\sqrt{l_1}$, giving

$$e_i\sqrt{l_i} = \sqrt{l_i}\,[F_i - A - B(t_i - \overline{T})] \ .$$

Thus, the quantity

$$l_i e_i^2 = l_i[F_i - A - B(t_i - \overline{T})]^2$$

is to be minimized. The values of A and B which accomplish this are found by solving the set of two equations formed by setting the partial derivatives of the above with respect to A and B equal to zero. The results are

$$A = \Sigma f_i/L \qquad B = [\Sigma f_i(t_i - \overline{T})]/[\Sigma l_i(t_i - \overline{T})^2] \ .$$

The variances of A and B, required in determining the confidence intervals for the annualized savings, are found by evaluating the following

$$\sigma_A{}^2 = \Sigma\left(\frac{\partial A}{\partial Z_i}\right)^2 \sigma^2 \qquad \sigma_B{}^2 = \Sigma\left(\frac{\partial B}{\partial Z_i}\right)^2 \sigma^2$$

where

$$Z_i = \sqrt{l_i}\ F_i \qquad \text{and} \qquad \sigma^2 = \text{var}(\sqrt{l_i}\ F_i)$$

The algebraic manipulations produce

$$\sigma_A{}^2 = \sigma^2/L \qquad \sigma_B{}^2 = \sigma^2/[\Sigma l_i(t_i - \overline{T})^2]$$

with

$$\sigma^2 = \mathrm{var}\,(\sqrt{I_i}\ F_i) = 1/(N-2)\,\Sigma\, I_i[F_i - F(t_i)]^2$$

where N equals the number of observations.

Normalized Annual Heating Consumption and Savings

The furnace fuel consumptions determined for the pre- and post-retrofit periods must be "normalized" to a common weather base before their comparison will properly indicate fuel savings. The weather base chosen was a 36-year average of ambient temperatures recorded for Madison, Wisconsin. From the data base, the quantities, W(T), were determined. These values equal the average number of weeks per year in the 36 years having an average temperature in a one degree band about T.

The normalized annual heating consumption is then computed as

$$\mathrm{NAHC} = \Sigma\, W(T)F(T)$$

where

$$F(T) = A + B(T - \overline{T})$$

as determined by the linear regression. The temperature, T, ranges from the minimum to maximum temperatures for which heat was required, in one degree intervals. The quantity, T, is the average ambient temperature during actual measurement of the data. The NAHC's are the values reported in columns (2) and (3) of Table 5.2.

The normalized annual heating savings, NAHS, is simply the difference in NAHC's before and after the retrofits.

$$\mathrm{NAHS} = \mathrm{NAHC}_{pre} - \mathrm{NAHC}_{post}$$

Confidence Interval for Savings

The 90% confidence limits on the savings are computed from the variances of the consumptions. The variances of the NAHC's are found by substituting the definition for NAHC into the expression

$$\sigma_{NAHC}^2 = \left(\frac{\partial\, NAHC}{\partial A}\right)^2 \sigma_A^2 + \left(\frac{\partial\, NAHC}{\partial B}\right)^2 \sigma_B^2$$

where σ_A^2 and σ_B^2 were given previously. The results are

$$\sigma_{NAHC}^2 = W_B^2\,[\sigma_A^2 + (T_{WB} - \overline{T})^2\, \sigma_B^2]$$

with

$$W_B = \Sigma W(T) \qquad T_{WB} = [\Sigma TW(T)]/W_B$$

where each sum extends only up to the temperature, T_B, above which no heating is required, as determined by the linear regression. That is, T_B is that temperature such that

$$F(T_B) = 0 = A + B(T_B - \overline{T}) \Rightarrow T_B = \overline{T} - A/B\ .$$

The variance of the savings is the sum of the variances of the pre- and post-retrofit consumptions,

$$\sigma_{NAHS}^2 = \sigma_{NAHC,PRE}^2 + \sigma_{NAHC,POST}^2\ .$$

The confidence interval for the savings, reported in column (5) of Table 5.2, is computed as

$$CI_{90\%} = \sigma_{NAHS} \times t_{90\%}\,(N_{pre} + N_{post} - 4)$$

where $t_{90\%}(N)$ is the student's t-statistic for N observations and a 90% confidence interval. The 90% confidence interval defines a bandwidth on either side of the mean, NAHS, in which there is a 90% probability of finding the actual value.

Grouped Statistics

In order to assess the significance of the mean savings and compare the results of the blower door houses with those of the control houses, statistics which are representative of each group as a whole must be determined. Simple algebraic means of savings and consumptions for the houses in each group may be used. Two grouped confidence intervals of these means are computed. One, the confidence interval of the measure, represents the uncertainty in the individual measurements of fuel consumptions and their effect on the resulting average savings. This statistic is based on the sum of the variances for the measurements in the individual houses. Its value is computed as

$$CIM_{90\%} = 1/M\,[\Sigma\,\sigma_{NAHS}{}^2]^{1/2}\,t_{90\%}\,(M-1)$$

where the sum is now over the number of houses in the group, M, not a number of periods. Confidence intervals of measure for the consumptions are determined analogously, using $\sigma^2{}_{NAHC}$ instead of $\sigma^2{}_{NAHS}$.

A second confidence interval is determined to allow comparison of the grouped statistics of the two groups. This statistic not only includes the contribution above, representing the uncertainty in the individual measurements, but also a contribution from the scatter of the savings or consumptions about their means. This second contribution, called the confidence interval of the sample, represents a variability in the house characteristics and their response to the retrofit, rather than uncertainty in the measurements themselves. This must be included since the control house group contains a totally different set of houses from the blower door group. The confidence interval of the sample is defined as

$$CIS_{90\%} = 1/[M(M-1)]\,\Sigma\,[(NAHS - \overline{NAHS})^2]\,^{1/2}\,t_{90\%}\,(M-1)\ .$$

Again, the summation is over the number of houses in the group, and NAHS is the algebraic mean of the savings for the individual houses of the group. The confidence interval of the sample for the consumptions are computed in the same manner except using NAHC's instead of NAHS's.

The total 90% confidence interval is the square root of the sum of the squares of the intervals for the measure and sample.

$$CIT_{90\%} = (CIS^2_{90\%} + CIM^2_{90\%})^{1/2} \,.$$

These grouped confidence intervals are the values reported in Table 5.4.

APPENDIX E

EFFECT OF VARYING INDOOR SETPOINT TEMPERATURE

The analyses, both for measured and predicted results, assume a constant indoor temperature, or at least consistent trends in both pre- and post-retrofit periods. In three of the homes analyzed, additional instrumentation was installed to allow determination of the effects of occupant behavior. (See ORNL/CON-228/P4.) The three homes thus instrumented were R03, R21, and R22. The study found average increases in indoor air temperature of 0.7, 1.1, and 1.2°F, respectively, from pre- to post-retrofit periods. An increased indoor temperature between periods implies a greater need for heating after the retrofit than before, assuming equal climates for the two periods.

An estimate of the effect of this indoor temperature change may be made by assuming the heating consumptions are proportional to a difference between the average ambient temperature of the period during which heat was required and a normal indoor temperature, say 70°F. This difference is about 40°for the three houses being considered. Thus, the 1.1°increase in indoor temperature of house R21 would have caused an overestimation of the post-retrofit heating consumption by an amount approximately equal to

$$1.1/40 * 748 = 21 \text{ therm.}$$

Therefore, the post-retrofit normalized annual heating consumption without indoor temperature alteration would have been 748 - 21 = 727 therm, and the annual heating savings increased to 141 therm.

Houses R22 and R03 have similarly computed adjusted savings of -72 and 187 therm, respectively. These values are shown in parentheses in column (4) of Table 5.2. The adjustment places the savings of both R21 and R03 as significant, based on the 90% confidence interval criteria. The increase in energy use seen in house R22 becomes only barely significant.

If the average indoor air temperature change seen for the three houses, 1°F, is assumed to have been present in all houses, the effect raises the average savings for all houses to -9 therm, far from sufficient to explain the overall lack of savings measured. It must be remembered that the above computations are approximate and merely establish probable cause for trends seen.

Since no indoor temperature data are available for the other houses, no estimates of their effect can be made. The only other seemingly unresolved discrepancies lie in the negative savings seen in the three unretrofitted houses, R31, R04, and R27. The above computation may be applied in reverse to determine the increase in average indoor temperature from pre- to post-retrofit periods that would drop the magnitude of the negative savings to just below a significant level. The resulting increases are 7.0, 0.3, and 1.7°F for R31, R04, and R27, respectively. The latter two temperature increases appear possible, but the 7°average indoor temperature increase from the pre- to post-retrofit periods is highly unlikely.

The occupant behavior report also states "whatever the [setback] practice employed, it was maintained throughout the winter and was not affected by a retrofit installation." Thus, night setback strategy changes evidently are not significant in explaining the lack of metered energy savings resulting from the retrofits.

APPENDIX F

HOUSE BALANCE POINTS

Some insight into the discrepancy between predicted and measured results may be gained by examining the regressions of the metered data. The regressions give a linear relation between ambient temperature and furnace consumption. The temperature at which this relation shows no furnace consumption is called the balance point temperature of the house. It represents the ambient temperature above which the house requires no heating energy to maintain the indoor temperature above a desired setpoint. Typically, following a retrofit, the house would have a lower balance point than before the retrofit, indicating that the weather could become colder before heat would be required.

Figure F.1 lists the pre- and post-retrofit balance point temperatures taken from the fuel consumption-ambient temperature regressions. More than half the post-retrofit balance points are greater than or equal to the pre-retrofit values, counter to expectation. However, except for house R01, the relationship between the normalized annual heating savings and the change in balance point is totally consistent. Those houses whose balance points decreased following retrofit have positive changes, while those with increasing balance points have negative savings, that is, increased their energy consumption. Thus, regardless of the weather base used to normalize the data, the original fuel use versus ambient temperature readings do not consistently indicate savings from the retrofits.

Balance points are affected by all factors determining a home's energy efficiency, including infiltration. Thus, the increase in energy use seen is likely due to factors other than the infiltration characteristics of the house. If this is so, the retrofits may have been effective in reducing energy consumption, but other factors prevented their effect from being measured.

For example, due to its massiveness, the earth beneath and surrounding the house remains warmer well into the winter, gradually decreasing in temperature later in the winter. Thus, the house would lose more heat to the ground later in the winter, after the retrofits had been installed, than earlier, prior to the infiltration retrofits. Such effects may help explain the negative net savings seen.

Table F.1. Normalized annual heating savings and changes in house balance points.

HOUSE	PRE-RETR BAL PT (F)	POST-RETR BAL PT (F)	CHANGE IN BAL PT (F)	NAHS (THERMS)
R21	58	57	-1	120
R22	54	56	2	-100
R03	67	53	-14	173
R43	61	62	1	-24
D04	56	57	1	-26
R01	65	65	0	-195
R39	62	61	-1	37
R31	44	51	7	-116
R04	61	63	2	-37
R27	57	63	6	-157
G01	53	51	-2	29

APPENDIX G

COMPUTATION OF ALTERNATE PREDICTED RESULTS

The alternate predicted energy savings were computed from the recorded pre- and post-retrofit air leakage rates, in ACH50, air changes per hour at 50 pascals depressurization. The formulas below implement a variation of the variable base degree day method. (See ASHRAE Handbook of Fundamentals, 1985, p.28.4.) The 36-year average Madison weather data was used to compute heating degree weeks as functions of a house's balance point temperature. The individual house balance points, listed in Table F.1, were determined from the regressions of metered fuel consumptions against ambient temperature.

ENERGY SAVINGS (THERM) = [ACH50pre * HDW(BPpre) - ACH50post * HDW(BPpost)] * 0.05 ACH/ACH50 * 168 hrs/wk * HVOL * CAIR / FEFF * 1 THERM/10^5 BTU

where,

ACH50 = Pre- and Post-Retrofit Leakage Rates at 50 Pascals.

ACH/ACH50 = Suggested conversion from air infiltration at 50 Pascals pressure to infiltration under actual conditions.

BP = Pre- and Post-Retrofit Balance Point Temperatures.

and,

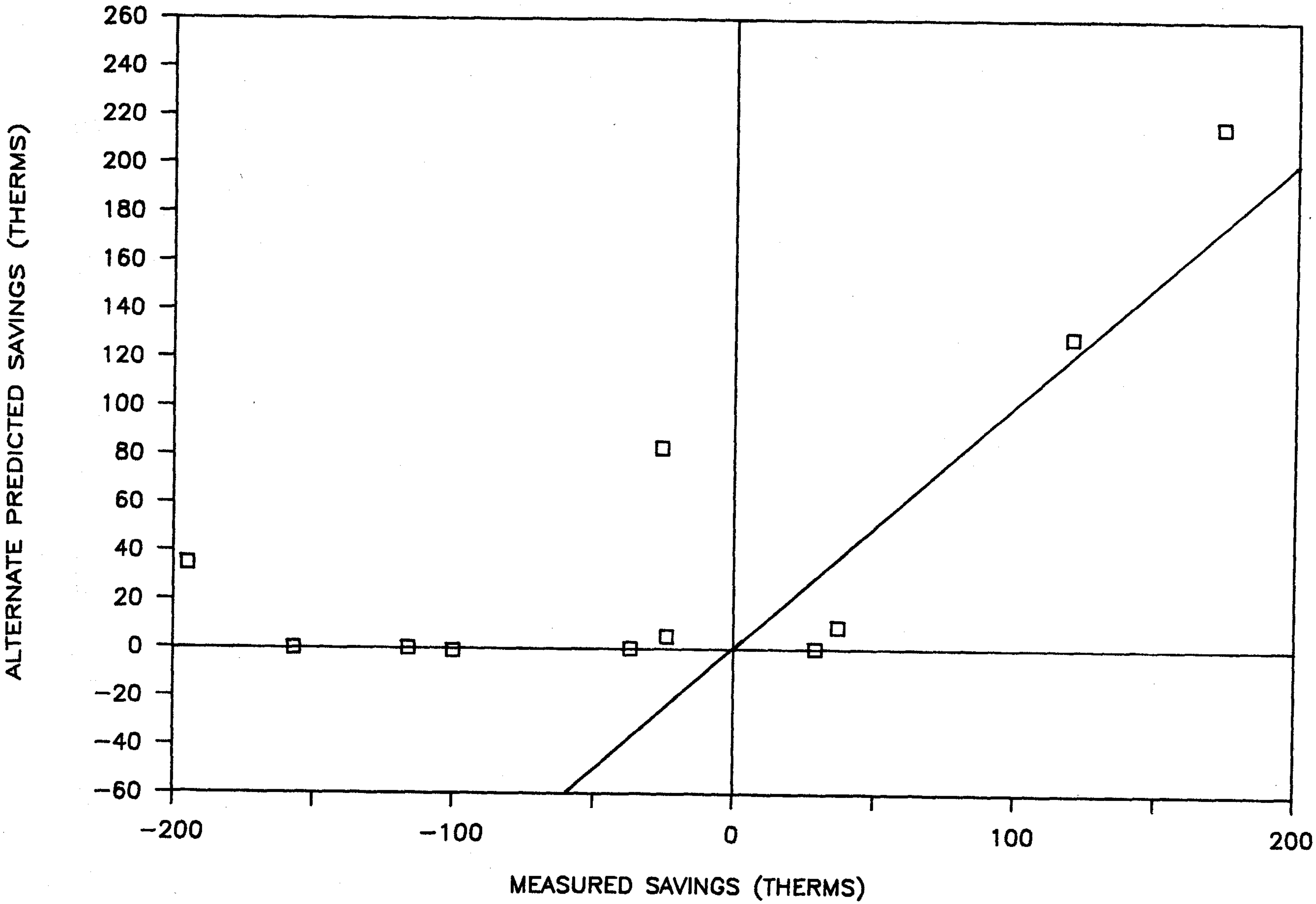
HVOL = House Volume (cuft)

CAIR = Heat Capacity of air = 0.0183 Btu/cuft/F

HDW = Heating Degree Weeks at specified balance point temperature

FEFF = Furnace Efficiency = 0.75

Figure G.1 compares the alternate predicted savings with the measured savings, as in Fig. 5.1 using the original predicted savings. The correlation coefficient for the alternate comparison is .71 compared with the original coefficient, .34.


ALTERNATE PREDICTED SAVINGS (THERMS)
MEASURED SAVINGS (THERMS)
260
240
220
200
180
160
140
120
100
80
60
40
20
0
−20
−40
−60
−200
−100
0
100
200

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