ARE AIR LEAKAGE REDUCTION ELEMENTS OF WEATHERIZATION PROGRAMS EFFECTIVE?

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ABSTRACT

An important element of residential weatherization programs is sealing air leakage sites in dwellings to reduce air infiltration. Progressive programs often use a blower door to help locate leakage sites and determine when work is no longer cost effective, even though there are few definitive data quantifying increased performance using blower doors. Measures such as high-density wall insulation can also help reduce house air leakage by sealing leakage paths in sidewalls, building overhangs, and other unique building structures.

A two-year field test involving more than 300 fuel-oil-heated houses weatherized under the U.S. Department of Energy Weatherization Assistance Program was conducted in nine northeastern states. Pre- and post-weatherization air leakage measurements from these houses are presented to confirm that the use of blower doors and installation of high-density wall insulation achieved greater-than-average leakage reductions. The measurements also indicated that air leakage reduction work can still be improved considerably, as post-weatherization air leakages remained well above minimum guidelines for most houses.

Air leakage measurements and occupant perceptions of indoor conditions before and after weatherization showed that although most houses may still be considered leaky, the occupants felt that indoor comfort and draftiness showed substantial improvement.

INTRODUCTION

In 1989 the U.S. Department of Energy (DOE) Weatherization Assistance Program Division requested that a national laboratory conduct an up-to-date assessment of its program. One part of the study involved single-family, fuel-oil-heated houses in nine northeastern states and was conducted during program years 1991 and 1992. A split-winter experimental design was used that involved a total of 337 houses—222 weatherized and 115 controls. No weatherization work was done on the control houses during their respective test heating season. Each house was instrumented and monitored for one heating season to obtain field measurements of fuel-oil consumption and indoor and outdoor temperatures for the pre- and post-weatherization parts of the heating season. Information supplied by local agencies about the weatherization work done on each house, and the authors' own measurements of on-site fuel use, the envelope, blower-door leakage, furnace efficiency, and safety were used in the evaluation. Evaluation results are presented in several papers (Levins and Ternes 1993, 1994). This paper describes the air-leakage measures performed and their effectiveness.

HOUSE CHARACTERISTICS

An average house participating in the field test was 63 years old (it was built in 1928) and had two floors built over a concrete basement. The nonbasement floor area of the house averaged 1,332 ft^2 (1,989 ft^2 including the usually unheated basement). A 19-year-old oil-fired, forced-air furnace or hydronic boiler heated the house. There was some insulation in the attic and in the exterior walls, but none in the floors or foundation. The wood-framed houses had an exterior wall area of 1,608 ft^2 and an average window area of 169 ft^2. The predominant type of window was wooden single-pane with a metal storm window.

TABLE 1 **Comparison of Mean Values of Selected House Characteristics**

Category	Control	Weatherized
GENERAL INFORMATION		
Number of occupants	3.25	2.84
Year house built	1930	1927
HOUSE AREAS (ft^2)		
Basement	747	667
Living space	1372	1313
Heated living space	1337	1243
External wall	1670	1578
Window	180	164
Finished attic	794	713
Unfinished attic	839	792
INSULATION PRESENT (% of Houses)[a]		
Foundation ceiling	8%	21%
Foundation wall	6%	6%
Exterior wall	52%	60%
Attic	82%	91%

[a]These conditions existed at the end of the heating season, after weatherization had been done on the weatherized houses. The control houses had not been weatherized.

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The test houses were randomly divided into weatherized and control groups to remove bias between the groups. While it is impossible to achieve absolute "equality" among the houses in each group, the random assignment procedure appeared to work well. Table 1 shows that the groups were similar in most areas. The insulation category in Table 1 compares conditions in weatherized houses after weatherization to the control houses, which received no weatherization. The insulation existing in the weatherized houses before weatherization is not known.

AIR LEAKAGE MEASUREMENT PROCEDURES

Blower doors were used to test the air leakage of each weatherized house before and after weatherization to determine changes in house air leakage caused by the combined weatherization measures. Control houses were also tested during the pre- and post-weatherization periods. Data collected included blower door airflow rates at several pressure differences between the inside and outside of the house, indoor and outdoor temperatures during the test, and local shielding class.

The air leakage tests were performed using a standard procedure, adapted from a utility, for evaluating more than 500 Northwest houses (Palmiter 1989), that minimized errors from procedural differences between technicians as well as gauge-induced errors from calibration and hysteresis. The procedure ensured comparability of individual house measurements made under this study even though tests may have been performed by different organizations or personnel using different brands of blower doors on houses with different air leakage rates located in a wide variety of locations, elevations, and terrains.

Testing was done only with the house depressurized because studies performed by Sherman (1984) and the utility project indicated that pressurization tests did not improve the accuracy of air leakage measurements or reduce standard errors.

Each house was measured in its normal leakage condition in this study. Only those openings in the envelope that could naturally be shut (such as windows, external doors, and fireplace dampers) were closed for the test rather than sealing all possible openings in the envelope (such as vents, animal gates, and window air conditioners). Reasons for this choice were to represent the "as found" condition of a house desired for the evaluation, to test a house in the condition requiring the least modification by testing personnel, and to limit the set-up time required for a house.

WEATHERIZATION MEASURES THAT AFFECT AIR LEAKAGE

Air leakage measures were the most common weatherization measure installed in this study, with 96% of the houses receiving them. General caulking and weatherstripping of doors and windows was performed on 86% of the weatherized houses, making it the most frequent air leakage measure done. Another important air leakage measure was air-sealing work (defined as work emphasizing air leakage bypasses), which was performed in 54% of the houses, most often using a blower door. Air distribution system leaks were repaired in only 18% of the houses, but this represents about 50% of those houses with air distribution systems. These frequencies follow those of a companion evaluation of single-family and small multifamily houses heated by all fuel types (Brown et al. 1993). They found that 95% of the houses in the cold weather region (primarily those states bordering Canada, including Maine, New Hampshire, and Vermont) received some type of air leakage measure, 81% received general caulking, and 36% received air-sealing work using a blower door. However, only 7% of the total houses in the single-family study (or 10% of those with distribution systems) received any distribution system work.

Installation of attic insulation (either for the first time, where no insulation previously existed, or added to existing insulation) was commonly performed, and rim or band joist insulation was installed in about one-third of the weatherized houses. Floor and wall insulation were installed in 25% and 20% of the houses, respectively. The standard, two-hole technique for installing wall insulation was usually employed, although some installations used a single-hole, tube-fill approach that allowed wall insulation to be installed at higher densities. The latter method can decrease air infiltration, and it emphasizes concurrent sealing of major air leakage bypasses while insulating the walls.

Energy-efficiency improvements to windows and doors were performed more frequently in 1992 (in 53% of the houses) than in 1991 (28% of the houses), with storm windows causing the main difference, as they were installed in 25% of the houses in 1991 and in 37% in 1992. Storm doors were installed in only 6% of the houses.

Structural weatherization measures, performed in more than 80% of the houses, included replacing broken window panes or entire window units, reglazing windows, and fixing or replacing doors. Window-glazing activity in more than 50% of the houses is consistent with the level of caulking and weatherstripping performed as an air leakage measure.

AIR LEAKAGE ANALYSIS

Differences between pre- and post-weatherization measurements in the weatherized houses represent changes due to all work performed in the houses (including, for example, wall insulation and storm windows) rather than just specific infiltration reduction work, because our measurements were made at the beginning and again at the end of the heating season.

Pre- and/or post-weatherization measurements were made in 329 houses, but both pre- and post-weatherization measurements were made in only 250 of these houses (for a variety of reasons, including illness, "don't want it done," nobody home, etc.). The data set was further refined by only including houses with high-quality pre- and post-weatherization air leakage data (coefficients of determination, R^2, greater than 0.96) and with consistent basement door positions (closed or open) for the pre- and post-weatherization measurements (most measurements were performed with the basement door closed). The final sample size was 167 houses (54 control houses and 113 weatherized houses). The coefficient of determination criteria eliminated 35 houses and the basement door position criteria eliminated the remaining 48 houses. Raising the coefficient of determination cutoff to 0.98 would have reduced the sample size by another 19 houses.

The airtightness of the houses and the change following weatherization were analyzed using the airflow rate at a 50-Pa pressure difference (house depressurized) across the building shell (cfm50).[2] The cfm50 value was calculated from the data collected under the air leakage tests. An air leakage test consisted of a series of airflow measurements (Q) made at pressure differences between the inside and outside of the house (ΔP). These data follow the power law form

$$Q = C(\Delta P)^N \tag{1}$$

where C and N are constants. These values were regressed by the method of weighted least squares (CGSB 1986) to determine the best values of C and N because $\ln(Q)$ vs. $\ln(\Delta P)$ is a linear relation. Values of Q can then be estimated for selected values of ΔP. The cfm50 value was calculated using Equation 1 and 50 Pa as the value of ΔP.

RESULTS

Table 2 contains results of the analysis. The average sample pre-weatherization air leakage was 3,468 cfm50 for the control houses and 3,295 cfm50 for the weatherized houses. The two groups were statistically the same at a level of significance of 0.05.

TABLE 2 **Control and Weatherized House Air Leakages**

	Control houses	Weatherized houses
Number of houses	54	113
Pre-weatherization air leakage (cfm50)	3468	3295
Post-weatherization air leakage (cfm50)	3304	2725
Air leakage reduction (cfm50)	164	570

[2]Other possible indicators include effective leakage area, average seasonal air exchange rate ($cfm_{natural}$), and these indicators normalized to the total exposed surface area of the house or house volume.

Distributions of pre-weatherization air leakages are shown in Figure 1. The distributions of the two groups were generally similar, with the majority of the houses (69% of the control houses and 78% of the weatherized houses) having air leakages between 1,500 and 4,500 cfm50. Pre-weatherization air leakages were less than 1,500 cfm50 in 11% of the control houses and 4% of the weatherized houses. Houses in the Northeast with air leakages between 1,000 and 1,400 cfm50 are generally considered to be tight, yet still have enough air exchange with the outside to supply combustion air and remain "healthy" (Tsongas 1993), requiring no infiltration reduction work.[3] Any infiltration reduction work performed on such houses would achieve small reductions and could potentially cause indoor health and moisture problems.

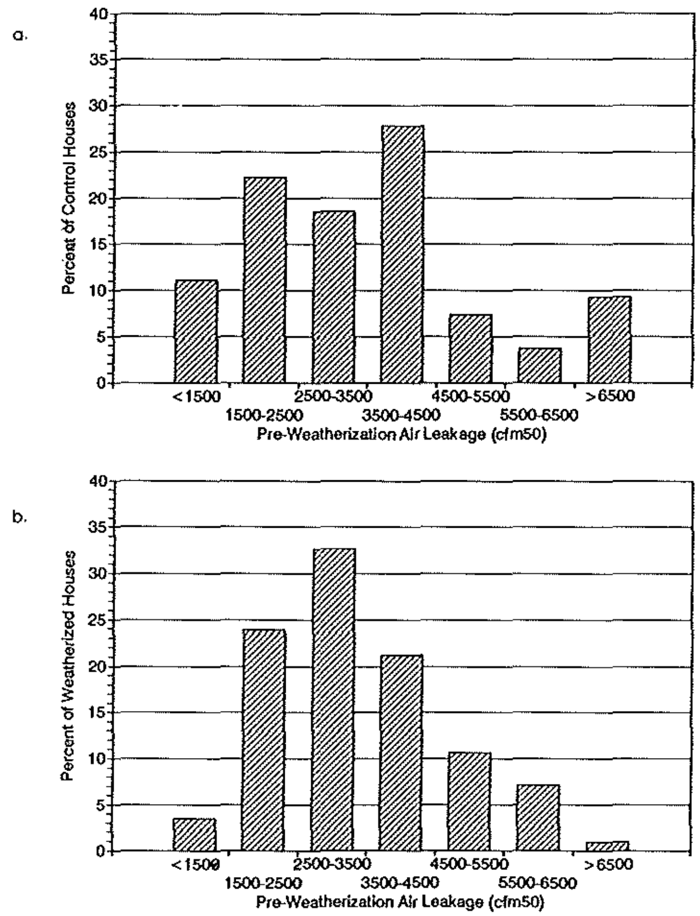

Figure 1 *Distribution of pre-weatherization air leakages for the control (a) and weatherized (b) houses. For the control houses, the mean was 3,468 cfm50 and the standard deviation was 1,735. For the weatherized houses, the mean was 3,295 cfm50 and the standard deviation was 1,263.*

[3]This range assumes five or fewer occupants live in the house, normal shielding, and a living area less than 1610 ft^2. The range is higher for more occupants, better shielding, and larger living areas.

On the other hand, 9% of the control houses and only 1% of the weatherized houses had pre-weatherization air leakages greater than 6,500 cfm50. These houses have severe air leakage problems that should benefit considerably from air-sealing work.

Weatherization work performed under the study achieved statistically significant reductions in air leakage. Table 2 shows that the average sample air leakage reduction was 164 cfm50 for the control houses and 570 cfm50 for the weatherized houses. The average control house reduction was not statistically different from zero at a 0.05 level of significance. The average weatherized house reduction was statistically different from zero and from the control house reduction at this same 0.05 confidence level.

Berry and Brown (1994) found in their single-family study that control houses in cold and moderate regions had average measured air leakages of 2,807 and 3,354 cfm50, respectively, while weatherized houses measured 2,378 and 2,968 cfm50 after weatherization for the two regions. Their moderate region included Massachusetts, Connecticut, Rhode Island, New York, New Jersey, and Pennsylvania, among others. Both their measured air leakage levels and calculated reductions of 429 and 386 cfm50, caused by weatherization, are in good agreement with our results.

Distributions of the air leakage reductions for the control and weatherized houses are shown in Figure 2. A majority of the control houses had reductions between −500 and 500 cfm50, with 43% of the control houses having negative reductions (an increase in the air leakage) and 57% having positive reductions.[4] The distribution for control houses was expected to be more closely distributed around zero, as no weatherization work was performed in them. Changes observed for individual houses could be due to random measurement errors, although the test procedure was intended to minimize this.

About one-third of the weatherized houses had relatively small air leakage reductions (0 to 500 cfm50) and about one-third had reductions between 500 and 1,500 cfm50. Negative reductions were experienced in 21% of the houses, mainly between 0 and −500 cfm50.[5] The shift to lower air leakages is evident in comparing the post-weatherization distribution in Figure 3 to the pre-weatherization distribution in Figure 1b. Following weatherization, 76% of the weatherized houses had air leakages of less than 3,500 cfm50, while 60% did before weatherization. Figure 4 shows that the air leakage reductions of

[4]Similar results are reported for control houses from other field tests (Ternes et al. 1991), although the reductions are more closely distributed around zero than they are here. On the other hand, consistent air leakages can be measured as demonstrated in other field tests (Ternes et al. 1993).

[5]Previous field studies (Ternes et al. 1991; Ternes and Levins 1992) report few weatherized houses with negative reductions.

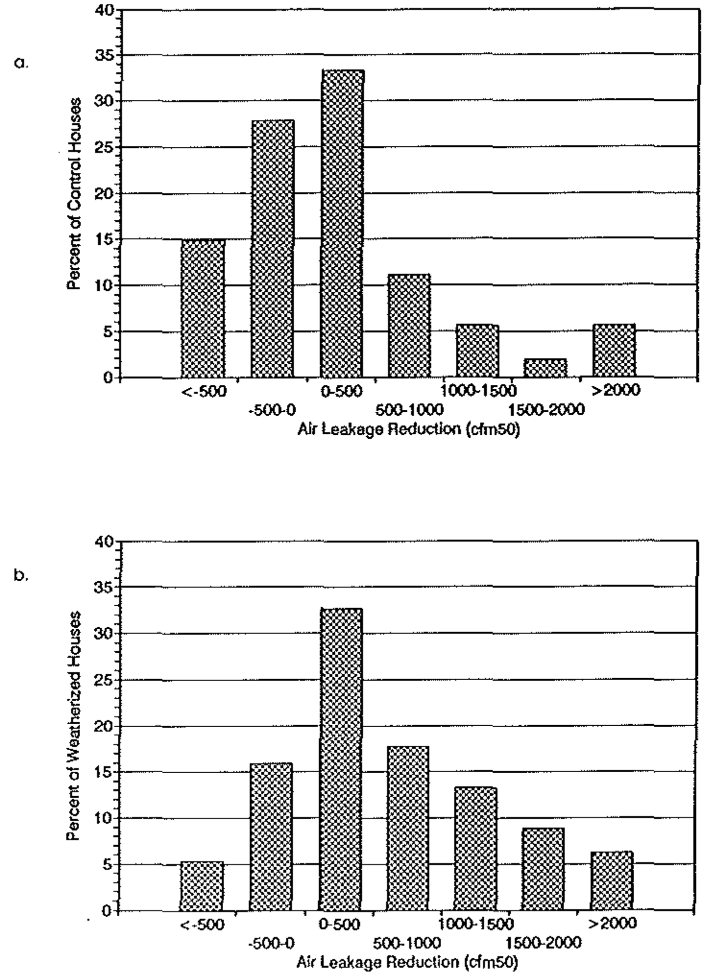

Figure 2 *Distribution of air leakage reductions in the control (a) and weatherized (b) houses. For the control houses, the mean was 164 cfm50 and the standard deviation was 1,099. For the weatherized houses, the mean was 570 cfm50 and the standard deviation was 821.*

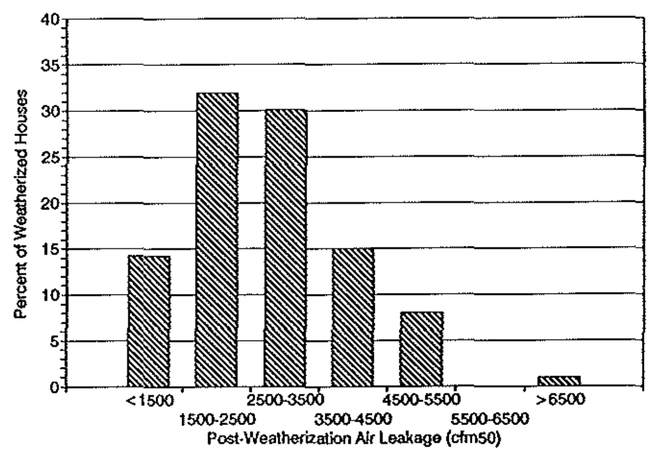

Figure 3 *Distribution of post-weatherization air leakages for the weatherized houses. The mean was 2,725 cfm50 and the standard deviation was 1,165.*

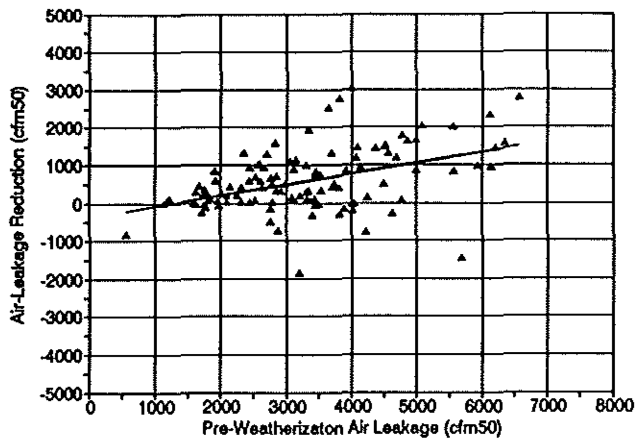

Figure 4 *Relationship between pre-weatherization air leakages and air leakage reduction for the weatherized houses.*

the weatherized houses were somewhat dependent on pre-weatherization air leakages, although significant scatter does exist. Small reductions were generally achieved from houses with pre-weatherization air leakages of less than 2,000 cfm50.

Of the 21% of weatherized houses showing increased air leakage, about 40% showed increases less than 75 cfm50, or less than 3% of the pre-cfm50. Such values are less than the stated accuracy of blower door readings, especially when the readings were taken from six to nine months apart, implying that these small increases are not statistically different from zero.

About half the weatherized houses showing increased air leakage had increases above 200 cfm50, and 65% of this group only received weatherstripping/caulking as an air leakage measure. This does not explain why these houses showed increases, but only that minimal air leakage reduction work was performed on many of these houses. Any other explanations for increased air leakage after weatherization are both speculative and qualitative—additional air leakage paths may have developed, occupant behavior may have negated gains, etc.

The effect of the following factors on air leakage reductions achieved in the weatherized houses was investigated, and the results are summarized in Table 3: use of a blower door to perform infiltration reduction work, presence of a forced-air distribution system in the house, and installation of normal and high-density wall insulation. Average pre-weatherization air leakages were statistically the same for houses with the factor as without in all cases. This result implies that:

- Houses weatherized using a blower door were not leakier than other houses to begin with (leaky houses did not receive preferential treatment).
- Houses with forced-air distribution systems did not have natural infiltration rates greater than houses with other distribution systems (although when the forced-air distribution system is operating, it may still affect house air leakage).
- Houses receiving wall insulation were not inherently leakier than houses that did not. This result does not address the question of whether houses without wall insulation were more leaky than houses with insulated walls because all houses without wall insulation did not necessarily receive this measure.

Air leakage reductions averaged 240 cfm50 greater in houses in which blower doors were used in sealing work compared to houses not receiving this treatment. Similarly, reductions were 175 cfm50 greater in houses receiving wall insulation and 300 cfm50 greater in houses receiving high-density wall insulation. Houses with forced-air distribution systems did not have greater air leakage reductions than houses without forced-air distribution systems, despite the fact that air distribution systems are often leaky and contribute to total house leakage. None of these differences was statistically significant at a 0.10 level of significance (using a blower door and installing high-density wall insulation would just be significant at a 0.20 level of significance).

TABLE 3 **Factors and Air Leakage Reductions in the Weatherized Houses**

Factor	Number of Houses in the Sample	Pre-Weatherization Air Leakage (cfm50)	Air Leakage Reduction (cfm50)
Blower door used	88	3290	623
Blower door not used	25	3312	383
Forced-air distribution system present	56	3217	588
Forced-air distribution system not present	57	3372	552
Wall insulation installed	43	3271	678
Wall insulation not installed	70	3310	503
High-density wall insulation installed	14	3253	833
High-density wall insulation not installed	99	3301	533

INDOOR CONDITIONS

Occupants were asked to rate the comfort and draftiness of their houses before and after weatherization on a scale of 1 to 7, where 1 was poor and 7 was very good. Draftiness relates more closely to air leakage, while comfort is affected more by increased surface temperatures due to such things as insulation. Table 4 summarizes the results. The control house responses to both categories did not change significantly from the pre-weatherization period to the post-weatherization period, while comfort, and especially draftiness, improved after weatherization according to weatherized house responses. The average value of the control house responses was higher than that of the weatherized house responses for both in the pre-weatherization period, which could illustrate some bias to the weatherized group responses—they may have been thankful for the weatherization work and wanted to make us feel good. Nevertheless, weatherized house responses were higher than control house responses in the post-weatherization period, indicating improved satisfaction from weatherization.

TABLE 4 Occupants' Perceptions[a] of Comfort and Draftiness Before and After Weatherization

	Before weatherization response		After weatherization response	
	Controls	Weatherized	Controls	Weatherized
Comfort	3.5	2.9	3.5	4.2
Draftiness	3.6	2.6	3.6	5.6

[a]Ranking scale boundaries: 1 = poor, 7 = very good.

COSTS

The region-wide mean value for installation costs averaged $1,192 for program years 1991 and 1992. Material costs for these years were $745 for an average house weatherized, and labor costs were $447. A cost breakdown of materials for an average weatherized house (Figure 5) shows that insulation materials accounted for a third of the total materials, while air leakage, window and door, and space-heating system materials were approximately equal at 12% to 18%.

ENERGY SAVINGS ASSOCIATED WITH INSTALLED MEASURES

An analysis conducted to determine which measures provided the most savings in this study was difficult. Many different measures and procedures were applied

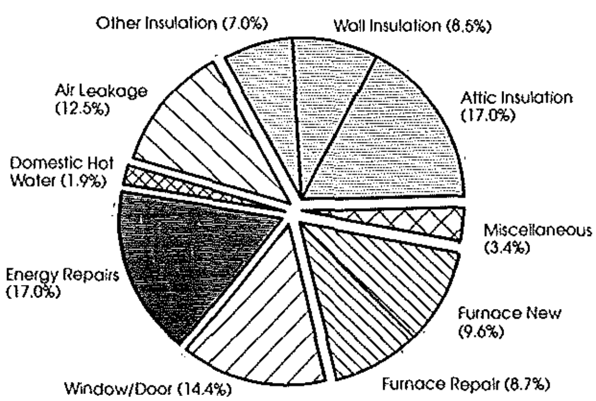

Figure 5 *Material cost breakdown for an average weatherized house (average material cost for a house was $745).*

to or performed on the tested single-family fuel-oil-heated houses. The houses had many different construction characteristics and occupant types. Identical measures often perform differently with different types of houses or different conditions existing in the same type of house.

Average measured savings in houses receiving a particular measure during weatherization were compared to the remaining houses to determine the savings associated with the particular measure. Table 5 contains a summary of the average measured savings in houses receiving a particular measure during weatherization. Measures were divided into three different major groups in the table—houses receiving air leakage control, insulation, and window and door measures.

Since several different measures were usually installed in a house, the savings shown are for the house with the specific measure in question plus all other measures that may have been installed. It is not possible to precisely estimate the energy saved by a single measure from the analysis because the particular measure may not be the cause of a significant difference in energy savings, and many measures can be correlated, such as new attic insulation and attic ventilation. It is obvious that attic ventilation alone will not decrease energy consumption, but about 80% of the houses receiving first-time attic insulation also received an attic ventilation measure. First-time attic insulation usually does decrease energy consumption. Another important factor was that all weatherized houses did not start out at the exact same condition (some already had attic insulation and some did not, etc.).

The only air leakage control measure that showed statistically significant (0.05 level of significance) higher than average savings was using a blower door for sealing. Houses receiving this treatment also appeared to have higher than average pre-weatherization fuel-oil consumption. No statistically significant differences existed between houses receiving general caulking, distribution system work, or other infiltration reduction techniques and houses not receiving these measures, although houses that had distribution system leaks addressed had the highest mean savings.

CONCLUSIONS AND RECOMMENDATIONS

The authors conclude that weatherization as performed under the Weatherization Assistance Program is effective in reducing air leakage, but that opportunities for further reductions remain. These air leakage measurements showed that weatherized houses were more airtight following weatherization than before, but they are still much leakier than minimum ventilation guidelines. This means that either air leakage reduction work is either not being done properly or options for further reductions are not being pursued. We believe the latter

TABLE 5 House-Level Fuel-Oil Savings Associated with Selected Measures

Houses Receiving Measures Including	Annual Pre-Weatherization Consumption (gallons)	Annual Savings (gallons)	Number of Dwellings	Significance Level
All Houses	930	162	149	
Air Leakage				
General caulking	936	168	136	—
Air sealing without a blower door	919	162	77	—
Air sealing with a blower door	1041	193	40	•
Distribution system	952	206	26	—
Other	924	195	31	—
Insulation				
Attic insulation, first time	1032	237	54	•
Attic insulation, added	829	165	55	—
Wall insulation, standard	970	223	42	•
Wall insulation, high-density	965	313	16	•
Rim or band joist insulation	1012	171	32	—
Floor insulation	970	194	58	—
Other	986	193	33	—
Windows and Doors				
Storm window(s)	951	154	46	—
Storm door(s)	784	30	7	•
Other	795	71	6	—

• = differences in savings between houses receiving this measure (along with any other measures) and houses not receiving this measure (but receiving any other measures) are different from zero at the 0.05 level of significance.

— = differences in savings are not significantly different from zero.

to be the case because houses cannot be cost-effectively tightened to minimum ventilation standards.

We also conclude that using blower doors to assist in air-sealing work, and installing normal and high-density wall insulation produce greater than average air leakage reductions, even though it cannot be verified statistically. These same air leakage measures are also associated with statistically significant, higher than average fuel-oil savings.

Another fact demonstrating the effectiveness of air leakage reduction measures is that most occupants of weatherized houses thought their houses were more comfortable and much less drafty after weatherization than before.

We recommend additional technology transfer effort to increase blower door use during air-sealing work, since only half the weatherized houses used a blower door for that measure. A guidebook developed by a committee of experts covering air leakage theory, using a blower door, measuring air leakage, finding and sealing leakage sites, and incorporating a blower door into a weatherization program would be a useful technology transfer and training document.

Existing state and local weatherization agency data should be collected to further study air leakage reductions being achieved and the tightness of houses before and after weatherization.

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