 #10534

Evaluation of Residential Duct-Sealing Effectiveness

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ABSTRACT

The purpose of this project was to evaluate duct sealing as a means of reducing the energy consumption of hot air distribution systems in central Pennsylvania houses. Five houses were studied, all of which were heated with forced-air electric heat pump systems. During the winter of 1995, the heat pump energy consumption, supply air temperature, and the temperature at the thermostat were monitored continuously for approximately two months prior to the duct retrofit. A test also was performed to measure the leakiness of the ductwork. The ducts were then sealed, concentrating on duct leakage to unconditioned spaces. After the duct-sealing project was completed, another test measuring the leakiness of the ductwork was performed to determine changes in duct leakage characteristics. Finally, the heat pump energy consumption was monitored for another month. Energy consumption was then corrected for weather changes, and the results were compared to the results from the previous two monitoring periods to determine the impact of the duct-sealing retrofit on energy consumption. Based on the heating loads during the two monitoring periods, it was found that the retrofit had a significant impact on energy consumption in only one of the houses studied.

INTRODUCTION

This study evaluated the effectiveness of sealing leaks in the ducting of residential heat pump systems to save energy during the Pennsylvania heating season. Energy loss due to duct leakage occurs when there are air leaks in ducts located outside the conditioned space in areas such as attics, crawl spaces, and basements. Studies have shown that this energy loss can be reduced by sealing the leaks in these areas (Jump and Modera 1994; Palmiter et al. 1994). Although it may reduce thermal comfort, duct leakage to conditioned spaces is not a source of energy loss because it still provides heating to the house. Duct leakage has been found to be a major source of energy loss for some heating and cooling systems in some climates. However, many of the studies done in this area focus on houses with ducting located in attics and ventilated crawl spaces. Other studies have indicated that the savings may not be as significant for houses with ducting located in basements (Blasnik and Ide 1995). This duct-sealing project focused on central Pennsylvania houses with most ductwork located in basements (some was in attics) to see if a significant energy savings could be realized.

GENERAL APPROACH

Houses Studied

Five houses located in Centre County, Pennsylvania, and between one and nine years of age were selected for this duct-sealing project. All of these houses were heated using standard air-source electric heat pump forced-air systems. The heat pumps were all located in unconditioned basements, along with some portion of the ductwork. Two of the houses studied had two heat pumps—one located in the attic and one located in the basement of each home. For this study, only the basement systems were monitored and had their ductwork sealed. Two of the houses in this study also had a small portion of their ductwork located in an unconditioned attic or crawl space. At the start of the study, airtightness tests were performed on each house. Results are shown in Table 1 in the form of equivalent leakage area (ELA) at 0.016 in. w.g. (4 Pa) (ASHRAE 1993).

Monitoring Period

The changes in energy consumption as a result of duct sealing were evaluated by monitoring the energy consumption of the entire HVAC system in each home for two months before the ducts were sealed and for one month after the ducts were sealed. Monitoring began in December 1994 and continued until May 1, 1995. The ducts were sealed in late February and early March. The

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TABLE 1
House Characteristics

Home	Age of House	No. of Stories	Floor Area, Approx., ft^2 (m^2)	Heat Pump Location	Location of Ducting	ELA $in.^2$ (cm^2)
House 1	9 years	2	2,800 (260)	2—Basement & Attic	Basement	151 (974)
House 2	3 years	2	2,400 (223)	2—Basement & Attic	Basement	48 (310)
House 3	3 years		2,000 (186)	Basement	Basement	103 (665)
House 4	3 years	2	2,300 (214)	Basement	Basement & Attic	154 (994)
House 5	2 years	2	3,300 (307)	Basement	Basement & Attic	123 (794)

range of average daily outdoor temperatures occurring before the ducts were sealed was 54°F (12°C) to 6°F (−14°C). After the ducts were sealed, the area experienced average daily outdoor temperatures ranging from 61°F (16°C) to 21°F (−6°C). During the test period, residents were permitted to use night setbacks if desired but were asked to operate their thermostats in the same way each day.

Energy Consumption

Once the energy consumption data were collected, they were corrected for weather, and the results from before and after the duct sealing were compared. The five houses were equipped with portable data loggers to measure the current drawn by the compressors and the supplementary electric coils, as well as supply and room air temperatures. Standard kilowatt-hour meters were used in some of the houses as a backup to the data loggers.

Diagnostic Testing

As a part of this study, diagnostic tests were performed to measure the leakage of the ductwork before and after it was sealed. Two of the houses studied had ductwork in unheated attics and all five had ductwork in unheated basements. To determine the amount of leakage to the outside, the unconditioned spaces were opened to the outside and closed off from the rest of the house. This was done by opening doors and windows to the outside and closing doors to the rest of the house. Using a blower door, the house was pressurized. A pressurization fan placed at the supply grille closest to the heat pump was then used to pressurize the ductwork to the same pressure as the house. Duct pressure was measured in the return duct at a location close to the heat pump. This test was performed at various pressures between 0.05 and 0.2 in. w.g. (12.4 to 50 Pa). The results were fit to a power law relationship, and the flow rate at 0.1 in. w.g. (25 Pa) was used in calculating leakage areas.

Theoretically, with the house and ductwork at the same pressure, the flow provided by the pressurization fan is entirely due to leakage to the outdoors. However, it was found during this testing that a significant pressure drop exists along the length of the duct. For example, in the smallest of the houses, pressures as high as 0.14 in. w.g. (35 Pa) and as low as 0.06 in. w.g. (15 Pa) were measured in the duct when the reference point was pressurized to 0.1 in. w.g. (25 Pa). Therefore, leakage to the outdoors was overestimated for ductwork in the house located between the pressurization fan and the reference point and underestimated for ductwork in the house located on the opposite side of the reference point. These imbalances in in-house leakage on either side of the reference pressure point may have significantly impacted the results of this test. Although this method of estimating duct leakage works well in many geographical areas (Jump and Modera 1994; Palmiter et al. 1994), a test method that pressurizes the ductwork using the air handler fan may be a better choice for Pennsylvania houses. Construction practices in Pennsylvania result in a large amount of in-house duct leakage, and this leakage caused the significant pressure drop along the duct.

Also, as a part of the diagnostic testing, combustion safety tests were performed in houses that had gas appliances. Since most of the houses in the study were all electric, only two gas appliances were encountered. Changing the duct leakage characteristics of a house may change the depressurization that can occur in rooms that have gas appliances. The worst depressurization that could occur was measured before and after the duct retrofit to ensure that no houses would be left with a potential combustion safety problem.

Duct-Sealing Retrofit

The duct retrofit concentrated on three main areas: the heat pump, duct connections, and the ductwork itself. Leaks around the removable panels on the heat pump were sealed by applying weatherstripping around the inside edges of the panel. Sheet metal seams in the heat pump were sealed with caulk and metal tape. Duct connections were found to be a major source of duct leakage. In house 1, a supply duct had become disconnected where it passed through a partition in the basement and had to be reattached. Connections in all of the other houses appeared to be in good shape but were still found to be sources of leakage. Gaps were sealed with caulk and taped over until no leakage was present. The ductwork itself was found to be in good condition. Only a few small holes were found on the surface of the ductwork. Ducts that had ceiling joists or wall studs as a part of their construction were a major source of leakage. In many cases, there was not a tight fit between the duct board and the wall or ceiling. Gaps were filled in using caulk, and tape was applied until the leakage was eliminated.

RESULTS

Determination of Leakage Areas

Leakage areas were determined based on the results of the diagnostic test that was performed before and after the retrofit. Flow rates at various duct pressures were plotted and these data were fit to the power law relationship $Q = C\Delta P^n$, where C and n are empirically determined constants. From this power law relationship, the flow rate at 0.1 in. w.g. (25 Pa) was calculated. Leakage area is defined as the flow rate divided by the velocity of the flow:

$$A = Q/V$$

where

A = equivalent leakage area,
Q = flow rate, and
V = flow velocity.

The velocity of the flow was calculated using the relation:

$$\Delta P = \rho V^2/2g_c$$

where

ΔP = change in pressure,
ρ = density of air,
V = flow velocity, and
g_c = gravitational constant (32.17 lbm·ft/lbf·s^2).

All leakage areas obtained were calculated at a pressure of 25 Pa (0.1 in. w.g.).

Reductions in Leakage Area

Reductions in leakage area in the five houses ranged from 4.57% in house 4 to 93.45% in house 1, where a supply duct had become disconnected (Table 2). Neglecting house 1, the average reduction was only about 16%, although all visible leaks were sealed. While information about leakage areas is informative because it gives a general idea of how effectively the ducts were sealed, one needs to be careful about making direct comparisons between houses. The diagnostic test used in determining leakage areas assumes that duct pressure is constant along the duct (i.e., that there are no frictional losses along the ductwork). This test is standard practice; however, frictional losses do exist along the ductwork. Therefore, duct leakage inside the house will impact the results of this test. For example, large leaks located in the house between the pressurization fan and the pressure reference point will cause overestimation of leakage to the outside. The calculated leakage area will also depend on the location of the leaks in relation to where the duct pressure is measured. A leak located between the pressurization fan and the reference point will tend to be overestimated, for example, while a leak located far downstream of the reference point will be underestimated. Therefore, energy consumption is likely to be a better indicator of duct-sealing effectiveness than leakage area. House 4, with only a 4.57% improvement, did have a significant portion of its leakage occurring far from the pressurization fan, which may be why the measured reduction in area was so low.

TABLE 2
Reduction in Leakage Area

Home	Reduction in Leakage Area, ft^2 (m^2)	% Reduction
House 1	0.157 (0.014)	93.45%
House 2	0.0379 (0.0034)	9.66%
House 3	0.034 (0.0032)	8.48%
House 4	0.022 (0.0021)	4.57%
House 5	0.126 (0.012)	41.18%
Average Reduction	0.095 (0.0088)	31.47%
Corrected Average[a]	0.055 (0.0051)	15.97%

a Corrected average does not include house 1.

Analysis of Energy Consumption Data

Figures 1 through 5 show plots for houses 1 through 5 of the total energy consumption of the heat pumps for five-day periods plotted as a function of the heating degree-days in each period. Similar plots not shown here were constructed and evaluated for the other three houses.

Traditionally, a heating degree-day is defined as the difference between 65°F (18.3°C) and the average daily temperature.

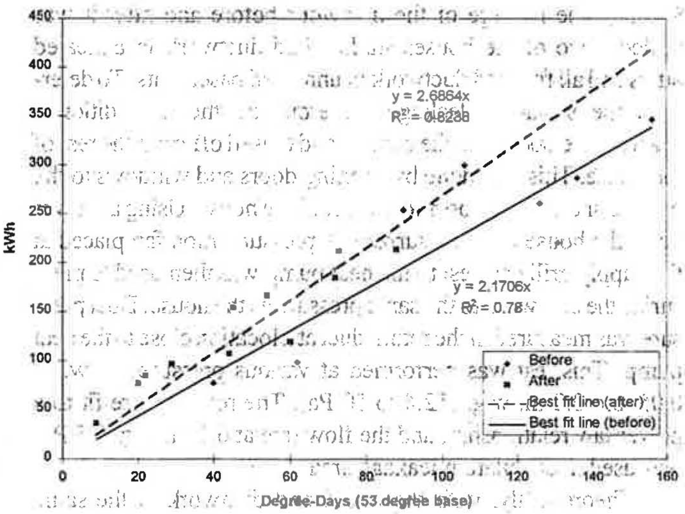


Figure 1 House 1 energy consumption.

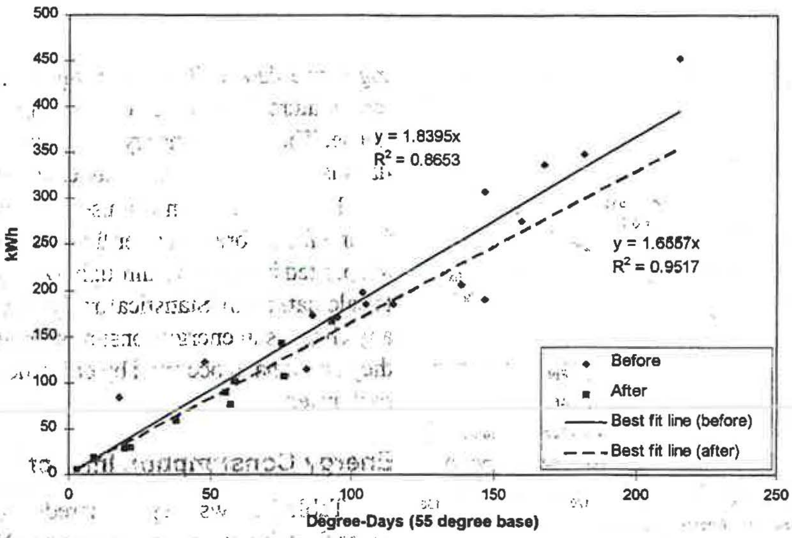


Figure 2 *House 2 energy consumption.*

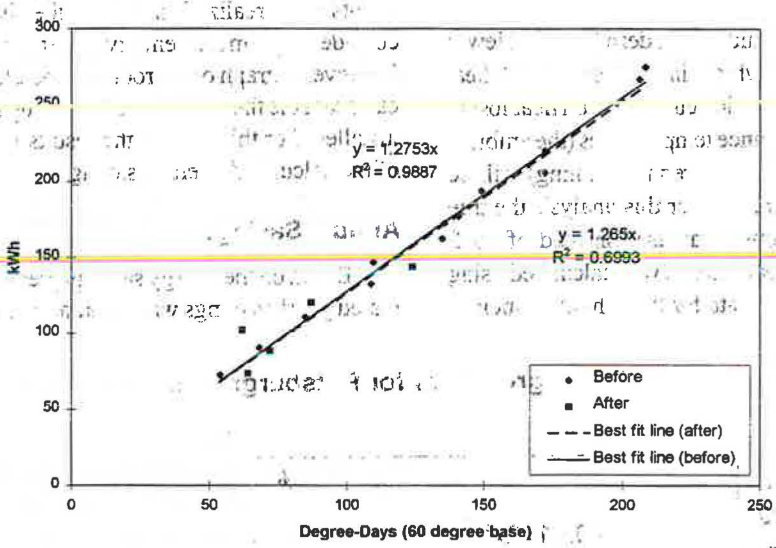


Figure 3 *House 3 energy consumption.*

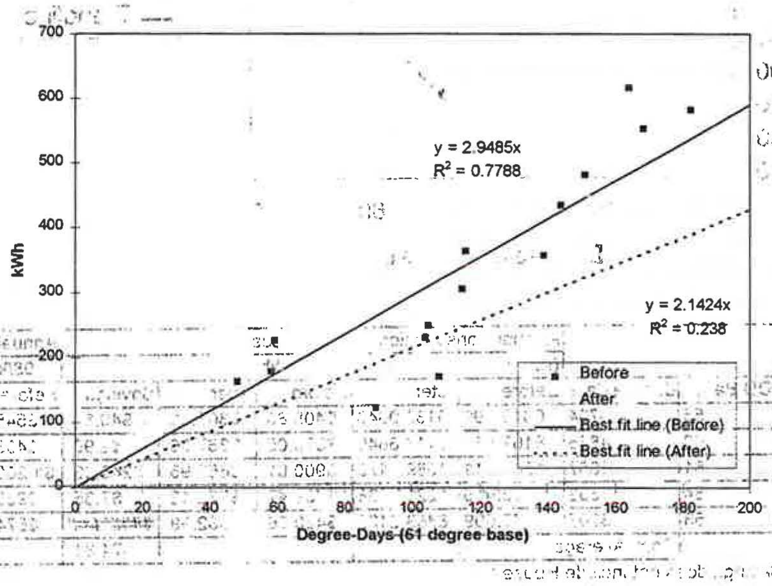


Figure 4 *House 4 energy consumption.*

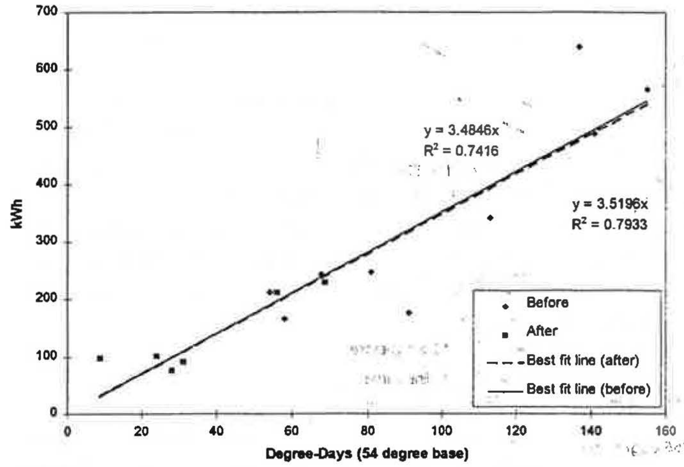


Figure 5 *House 5 energy consumption.*

However, this definition is not valid for modern houses. Newer homes have more appliances, which increases internal heat generation, and more insulation, which cuts down on heat lost to the outdoors. As a result, their balance temperatures (the ambient temperatures above which they do not require heating) will be lower than in older houses. Therefore, for this analysis the true balance temperature of each house was used instead of 65°F (18.3°C). The balance point for each house was calculated using all available energy consumption data for these houses, including some data collected during unrelated tests. This balance temperature was used to compute heating degree-days for each house. The plot of energy consumption versus heating degree-days is a straight line that passes through the origin.

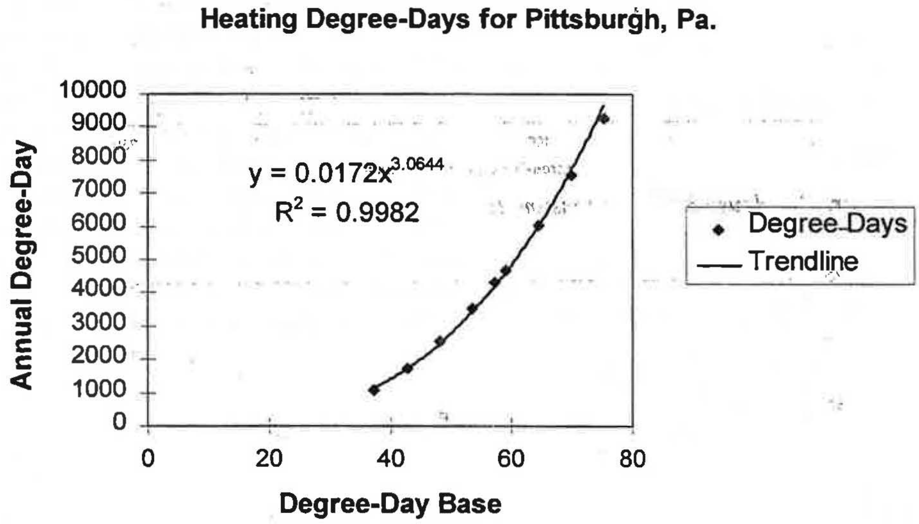
Linear regression was used to calculate the slope of the best fit line for before and after the duct retrofit. These best fit lines are plotted in Figures 1 through 5 along with the data points used to calculate them. Statistical analysis was used to predict whether any changes in energy consumption were truly significant, or if they could have occurred by coincidence if no retrofit had been performed.

Energy Consumption Impact

Table 3 shows the percent reduction in energy consumption for each of the five retrofitted houses. Note that a negative reduction represents an increase in energy consumption. Significant results were realized in four of the five houses. House 1 used considerably more energy after the duct-sealing project. However, a graph of the room temperature at the thermostat indicates that the thermostat was turned up after the duct retrofit was installed. For this reason, the results from house 1 were left out of the calculated average savings.

Annual Savings

Based on the energy savings predicted by this study, an estimated yearly savings was calculated. Since the degree-day base



	Slopes (kWh=slope*DD)				Annual Consumption (kWh)		Annual cost ($.06/kWh)			Annual cost ($.08/kWh)		
Homeowner	Before	After	DD Base	degree days	Before	After	Before	After	Savings	Before	After	Savings
Belden	1.8395	1.6557	55	3704	6813.899	6133.0643	$408.83	$367.98	$40.85	$545.11	$490.65	$54.47
Bittner	1.2753	1.265	60	4836	6167.476	6117.6646	$370.05	$367.06	$2.99	$493.40	$489.41	$3.98
Clark	2.9485	2.1424	61	5087	15000.11	10899.178	$900.01	$653.95	$246.06	$1,200.01	$871.93	$328.07
Gant	3.5196	3.4846	54	3502	12324.5	12201.938	$739.47	$732.12	$7.35	$985.96	$976.16	$9.80
McLaughlin	2.1706	2.6864	53	3307	7177.599	8883.2135	$430.66	$532.99	########	$574.21	$710.66	########
				Corr. Average					$74.31			$99.08

* Corrected Average Savings does not include House 1

Figure 6 *Expected energy consumption and degree-days.*

TABLE 3
Savings Associated with the Duct Retrofit

Home	% Savings
House 1[a]	−23.74%
House 2	9.99%
House 3	0.81%
House 4	27.34%
House 5[b]	0.99%
Corrected Average Savings	**9.44%**

a Due to a change in the thermostat setting in this house, these data are not included as a part of the corrected average.
b These changes were found to be statistically insignificant

TABLE 4
Expected Annual Savings Associated with Duct Sealing

Home	Savings ($0.06/kWh)	Savings ($0.08/kWh)
House 1[a]	$−102.34	$−136.45
House 2	$40.85	$54.47
House 3	$2.99	$3.98
House 4	$246.06	$328.07
House 5	$7.35	$9.80
Corrected Average	**$74.31**	**$99.08**

a Corrected average does not include house 1.

TABLE 5
Confidence Levels Associated with Significance of Results

Home	Method 1: Energy Consumption	Method 2: Heating Load
House 1[a]	98%	98%
House 2	95%	not significant
House 3[b]	80%	not significant
House 4	98%	98%
House 5[b]	not significant	not significant

a This decrease is known to be due to a change in the thermostat setting for this heat pump.
b These changes were found to be statistically insignificant.

varies from house to house, the number of degree-days in a typical year was different for each house even though they are located in the same city. ASHRAE degree-day data calculated for Pittsburgh, Pennsylvania (chosen as the closest location with tabulated values available), at several different degree-day bases were fit to a power law relationship so that the number of annual degree-days for any degree-day base could be obtained. The total number of annual degree-days for each house was calculated and used to predict energy consumption before and after the ducts were sealed. The total cost of energy used for heating and the expected annual savings associated with sealing the ductwork was calculated for electric utility rates of $0.06/kWh and $0.08/kWh. Figure 6 shows the expected energy consumption and degree-days for each house. Table 4 shows the expected annual savings in each house with utility rates of $0.06/kWh and $0.08/kWh. Again, the corrected average savings does not include house 1.

Alternate Analysis Method

Because electric heat pump systems use both heat pumps and electric resistance heaters, they do not operate at constant efficiency. In warmer weather, they usually have higher efficiencies than in colder weather. Since the weather was warmer after the duct sealing than before, an alternate method of analysis was used to correct for the effects of weather on the efficiency of the heating system.

To account for weather changes, the heating load on the system was used to compare the energy use before and after the sealing of the ducts. The heating load of the electric resistance heaters is equal to the power consumed. The heating load of the heat pump is equal to the power consumed multiplied by the heat pump coefficient of performance (COP). Since the current drawn by the resistance heaters and the outdoor unit of the heat pump (the compressor and outdoor fan) were logged separately, it was possible to multiply the power consumption of the outdoor unit by the COP of the heat pump and obtain the heating load for each of the monitoring intervals. Figures 7 through 11 show plots of heating load versus degree-days for houses 1 through 5 for the same five-day intervals that were plotted using the original analytical method. Again, similar plots were made and evaluated for the remaining three houses. Linear regression was again used to calculate the best fit lines, and the anticipated savings are summarized in Table 5. For this analysis, only the data for houses 1 and 4 were found to be statistically significant.

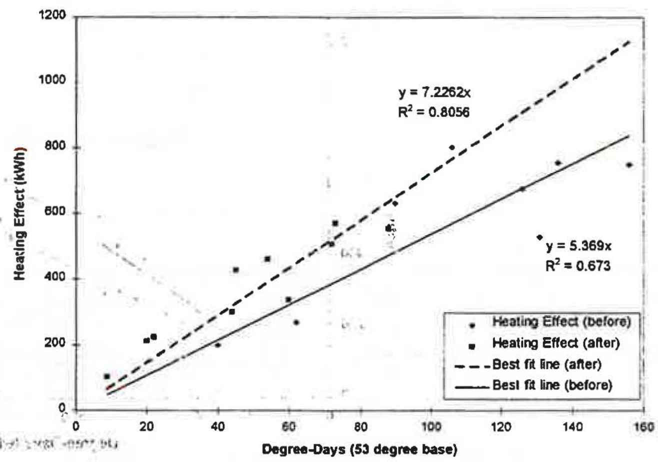


Figure 7 House 1 heating load.

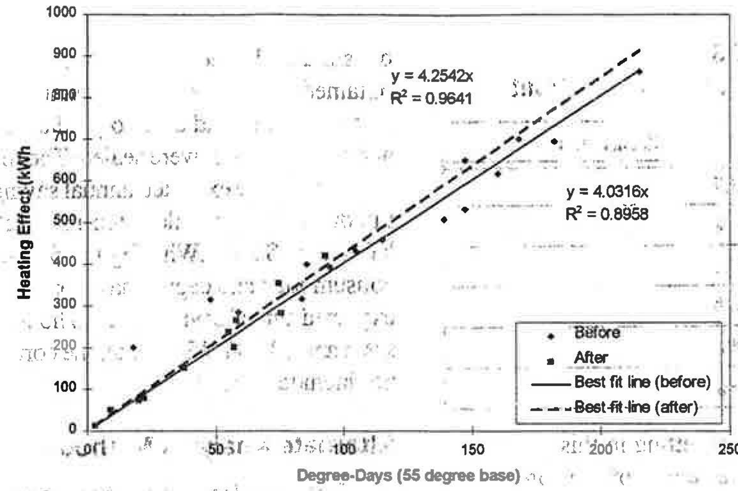


Figure 8 House 2 heating load.

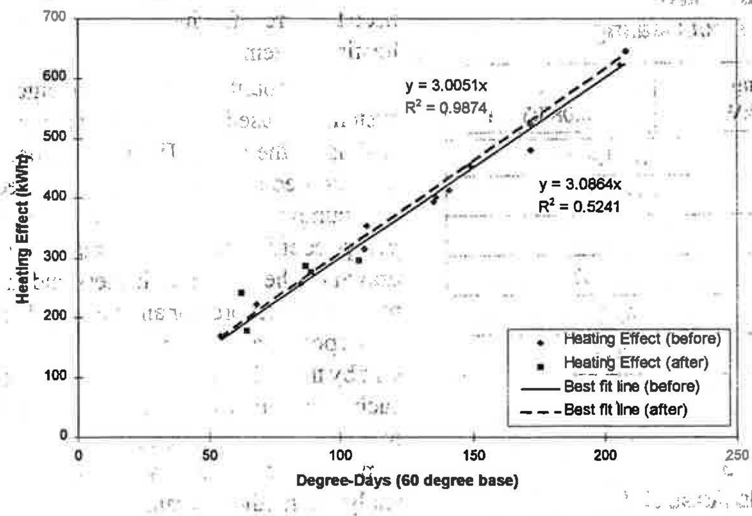


Figure 9 House 3 heating load.

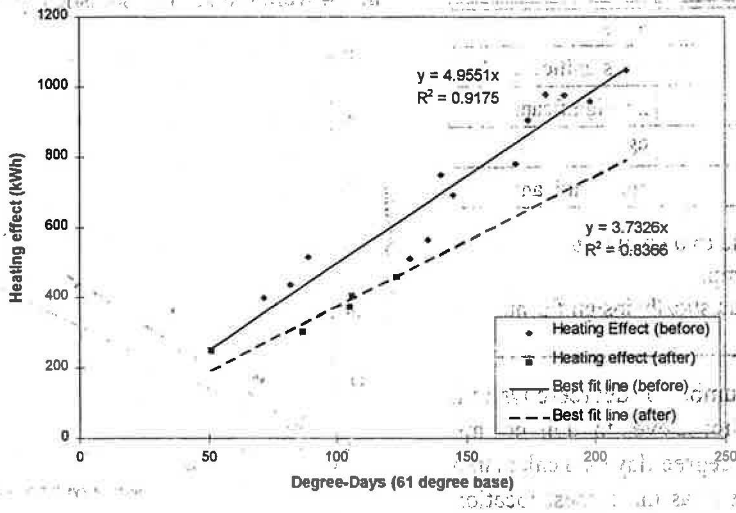


Figure 10 House 4 heating load.

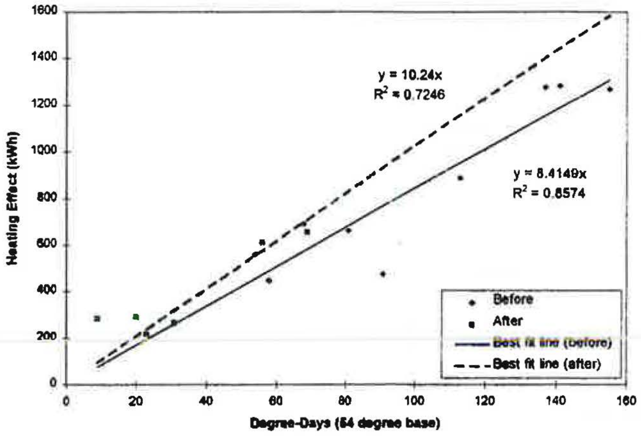


Figure 11 House 5 heating load.

Statistical Significance of Results

A statistical analysis was performed to determine if the savings predicted by this study were truly significant or if they could have occurred purely by chance even if no retrofit had been done. To determine if the predicted best fit lines were significantly different from one another, a two-sample t-test was used. The slope of each point was calculated, and the points from data collected before and after the duct sealing were compared. With a confidence level of 80% or better, significant decreases in energy consumption were found in three of the houses and a significant increase was found in house 1 due to a change in its thermostat setting. However, when heating load was considered, significant changes were found only in houses 1 and 4. Table 6 shows which houses experienced statistically significant changes for each of the two analytical methods used. Where significant changes occurred, the confidence level of the difference between the two sets of data is shown as a percentage.

CONCLUSIONS AND RECOMMENDATIONS

The ductwork in the houses studied was found to be leaky, and sealing the ducts significantly reduced leakage to unconditioned spaces. However, the duct retrofit did not result in a significant energy savings in most of these houses. This may be partly because their basements are semiconditioned spaces used for some activities such as doing laundry. Under these circumstances, some heating of the basement due to duct leakage is desirable. Also, stack effect causes air to move from the basement to the upper areas of the house, so most of the heat lost to the basement is eventually recovered. For this reason, a house with most of its ductwork located in the basement may see little energy savings even when extremely leaky ductwork is sealed. The results of other projects have also indicated that this is true (Blasnik and Ide 1995).

One house in this study did benefit greatly from the duct retrofit. This house had a significant portion of its sealed leakage in the attic, indicating that, in this climate, leakage in attics may cause a greater energy loss than leakage in basements. However, another house in this study also had ductwork located in the attic, and it did not realize a significant savings after the duct retrofit. These results indicate that duct sealing is not likely to result in worthwhile savings in many central Pennsylvania houses, especially if most of the ductwork is located in heated spaces or in basements.

This study did not consider the energy impact of duct sealing during the summer air-conditioning season. Basements in Pennsylvania often remain cool during the summer. Sealing of duct leakage that allows exchange of air between the basement and the rest of the house will cause an increase in the sensible cooling load. This could increase the peak cooling load in the summer months.

The results of this study do not indicate that duct sealing will result in energy savings in Pennsylvania, as significant savings were only realized in one of the houses when heating loads were considered. However, due to the small number of houses tested, this study should not rule out the possibility of energy savings as a result of duct sealing. More study may be needed to identify the types of houses that would benefit from duct sealing in this climate.

ACKNOWLEDGMENT

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