Are Heating-System Retrofit and Tune-Up Programs Really Increasing the Efficiency of Oil-Fired Systems?

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A space-heating-system component allowing installation of new energy-efficient equipment or component retrofits, cleaning and tuning of existing systems, and correcting safety deficiencies is an important part of progressive residential weatherization programs. Common sense tells us that a heating system, after it has been cleaned and tuned up, will usually have a higher steady-state efficiency, burn cleaner with less smoke and carbon monoxide, and reduce fuel bills. These should especially be true in fuel-oil-fired heating systems, which tend to burn dirtier than similar gas-fired systems.

Oak Ridge National Laboratory conducted a two-year field test involving over 300 homes to evaluate the U.S. Department of Energy Weatherization Assistance Program for low-income fuel-oil-heated houses. One conclusion was that houses receiving oil-burner clean and tune-ups did not increase in system steady-state efficiency any more than a similar group of weatherized and control houses not receiving clean and tune-ups. A set of oil-burner performance goals proposed by the Alliance to Save Energy were not attained by most of the tuned-up oil systems, thereby not achieving a major benefit of heating-system programs from current implementation methods.

Whole-system replacements produced higher-than-average savings and systems with flame-retention burners had higher steady-state efficiencies and used less fuel than normal burners. Other space-heating-system measures including setback thermostats were not statistically significant in reducing fuel-oil consumption. Secondary benefits of improved safety (such as lowering carbon monoxide concentrations in flue gases and inside houses) and reliability were present in weatherized houses, although not in as high a quantity as is often espoused.

Introduction

The U.S. Department of Energy (DOE) Weatherization Assistance Program Division requested Oak Ridge National Laboratory (ORNL) to conduct an up-to-date assessment of their program. One part of the study involved single-family, fuel-oil-heated houses in New England, New York, New Jersey, and Pennsylvania, and was conducted during program years 1991 and 1992. A split-winter experimental design involving 337 houses–222 weatherized and 115 controls–was used (Temes et al. 1992). 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 us by local agencies about the weatherization work performed on each house, and our own measurements of on-site fuel usage, the envelope, blower-door leakage, furnace efficiency, and safety were used in the evaluation. This paper discusses the heating-system measures that were performed and their effectiveness.

Approximately 80% of the weatherized houses used an audit or diagnostic procedure to identify needed space-heating system measures, and 53% of these houses received a measure. System clean and tune-ups were performed on 38% of the weatherized houses; new systems were installed in 4%; and component retrofits or repairs (new burners, cad cells, nozzle replacements, duct repairs, etc.) were performed on 26%. All space-heating work received a quality-control inspection after completion.

The Combustion of Fuel Oil

An oil-fired heating system should bum fuel oil efficiently and transfer heat generated from combustion to the living area. An efficient combustion process requires that fuel oil mix with oxygen (O_2) from air and bum completely, so the products of combustion are carbon dioxide (CO_2) and water (H_2O). Any inefficiency in the combustion process results in unburned fuel oil, carbon (soot or smoke), and carbon monoxide (CO), which reduce the amount of heat produced and also create potential health, safety, and operational problems.

Air is the source of 0_2 for the combustion process, and experience shows that 40% is usually the optimum amount of excess air to be mixed with fuel oil for proper combustion. The flue gas should contain about 11% CO_2 and 7% O_2 when 40% excess air is supplied (Alliance to Save Energy 1985).

Heat is removed from the hot combustion gas by a heat exchanger to heat a dwelling. Any soot formed represents reduced combustion efficiency and it may attach to the heat exchanger to further reduce the transfer of heat to a dwelling. Any heat not removed from the combustion gas is essentially wasted by going up the chimney, although some heat is needed to vaporize the fuel oil for combustion and to form a draft to vent combustion gases. The steady-state efficiency (SSE) is a measure of how completely a fuel burns and how well the heating system removes heat from the combustion gases under steady-state operation. The SSE is calculated from a measurement of stack O_2 (or CO_2 since they are related) concentration, stack temperature, room temperature, and stack smoke concentration.

About 13% of the heat generated in the combustion process is needed for proper operation of a natural-draft-vented fuel-oil heating system, so that 87% is the maximum obtainable SSE (Alliance to Save Energy 1985). The Alliance recommends a steady-state efficiency of 80%, an O_2 level of <7%, and a smoke number <1 (a scale from 0 to 9, where 0 is clean, 3 is marginal, and higher is too smokey) as a retrofit goal for fuel-oil systems receiving a clean and tune-up.

Clean and Tune-up Service

A clean and tune-up (C&T) is a measure performed on many fuel-oil heating systems during weatherization. This service ideally requires a licensed oil-burner technician to measure the initial SSE of the heating system. The technician then cleans the nozzle and heat exchanger, assures that the system is functioning and venting properly, and then tunes the system (adjusts the excess air supply, fan limit switches, etc.) so that it operates at its optimum efficiency. The technician should then measure the final SSE.

A C&T service should also assure that a system is functioning reliably and safely. Any malfunctions or repairs needed by other areas of a system (such as cad cells, ignitors, barometric dampers, limit switches, etc.) should be noted and taken care of at this time. Therefore, a C&T should promote increased reliability and safety, as well as efficiency in an oil-fired heating system.

Effectiveness of Clean and Tune-ups

All test houses that did not receive a new heating system or a new burner (the only measures that would affect the SSE other than a C&T) and that had valid SSE data for both pre- and post-weatherization periods were used for this analysis. A total of 208 houses were in the sample: 72 control houses and 136 weatherized houses. All 72 control houses and 65 of the weatherized houses did not receive a C&T, while 71 of the weatherized houses did receive a C&T.

We measured SSES at both the beginning and end of the respective heating season for each house. Table 1 summarizes these measurements. The average SSE value at the start of the pre-weatherization period was 75.0% for control houses, 77.2% for weatherized houses receiving no C&T, and 75.0% for weatherized houses receiving a C&T. Average SSE values at the end of the post-weatherization period were 76.6% for control houses (an average increase of 1.5 percentage points), 77.7% for weatherized houses not receiving a C&T (an average increase of 0.5 percentage points), and 75.8% for weatherized houses receiving a C&T (an average increase of 0.8 percentage points). The control houses, none of which received C&Ts, showed the greatest average increase of all three groups.

T-tests of SSE measurements among weatherized houses receiving a C&T, weatherized houses not receiving a C&T, and control houses showed that SSE changes were not significantly different from each other at a 95% confidence level. Berry and Brown (1994) came to the same conclusions about SSE changes in a study involving gas furnaces between weatherized houses receiving a C&T and weatherized houses not receiving a C&T. Table 2 summarizes the t-test results regarding SSE, smoke, and flue gas CO concentration among the three groups in question.

The data imply that clean and tune services as performed in the Weatherization Assistance Program do not work, are not done properly or completely, or are not long--lasting (our final SSEs were measured at the end of the heating season). These implications are surprising and contradict normal logic. Our measured data were taken by (often the same) personnel from the same contractor using new combustion analyzers supplied by us, so we believe that our data are sufficiently accurate and consistent.

Figures 1-3 show the distributions of the pre-weatherization SSEs and the changes in SSE for control

Table 1. Mean Values of Measured Space-Heating-System Performance Parameters

Group	Number in Sample	Adjusted Steady-State Efficiency Pre	Adjusted Steady-State Efficiency Post	Adjusted Steady-State Efficiency Difference	Smoke Number Pre	Smoke Number Post	Post CO in Flue Gas (ppm)	Age of HVAC System
WEATHERIZED								
No Clean & Tune	65	77.2	77.7	0.5	1.5	1.7	134	17.6
Clean & Tune	71	75.0	75.8	0.8	2.2	2.1	73	24.1
CONTROL								
No Clean & Tune	72	75.0	76.6	1.5	2.2	1.7	97	20.1

Table 2. T-Test Statistics Between Groups for Clean and Tune-Up Comparisons

Group	Are Values Different at 95% Confidence Level: Pre SSE	Post SSE	Difference	Pre Smoke	Post Smoke	CO in Flue
W C&T vs W No C&T	Yes	Yes	No	Yes	No	Yes
W C&T vs Controls	No	No	No	No	No	No
W No C&T vs Controls	Yes	No	No	No	No	No

Notes: W C&T vs W No C&T means Weatherized Houses with a C&T vs Weatherized Houses with No C&T.

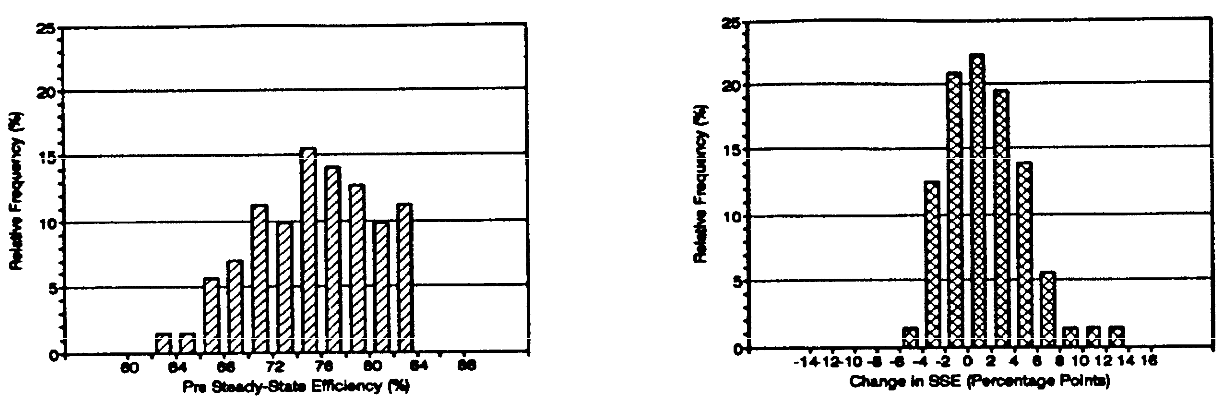

Figure 1. Distribution of Pre-Weatherization Adjusted Steady-State Efficiency (a) and Efficiency Change (b) for the Control Houses, None of Which Received a Clean and Tune-Up

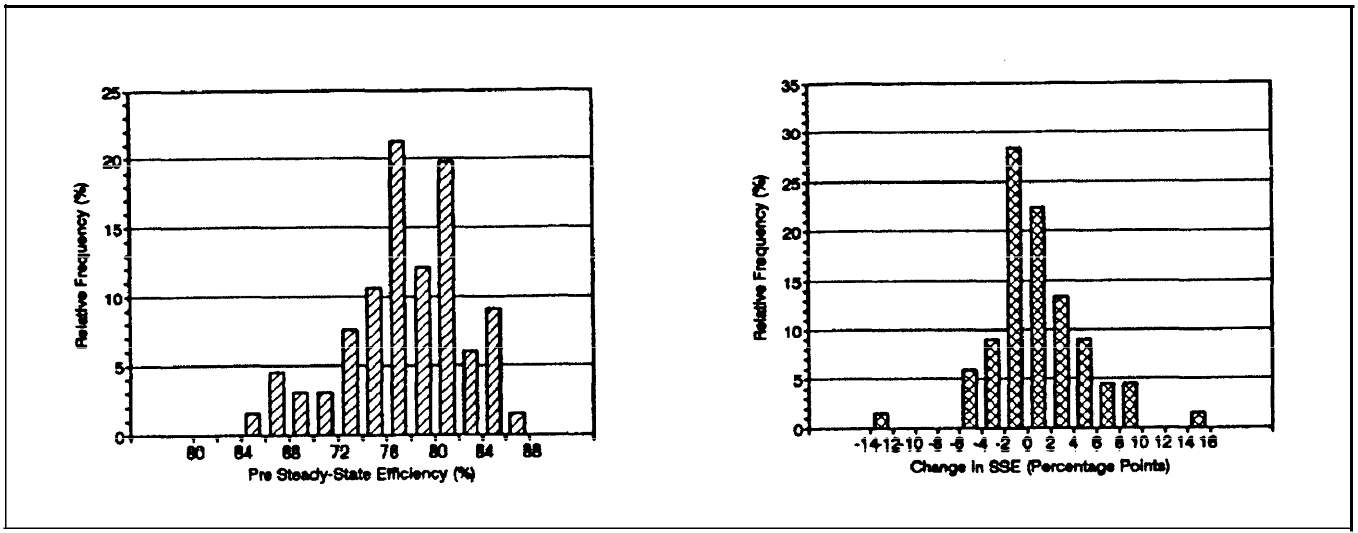

Figure 2. Distribution of Pre-Weatherization Adjusted Steady-State Efficiency (a) and Efficiency Change (b) for the Weatherized Houses, None of Which Received a Clean and Tune-Up

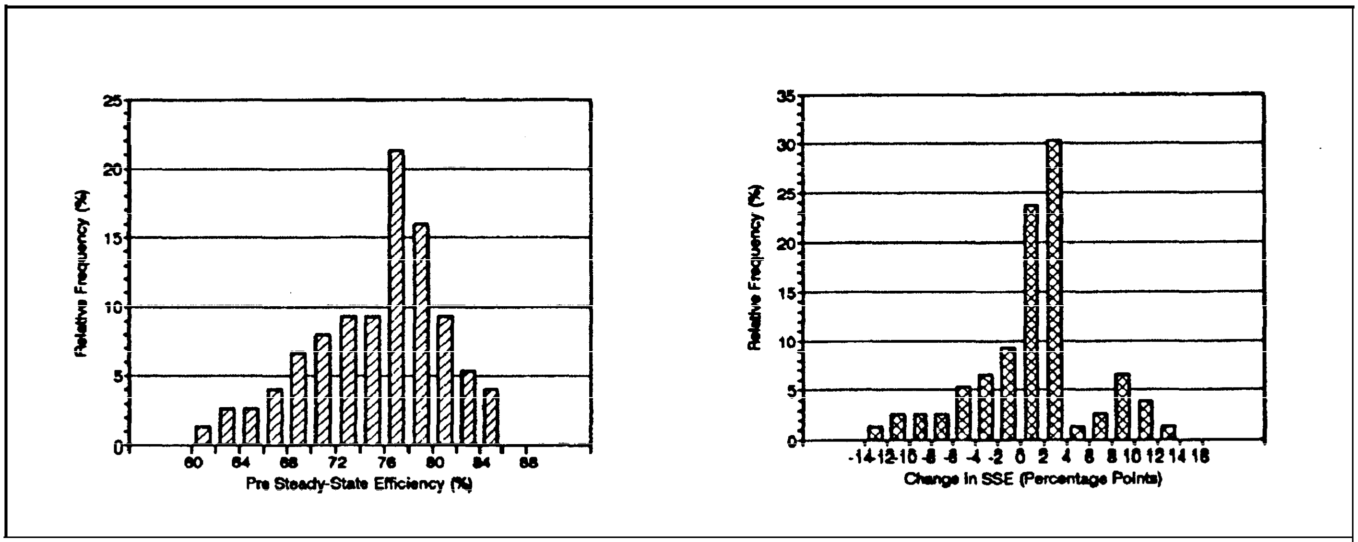

Figure 3. Distribution of Pre-Weatherization Adjusted Steady-State Efficiency (a) and Efficiency Change (b) for the Weatherized Houses Receiving a Clean and Tune-Up

houses, weatherized houses not receiving C&Ts, and weatherized houses receiving C&Ts, respectively. Table 3 contains a semi-quantitative comparison of these figures. The control and the weatherized houses not receiving a C&T, Figures 1 and 2, respectively, were similar in that they both showed a normal distribution around zero. About half of each group showed changes in SSE within a -2 to 2 percentage point range, with about 40% showing changes greater than 2 percentage points, and 15% showing changes of less than -2 percentage points.

Figure 3, the distribution for weatherized houses receiving a C&T, is somewhat skewed around zero. It shows a third of these houses changed in SSE from -2 to 2 percentage points, 45% had increases over 2 percentage points, and 22% changed less than -2 percentage points. The overall impression from Table 3 is that not much change in SSE has taken place on average among the three groups, which is in agreement with the t-tests of the data in Table 2.

Figure 4, a plot of pre-weatherization SSE vs change in SSE for weatherized houses receiving C&Ts, appears to offer more insight into the effectiveness of clean and tune services. It shows a general trend (the R^2 value of the regression line is low, about 0.2) for measured changes in SSE to increase for sites with low SSEs at the beginning of a heating season. If the pre-weatherization SSE was greater than about 77%, the change in SSE was usually negligible or negative. Conversely, about a 3% improvement was obtained at sites with a pre-weatherization SSE

Table 3. Comparison of Distribution of Steady-State Efficiency Changes

Group	SSE Distribution About Zero	Percent of Houses with SSE Changes ±2%	> 2%	< -2%
Controls	Normal	44%	43%	13%
Weatherized No C&T	Normal	50%	37%	17%
Weatherized with C&T	Skewed	33%	45%	22%

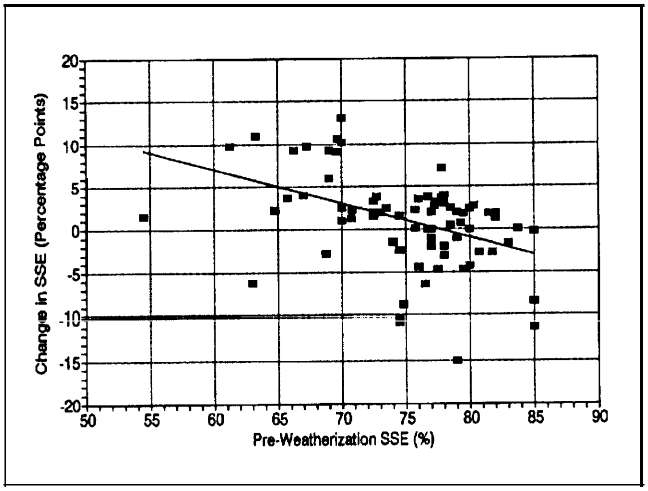

Figure 4. Comparison of the Change in Adjusted Steady-State Efficiency to the Pre-Weatherization Efficiency for Weatherized Houses Receiving a Clean and Tune-Up

of 70%. Temes et al. 1991 found the same type of behavior in SSE for weatherized houses receiving a C&T in a study dealing with gas space-heating systems in New York.

However, these same trends also hold for the weatherized houses not receiving C&Ts and for the control houses. This implies that performing a C&T on a system with a low SSE does not guarantee an increase in SSE. This is another perplexing conclusion that defies belief. The natural question arises again as to whether or not C&Ts are being performed properly.

No contradictions to the above conclusions appeared when the different subgroups of system types (forced-air systems and hydronic boilers) and systems with and without flame-retention burners (FRBs) were analyzed.

Table 1 also contains flue gas smoke numbers, flue gas CO concentrations at the end of the heating season, and estimated HVAC system age. Systems receiving C&Ts were older on average than those not receiving them, but the average age of each group was relatively old. The average flue gas CO concentration at the end of the heating season was less for systems receiving C&Ts than for those not receiving them, which is good. Smoke numbers were lower for systems not receiving C&Ts than for those receiving them, which is not good. However, T-tests of smoke numbers between C&T and non-C&T groups followed the same pattern as those for the SSE measurements—not significantly different from each other at a 95% confidence level.

Table 4 contains data for systems with and for those without FRBs. Although systems with FRBs were more efficient than non FRBs (77.2% versus 74.1% for weatherized houses receiving C&Ts, and 79.0.0% versus 73.9% for weatherized houses not receiving C&Ts), the changes in SSE for FRBs were small and essentially matched those in Table 1. FRBs are inherently more energy efficient than non FRBs, and our data reinforces that. Systems with FRBs were newer (average age of 12.6 years) than those without FRBs (average age of 28.3 years). Note that burner age and system age may differ, as an old system may have a newer burner installed.

The performance goals set forth for a C&T by the Alliance to Save Energy were generally not obtained as only 4% of the houses met all the criteria. If the 7% O_2 requirement is ignored, then 17% of the houses would meet them. However, the average pre-weatherization SSE for these 17% of the houses was 80.3%, already above the 80% goal before the C&T. If the smoke number requirement of <1 were also ignored, then 30% of the houses would pass.

It appears that, on average, changes in the SSE of an oil-fired system cannot be explained by C&T services. However, a C&T might improve the seasonal performance of an oil system. It can also assure that a system is operating properly, which should increase the reliability and safety of a system.

Table 4. Mean Values for Systems with and without Flame-Retention Burners

SYSTEMS WITH FLAME-RETENTION BURNERS	Number in Sample	Adjusted Steady-State Efficiency Pre	Post	Difference	Pre-Weath. Consumption (Gallons/Yr)	Heated Area (ft²)	Age of HVAC System
WEATHERIZED							
No Clean & Tune	40	79.0	79.5	0.6	802	1256	7.7
Clean & Tune	26	77.2	78.4	1.2	883	1314	19.9
CONTROL							
No Clean & Tune	34	76.7	78.8	2.1	864	1539	12.8
Overall Summary	100	77.8	--	--	844	1367	12.6
SYSTEMS WITHOUT FLAME-RETENTION BURNERS							
WEATHERIZED							
No Clean & Tune	22	73.9	74.5	0.6	1003	1482	35.0
Clean & Tune	43	74.1	74.4	0.3	994	1358	25.8
CONTROL							
No Clean & Tune	36	73.2	74.6	1.4	947	1360	27.1
Overall Summary	101	73.7	--	--	979	1386	28.3

Many states understandably require licensed technicians to audit systems and perform tune-ups because of code requirements and for legal reasons, but this leads to increased costs—and the energy savings are low. It is ironic that a licensed technician must be on site to take a measurement in order to decide whether or not a system should be cleaned and tuned. The cost of the C&T is rather small once the technician is on site and all set up. An agency auditor, however, could conduct a SSE measurement as part of an audit and avoid the cost of having a burner technician make a special trip to decide whether or not to conduct a C&T. This situation occurred at many agencies in our sample.

No-Heat Problems and Reliability

We devised a crude reliability index for furnaces by comparing the number of mechanical problems resulting in furnace malfunctions (no-heat situations) occurring in the pre-weatherization and post-weatherization periods between the control and weatherized houses. About 16% of both control and weatherized households had mechanical problems at one or more times in the pre-weatherization period resulting in their heating systems not being able to operate. Mechanical problems decreased during the post-weatherization period as 12% of both control and weatherized households had similar problems. Based on the number of mechanical problems, both groups appeared equally reliable.

Another crude reliability index was devised involving the severity of the mechanical problems—the total duration of no-heat days. This was obtained by summing the products of

[Occurrences x Duration Without Heat for the Occurrence].

The values for weatherized houses were 196 days for the pre-weatherization period and 31 days for the post-weatherization period, a very substantial decrease of 84%. Control houses went from 57 to 26 total no-heat days during the same period for a 54% decrease. Keep in mind that there were 222 weatherized and 115 control houses. The weatherized houses therefore underwent the larger reduction; hence their furnaces were more reliable than the control-house furnaces when viewed from the severity aspect.

Effect of Heating-System Measures on Savings

Since fuel savings obtained by a weatherized house is the combination of heating-system measures, envelope measures, and air-sealing measures, care must be taken in interpreting the findings-a multivariate approach must be taken. The savings discussed here are the overall savings resulting from all measures.

The one space-heating-system measure that statistically impacted savings was replacement of the entire heating system. Houses receiving this measure had about twice the average fuel-oil savings. The SSE for houses receiving new systems increased from 71.0% to 82.7%, a substantial increase. However, this measure was expensive, typically costing about $2000 to $2500 to implement. Houses receiving a new system had higher pre-weatherization consumption than average; in fact, houses receiving any space-heating-system measure generally had higher than average pre-weatherization consumption.

Systems with FRBs present somewhat of an anomaly when savings are considered. We stated that FRB systems had higher SSEs than standard systems. However, FRB systems had lower savings than standard systems. This is easily explained because FRB systems used less fuel before weatherization than standard systems. Table 4 shows that the annual pre-weatherization consumption of houses with FRBs was lower than that of houses without FRBs, 844 gallons vs 979 gallons (3194 liters vs 3706 liters).

Clean and tune-ups, set-back thermostats, and component retrofits showed no statistical significance on fuel-oil savings.

Furnace Safety Inspections

Each heating system was inspected at the conclusion of the heating season. The inspection was mostly visual, but some measurements were taken, such as time for back-drafting to stop, draft buildup time, and carbon monoxide concentrations in houses. Visual inspections showed little difference overall in safety-related problems between control and weatherized houses, although the severity of such problems can differ between groups. Table 5 contains the results of the safety inspection, and Figure 5 plots the differences between weatherized and control houses by item groups. One item in the HVAC External area (combustible material near flue), two items in the Distribution System area (structural problems and no return system present), and one item in the Chimney System area (no barometric damper) were the main differences between weatherized and control houses. All differences favored the weatherized houses, indicating that they were safer than the controls.

We also checked for the presence and settings of fan high and low limit switches and cutout (maximum operating temperature limit) switches. All forced-air heating systems in both groups had fan limit switches present. Average switch settings for control and weatherized forced-air heating systems were essentially the same. Fan-on (upper-limit) switches for control and weatherized houses both averaged 137°F (58°C), while fan-off (lower-limit) switches averaged 99°F (37°C) for control houses and 100°F (38°C) for weatherized houses. Cutout switch settings averaged 197°F (92°C) for control houses and 196°F (91°C) for weatherized houses. Two control houses (7%) and two weatherized houses (2%) were noted as having potentially dangerous fan-on settings of 190°F to 200°F (88°C to 93°C).

The average operating temperatures for hydronic boilers was 164°F (73°C) for both control and weatherized houses, and cutoff temperatures averaged 190°F (88°C). Two (4%) hydronic boilers in control houses had operating temperatures of 200°F (93°C), while three (4%) boilers in weatherized houses were operating above 195°F (91°C). These five systems were operating at too-high a temperature for maximum efficiency and safety.

The average time for all systems to establish a draft was about 9 seconds. However, two control and one weatherized systems took longer than 60 seconds to establish a draft, with one of each requiring 180 seconds to establish a draft. On average, hydronic boilers established a draft in 5 seconds, while forced-air furnaces took about 14 seconds to establish a draft.

Measurements of CO in flue gases, 5 ft (2 m) from furnaces, in living rooms, in kitchens, and from hot-air registers showed that no houses had an appreciable CO problem at the end of the heating season. Differences between control and weatherized houses were minor.

Conclusions and Recommendations

An important part of progressive residential weatherization programs is a space-heating-system component that allows installation of new energy-efficient equipment or component retrofits, cleaning and tuning of existing systems, and correcting safety deficiencies. Our evaluation of over 300 fuel-oil-heated homes weatherized under the DOE Weatherization Assistance Program confirmed some positive aspects of heating-system retrofit and tune-up programs. Whole system replacements produced statistically higher-than-average savings, but the measure was expensive. Heating systems with flame-retention burners

Table 5. Comparison of Safety Related Observations Between Groups

	WEATHERIZED HOMES			CONTROL HOMES		
	Yes	No	Percent	Yes	No	Percent
HVAC EXTERNAL						
Vent damper present	61	153	28.5	27	77	26.0
Wiring Secure	196	17	92.0	93	11	89.4
Electric cutoff switch present	201	11	94.8	95	8	92.2
Fan limit switch present	98	1	99.0	26	0	100.0
No combustible material near flue	166	42	79.8	85	14	85.9
No asbestos present on HVAC	172	38	81.9	85	20	81.0
DISTRIBUTION SYSTEM						
IH part structurally OK	35	4	89.7	22	3	88.0
UH part structurally OK	145	2	98.6	67	5	93.1
NH part structurally OK	10	2	83.3	0	1	0.0
No asbestos on system	152	38	80.0	73	18	80.2
Return system present	98	2	98.0	29	3	90.6
Return air filter clean	48	40	54.5	12	12	50
FUEL LEAKS						
No leaks in fuel-oil supply line	188	13	93.5	89	5	94.7
CHIMNEY SYSTEM						
Chimney structurally OK	191	12	94.1	93	5	94.9
Chimney extend 2 ft above roof	182	16	91.9	88	6	93.6
Chimney top have 10 ft clearance	173	17	91.1	85	6	93.4
No chimney leaks	175	19	90.2	81	12	87.1
No thick debris in chimney	161	19	89.4	75	13	85.2
Flue liner present in chimney	113	66	63.1	56	29	65.9
Barometric damper present	192	17	91.9	86	15	85.1
Barometric damper installed OK	171	18	90.5	75	10	88.2
HVAC INTERNAL						
No visual heat exchanger cracks	124	4	96.9	48	1	98.0
No flue gas odor in house	133	11	92.4	57	5	91.9
HVAC PERIPHERALS						
Circulating fan OK	115	2	98.3	35	0	100.0
Zone valves OK	23	3	88.5	24	2	92.3
No furnace leaks	87	13	87.0	54	5	91.5
Barometric damper work	146	18	89.0	62	9	87.3
House thermostat OK (on/off)	178	4	97.0	92	0	100.0
DOMESTIC HOT WATER						
No combustible material by flue	61	9	87.1	24	4	85.7
Pressure relief valve on tank	185	7	96.4	87	2	97.8

Notes: IH = Intentionally heated
UH = Unintentionally heated
NH = Not Heated

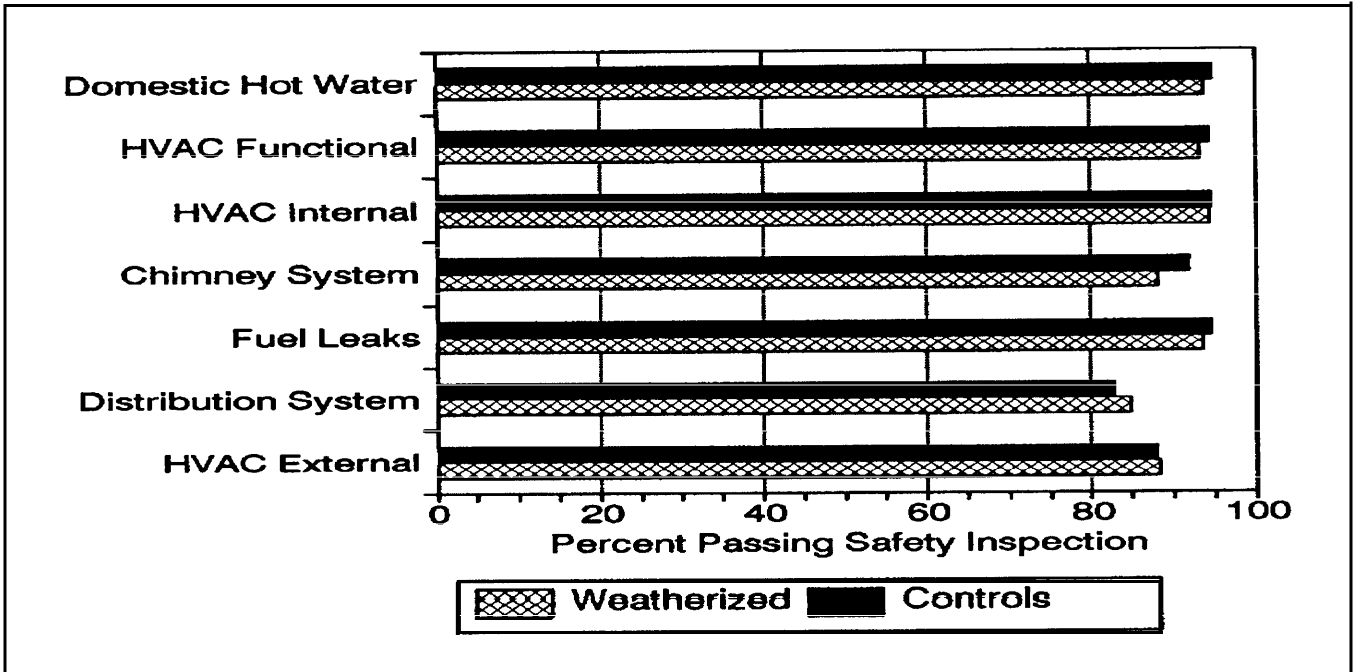

Figure 5. Safety Inspection Results Showing the Percent of Passing Evaluations for Each Safety Area Covered by the Inspection

have higher SSEs than those without them, and flame-retention burners should always be installed when a burner replacement is performed. Space-heating programs also appeared to increase the reliability of heating systems.

However, some expected positive aspects from space-heating programs could not be confirmed. Our data showed that system clean and tune-ups, the most frequent measure performed, were either not effective at improving the SSE of fuel-oil systems as performed, or the effects were not long lasting. A major benefit of heating-system programs is therefore not being achieved from current implementation methods. Space-heating-system measures such as setback thermostats and other component retrofits were not statistically significant in reducing fuel-oil consumption.

Most homes were found to be safe following a space-heating program. No houses had an appreciable problem with carbon monoxide levels inside the house. Only three furnaces took over 60 seconds to stop backdrafting. The differences in safety between control and weatherized houses were minor, however, indicating that unsafe conditions are not as prevalent as is often proclaimed.

The Weatherization Assistance Program and other sponsors of weatherization programs that include fuel-oil space-heating activities should investigate methods of improving the selection and/or application of space-heating-system tune-ups and actively promote improved tune-up procedures as a primary technology transfer activity. Problems to be solved include achieving performance goals, the need to use licensed technicians to perform SSE tests for an audit, and not tuning up systems already operating efficiently. A committee composed of experts in the field could be assembled to develop recommended approaches and consult with state personnel. Information collected by state and local agencies should be utilized to further study and refine tune-up techniques.

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