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Abstract

Inefficiencies in air distribution systems have been identified as a major source of energy loss in U. S. sunbelt homes. Research indicates that approximately 30-40% of the thermal energy delivered to the ducts passing through unconditioned spaces is lost through air leakage and conduction through the duct walls. Field experiments over the past several years have well documented the expected levels of air leakage and the extent to which that leakage can be reduced by retrofit. Energy savings have been documented to a more limited extent, based upon a few field studies and simulation model results. Simulations have also indicated energy loss through ducts during the off cycle caused by thermosiphon-induced flows, however this effect had not been confirmed experimentally.

A field study has been initiated to separately measure the impacts of combined duct leak sealing and insulation retrofits, and to optimize a retrofit protocol for utility DSM programs.

This paper describes preliminary results from 6 winter and 5 summer season houses. These retrofits cut overall duct leakage area approximately 64%, which translated to a reduction in envelope ELA of approximately 14%. Wrapping ducts and plenums with R-6 insulation translated to a reduction in average flow-weighted conduction losses of 33%. These experiments also confirmed the appropriateness of using duct ELA and operating pressures to estimate leakage flows for the population, but indicated significant variations between these estimates and measured flows on a house by house basis. In addition, these experiments provided a confirmation of the predicted thermosiphon flows, both under winter and summer conditions. Finally, average material costs were approximately 20% of the total retrofit costs, and estimates of labor required for retrofits based upon these experiments were: 0.04 person-hrs/cm^2 of duct sealed and 0.21 person-hrs/m^2 of duct insulated.

Introduction

Over the past five years, inefficiencies in residential duct systems have been identified as a major source of energy loss in sunbelt homes (Cummings 1990, Davis and Roberson 1993, Modera and Jansky 1992, Modera 1993, Palmiter 1993, Parker et. al 1993, Proctor 1991). This research has indicated that approximately 30-40% of the energy delivered to the duct systems passing through unconditioned spaces is lost through air leakage and conduction through the duct walls (Modera 1993, Palmiter 1993), and that leakage retrofits can significantly impact those energy losses (Cummings et. al. 1990, Davis and Roberson 1993, Proctor 1991). Field studies and simulations have also indicated that energy losses due to air leakage are approximately equal to energy losses due to conduction through the duct walls (Modera 1993, Parker et. al. 1993). Computer simulations have also indicated energy loss through ducts during the off cycle caused by thermosiphon-induced flows (Modera and Jansky 1992), however this effect has not been confirmed experimentally.

To further our understanding of attic duct system performance and its interactions with the building envelope and equipment, as well as to investigate a combined duct-sealing and insulation retrofit, a field study has been initiated to separately measure the impacts of combined duct leak sealing and insulation retrofits. This field study includes: 1) performing a diagnostic protocol on distribution systems in 30 houses, 2) performing short-term (~ 2-week) energy use and system-performance monitoring, including temperature measurements at key locations in the house and duct system, 3) having an HVAC contractor execute a combined duct sealing and insulation retrofit protocol on each of those houses, 4) retesting the houses with the diagnostic protocol, and 5) performing post-retrofit short-term (~ 2-week) energy use and system-performance monitoring.

To date, diagnostic measurements of envelopes and duct systems in 11 Sacramento houses have been made. This paper describes preliminary results from 6 winter and 5 summer season houses, including: 1) the reduction in overall duct leakage area, 2) the reduction in flow-weighted conduction losses, 3) a comparison of duct leakage estimated with duct ELA and operating pressures with that determined from measured register and fan flows, 4) an experimental confirmation of the predicted thermosiphon flows, 5) a sample of pre- and post-retrofit energy consumption, and 6) a limited analysis of retrofit costs.

Methodology

Participating houses were chosen by the electric utility with only a few stipulations. The primary stipulation was that an equal number of house utility bills fall on average into three usage categories: low (< 800 kWh), midrange (800 - 1500 kWh) and high (> 1500 kWh). Additionally, the houses were screened for central forced-air systems. Gas furnaces were included in the study, however the first six houses of the winter were heated with heat-pumps or electric resistance elements, thus all 11 houses reported in this paper were electrically heated or cooled. Table 1 summarizes the important characteristics of each house. Of note is house 9, which contained three heat pumps.

Testing for the 5 summer season houses began in late August, and ended in mid-October 1993. Winter season testing began in mid-November 1993 and continued through February 1994. Participants were not asked to operate their thermostats at constant setpoints during the monitoring period.

TABLE 1. Characteristics of Houses Tested

House	Year of Construction	Floor Area, m^2	System	Duct Surface Area, m^2	Existing Duct R-value
1	1959	135	A/C	31	4
2	1955	158	A/C	30	5.8
3	1983	127	A/C	12	5.8
4	1979	155	A/C	38	5.8
5	1980	78	A/C	11	5.8
6	1988	200	HP	41	5.8
7	1981	93	Resistance	15	5.8
8	1985	135	HP	30	5.8
9	1955	372	3 × HP	89	5.8
10	1957	223	HP	47	5.8
11	1988	186	HP	60	5.8

Diagnostic tests performed on the air distribution system both before and after the retrofits included measurements of house estimated leakage area at 4 Pa., of duct leakage areas at 25 Pa., of airflow into return registers and out of supply registers, of fan airflows and of operational pressures at plenums and registers. House leakage areas at 4 Pa were determined with a blower door according to ASTM Standard E779. Duct leakage areas were measured by single-point direct pressurization of the ducts. This involved taping over all registers except one, usually a return register, which was connected to the exhaust of a specially designed fan. The air flow into the ducts was determined by measurement of the pressure drop across the fan inlet surface and using a manufacturer supplied calibration. The fan airflow was controlled by varying the fan speed. Supply and return side duct leakage was measured separately by installing a seal at the central-system fan.

To measure the lower air flowrates found in residential systems, a flow capture hood was modified by attaching the calibrated fan to the free end and forcing all air across the fan's calibrated intake, shown in Figure 1. The total pressure in the flow capture hood was balanced against the room pressure by adjusting the fan speed control. This insured that the pressure drop across the register would be the same with the flow capture hood in place as in normal operation. The register air flowrate was determined by measuring the pressure drop across the fan intake and calculating the flow with the fan calibration. System fan airflows were measured with a constant injection tracer gas technique (ASTM Standard E741). Supply and return duct leakage airflows were determined from the difference between total supply and return register flows and the system fan flow. Total and static operational pressures were measured with a pitot tube.

Fast-response thermistors were placed in each supply and return register, in the plenums and at the thermostat to monitor the temperatures during the four week monitoring period of the program. Four thermistors were placed in the supply plenum and their outputs were averaged. Additionally, general purpose thermistors were placed outside, in the attic and crawlspace. The outside and attic temperatures were shielded with aluminum foil or reflective tubing to reduce radiation effects.

The power consumption of the HVAC system was monitored with clamp-on current transducers on the fan and compressor. For heat-pumps, the power demand in the strip heat was also monitored. The voltage output of each current transducer was calibrated with the actual power consumption measured by a wattmeter in a one-time test.

All cables from each sensor were connected to a central data acquisition system and computer. The computer recorded the time and channels and stored the daily data collected in compressed files for nightly transfer by cellular telephone. A computer based in the home office called each field unit and transferred and plotted the recorded data each night. A quick scan of the plots in the morning was enough to determine problems with the monitoring equipment as they arose. A total of five field units could be used simultaneously.

An HVAC contractor performed the retrofits according to a protocol developed for this study. The protocol called for direct fan pressurization of the duct system in order that the contractor have some direct indication of leak sealing progress. Direct pressurization also enabled the contractor to locate duct leaks more quickly. Regarding sealing, the protocol initially called for specific parts of the system to be sealed and the leakage savings and time required for the seal to be recorded. This was soon scrapped in favor of a more time-efficient procedure in which the contractor took an initial reading of the duct leakage, then sealed all of the most readily available leakage sites before remeasuring. Sealing efforts continued until a prescribed limit had been reached (85 m^3/hr at 30 Pa.) or the contractor determined that further efforts would not result in cost effective savings. The priority of leak sealing was highest at the plenums, and lowest at the registers. Duct leaks were primarily sealed with mastic. Butyl tape was used to cover some leaks where mastic could not be used. Seams in air handler panels were sealed with weather stripping, and badly deteriorated ducts were replaced.

Ducts were insulated with a reflective-backed R-6 duct wrap. The protocol called for wrapping suspended ducts and blanketing ducts laying on the attic floor. Plenums were wrapped with either duct wrap or fitted with ductboard. There was no time limit for duct insulation prescribed by the protocol and the contractor sometimes made a return visit on the following day to complete insulating the ducts.

Results

A. Duct Leakage Areas

Measured pre- and post-retrofit supply and return duct estimated leakage areas (ELA) are shown in Tables 2 and 3. The tables summarize the ELA, and the specific duct leakage area (SDLA), which is the duct ELA divided by the house floor area.

TABLE 2. Supply Duct Leakage Area[a] Before and After Retrofit, 13 Systems

	Pre-Retrofit cm^2	Post-Retrofit cm^2	Leakage Area Reduction cm^2	Pre-Retrofit cm^2/m^2	Post-Retrofit cm^2/m^2
minimum	63	28	30	0.23	0.12
maximum	287	115	172	1.85	0.74
average	135	60	75	0.80	0.35
std. dev., % of average	44	22	52	23	23

a. Duct ELAs calculated at 25 Pa.

TABLE 3. Return Duct Leakage Area[a] Before and After Retrofit, 13 Systems

	Pre-Retrofit cm^2	Post-Retrofit cm^2	Leakage Area Reduction cm^2	Pre-Retrofit cm^2/m^2	Post-Retrofit cm^2/m^2
minimum	16	10	3	0.07	0.03
maximum	756	126	716	3.39	0.99
average	131	35	96	0.72	0.22
std. dev., % of average	150	91	193	129	114

a. Duct ELAs calculated at 25 Pa.

The results in Tables 2 and 3 are consistent with those reported in earlier studies. As in previous studies the average return leakage was approximately equal to the average supply leakage, however there were more catastrophic leaks on the return side, and therefore a larger scatter in the pre-retrofit leakage. It also seems that the return leaks were more successfully sealed, perhaps due the fact that they were less diffuse. Overall, approximately 64% of the leakage area encountered (combined supply and return) was sealed.

Figure 2 presents the percentage of pre-retrofit duct leakage sealed as a function of the duct SLA (the pre-retrofit duct leakage area divided by the floor area of the house). This figure suggests that leakier systems are somewhat easier to seal, as would be expected. Not surprisingly, the R^2 for the regression is low, as only a portion of the scatter can be explained by that effect.

B. House Leakage Area

The average estimated leakage area of the envelopes (4 Pa) was 6.1 cm^2 per m^2 of floor area. This amount was 14% lower on average for post-retrofit measurements, indicating that a significant fraction of the envelope leakage area was reduced by simply sealing the ducts. Table 1 shows that five of the 11 houses in this study were built before 1980. The average envelope ELAs for these houses was 6.8 cm^2/m^2, while for the six houses built in 1980 and after, an average ELA of 5.5 cm^2/m^2 was measured. These results can be compared to results of an earlier field study (Modera, 1993) in which average ELAs in pre-1980 construction (19 houses) was found to be 6.0 cm^2/m^2 and in post-1980 construction (12 houses), the average envelope ELA was 3.9 cm^2/m^2. The houses in this study, especially the post-1980 construction houses, were much worse than in the previous field study.

C. Leakage Flow Reduction

There have been unresolved questions about the appropriateness of using $k\Delta P_{op}{}^n$ to estimate leakage during normal system operation (where ΔP_{op} is the average static pressure measured in the duct system, "k" is the duct leakage coefficient and "n" is the duct leakage exponent). We therefore compared $k\Delta P_{op}{}^n$ with differences of direct flow measurements at the supply registers, the fan and the return registers during normal operation. Tables 4 and 5 show this comparison. For the duct leakage predictions, "k" was obtained from the duct ELA at 25 Pa, "n" was assumed to be 0.65 and ΔP was set equal to the average ΔP between ducts and surroundings determined from static pressure measurements at the registers and plenums.

TABLE 4. Comparison of Measured[a] and Estimated[b] Supply Leakage Flows, m^3/hr (9 Systems)

	Pre-Retrofit			Post-Retrofit		
	Measured	**Estimated**	**% Diff.**	**Measured**	**Estimated**	**% Diff.**
minimum	143	131		0	41	
maximum	575	706		459	284	
average	360	310	14	221	134	39
std. dev.,% of average	47	67		73	58	

a. "Measured" = fan - register flow under normal operation

b. "Estimated" = $k\Delta P^n$ from ELA and operating pressures

TABLE 5. Comparison of Measured[a] and Estimated[b] Return Leakage Flows, m^3/hr (9 Systems)

	Pre-Retrofit			Post-Retrofit		
	Measured	Estimated	% Diff.	Measured	Estimated	% Diff.
minimum	38	40		0	26	
maximum	624	723		505	287	
average	363	289	20	214	120	48
std. dev.,% of average	57	95		84	83	

a. "Measured" = fan - register flow under normal operation

b. "Estimated" = $k\Delta P^n$ from ELA and operating pressures

TABLE 6. Reductions in Average Leakage Flows, m^3/hr (9 systems)

	Measured	Estimated
supply side	139	176
return side	149	178

Tables 4 and 5[1] suggest that $k\Delta P^n$ underestimates leakage flows, but slightly overestimates reductions in leakage flow due to retrofits. This is shown in Table 6.

The results in Tables 4 to 6 suggest that earlier analyses of the impacts of duct sealing on the population are fairly good, however we observed significant scatter in the house-by-house results which we will explore further. A leakage reduction of 38% on the supply- and 41% on the return side was realized. These amounts seem low in light of the 64% reduction in duct leakage area.

D. Conduction Losses

Conduction through the walls of each duct was determined by calculating the ratio of energy lost through the duct walls to the total energy entering the duct at the supply plenum assuming no leakage. This assumption may overestimate the conduction loss because it in effect assumes longer residence times in the duct. For a single duct, the conduction loss is the ratio of temperature differences between the supply plenum and register to that between the supply and return plenums. Register and plenum temperatures were chosen at the end of each cycle to minimize transient effects. To compare pre- and post-retrofit conduction losses, the percentages were compared at the same attic temperatures. The conduction losses were flow-weighted to eliminate the bias due to low-flow high-loss ducts. Each duct's flow weighted conduction loss was summed to determine the total fraction of duct conduction losses in the system. These results are compared statistically in Table 7.

1. Less than the total 13 systems have been analyzed for leakage flow due to problems in data collection.

One noteworthy observation based on Table 7 is that losses are lower than the previously reported 20% in Modera, 1993. This could be due to shorter duct residence times because of the focus here on heat pumps and not furnaces, or due to different weather conditions. Also, the lower conduction losses reported here may be due to the flow-weighting, as low-flow high-loss ducts were previously given too much weight.

TABLE 7. Summary of Flow-Weighted Conduction Losses (11 Systems)

	Pre-Retrofit %	Post-Retrofit %	Reduction[a] %
minimum	6.82	3.50	12
maximum	25.38	14.94	55
average	13.84	9.45	33
std. dev., % of average	40	44	42

a. from data, not calculated from pre- and post-retrofit columns

The conduction loss reduction was smaller than expected, most likely due to transient effects. Although register and plenum temperatures used in calculations were taken at the end of the cycle, often the temperature had not reached a steady-state value. This was the case for high capacity systems, which cycled frequently with very short on-times. Also, adding insulation increased the time constant of the ducts while simultaneously reducing the system on-time, further reducing the chance of achieving steady state. This is an area which will be examined further.

E. Thermosiphon

Duct systems may cause an unintended thermal bridge between house interiors and exteriors when the system is off. Thermosiphon mechanisms have been demonstrated in simulations of houses with crawlspace supply and attic return ducts (Modera and Jansky, 1992). In the simulated house, warm air resident in the ducts after system shut-off is cooled by conduction and a natural circulation loop is initiated. Cool air enters the house through floor supply registers and warm interior air exits the house through the ceiling return register. Modera and Jansky suggested an energy impact comparable to that of typical duct leakage during the fan off cycle, or approximately 5% of the building load.

Evidence of a thermosiphon mechanism has appeared in at least two houses in this study, even with all ducts located in the attic. A thermosiphon loop was set up in the supply ducts in one house which had a package unit heat pump located on the roof. Figure 3 shows register temperatures in two supply ducts located in separate rooms. The primary difference between these ducts was that one was significantly longer than the other. The temperature decay traces during off times indicated the shorter duct temperature cooled only to room temperature, while the longer duct cooled to the lower attic temperature. This indicated that warm interior air was entering the shorter duct and cool air was exiting the longer one.

Another thermosiphon loop was found in the cooling season for a different house, also with attic ducts, but with the air handler in a closet inside the house. The thermosiphon was evidenced by approximately 4 °C warmer temperatures in two ceiling registers during off-times as compared to all other registers, which were mounted only 30 cm lower in the walls. The interesting point is that in each case a small difference in height or duct length seemed to be enough to create the thermosiphon loop. A more quantitative analysis of this effect is underway.

F. Impact on Energy Consumption

Using the power consumption data collected in each 14 day period before and after the retrofit, the daily HVAC energy consumption was calculated and plotted against the average daily indoor-outdoor temperature difference. An example of such a plot is shown in Figure 4. The key point demonstrated in the figure is that the slope of the post-retrofit regression line has been reduced by 1/3 compared to that of the pre-retrofit data. Assuming that the envelope UA value and equipment efficiency are constant, the slope of the lines in Figure 4 are proportional to $1/\eta_{dist}$, the duct distribution efficiency. This plot is similar to those in Cummings et. al., 1990 and Davis and Roberson, 1993. A standard method to compute seasonal energy savings is to apply these regression fits to weather data for the region and to factor in heat-pump efficiencies etc. to determine the actual savings. However due to the greater detail of the data collected, other analysis alternatives will be explored, which include determining the impact of the duct repairs on system cycling as well as taking into account changes in heating or cooling equipment efficiency with outdoor temperature.

G. Retrofit Costs

Shown in Table 8 is a summary of the material and labor costs for sealing and insulating the duct systems only. The costs do not include the fixed costs per site such as travel time, etc. which would need to be included when analyzing sealing-only versus sealing-and-insulating duct repair programs. The material costs are approximately 20% of the total sealing and insulating cost. One interesting note relative to material costs was that the tape used to hold the insulation in place was quite expensive. As a result, the total tape cost per house was one half to two thirds of the cost of the insulation used. The labor time in terms of effective duct leakage area sealed was calculated to be 0.04 person-hrs./cm^2 ducts sealed.

Conclusions and Future Directions

Based upon the reported results, four conclusions can be drawn. First, on average 56% of the existing supply duct leakage was sealed in the tested houses. On the return side, this figure was 73%. This indicates that return leakage is much less diffuse and thus easier to seal. In terms of airflow, sealing efforts resulted in a 38% reduction in both the supply and return leakage airflows, an amount which seems low in comparison to the leakage area sealed. The second conclusion concerns the appropriateness of using $k\Delta P_{op}{}^{n}$ as an indicator of duct leakage. We found that it was a good predictor of duct leakage for the population, however there was significant scatter from house to house between this technique and the direct measurements.

Third, thermosiphon flows have been experimentally observed in both heating and cooling mode in two separate test houses. One key point is that the thermosiphon loops were setup in attic only supply ducts. Also, differences in duct length or small height differentials between registers seem to be enough to create the effect. The impact of thermosiphon flows should be more carefully examined. Finally, conduction energy losses were found to be lower than in previous studies and their reduction also lower than expected. While flow-weighting and focusing on heat pumps as opposed to furnaces in this study account for some of the difference, this work demonstrated that transient effects are important and must be more thoroughly considered.

A more detailed analysis of the data taken to date, and the data from the remaining 20 houses should prove to be valuable both for understanding duct system performance and for duct retrofit program design.

TABLE 8. Retrofit Costs in Dollars per m^2 of Duct Surface Area[a]

	Sealing			Insulating			Total per House[b] (in $)
	Material Cost	Labor		Material Cost	Labor		
		Time[c]	Cost[d]		Time	Cost	
minimum	.36	0.40	2.32	0.86	0.49	2.78	378
maximum	2.63	0.06	22.75	6.45	0.07	19.95	1069
average	1.21	0.21	8.33	3.60	0.21	8.59	683

a. all values except those in last column based on m^2 duct area

b. total costs do not include fixed costs per site (i.e. travel time, safety tests, etc.)

c. person-hrs per m^2 duct area

d. labor charges based on an hourly rate of $40.50

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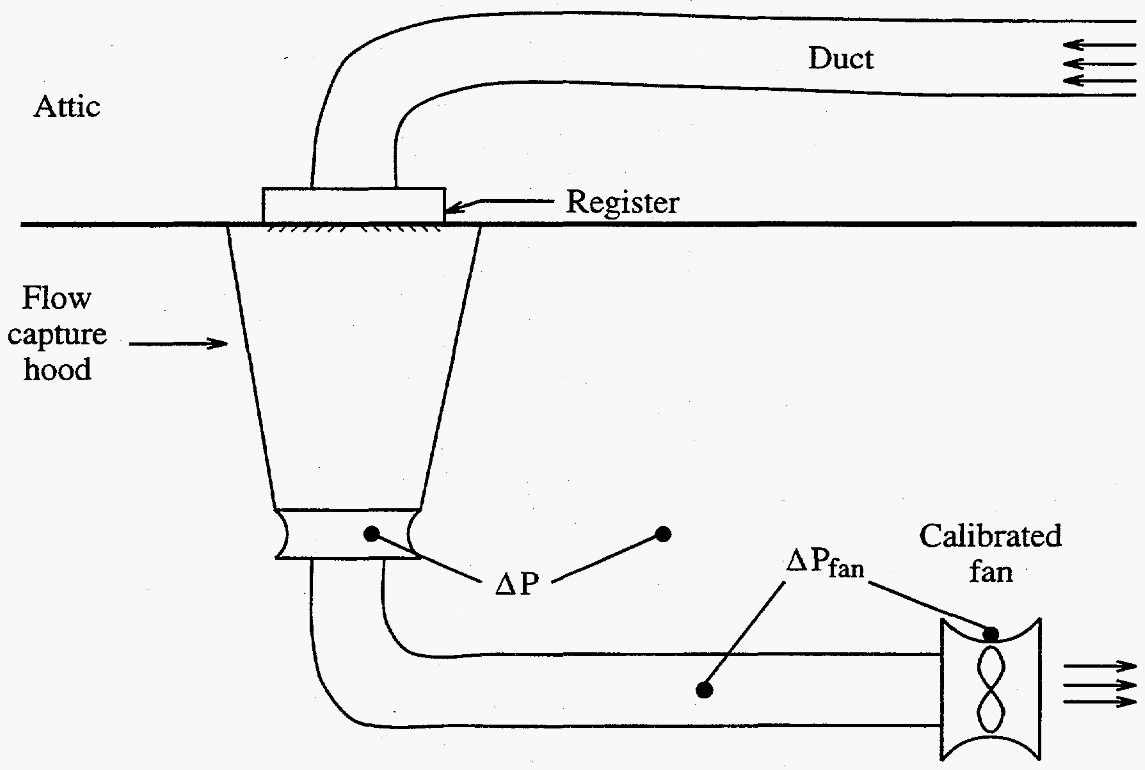

FIGURE 1. Arrangement of flow capture hood and calibrated fan demonstrating measurement of air flow out a supply register.

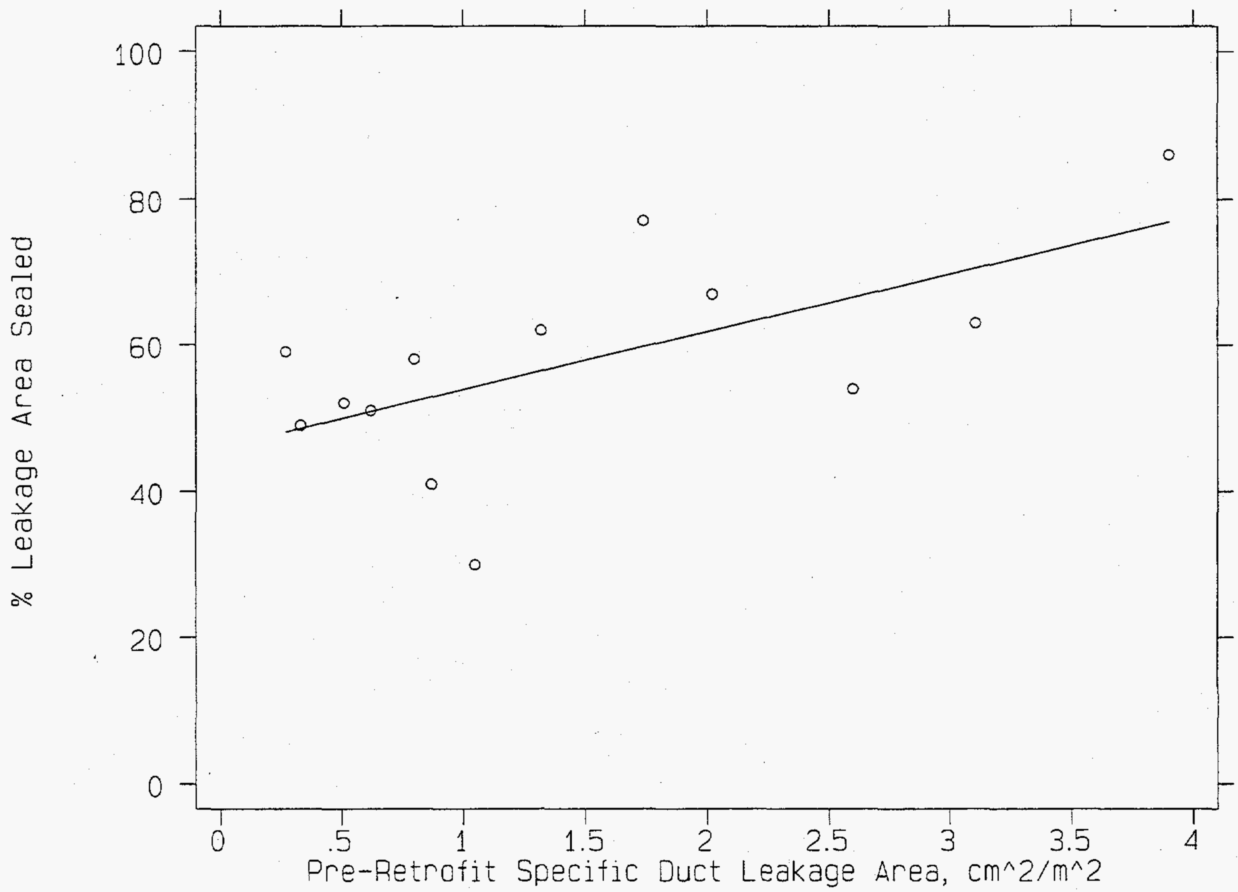

FIGURE 2. Percentage of total duct leakage sealed as a function of the duct leakage area per unit house floor area. Regression line is 46% + 8% × SLA (R^2 = 0.39)

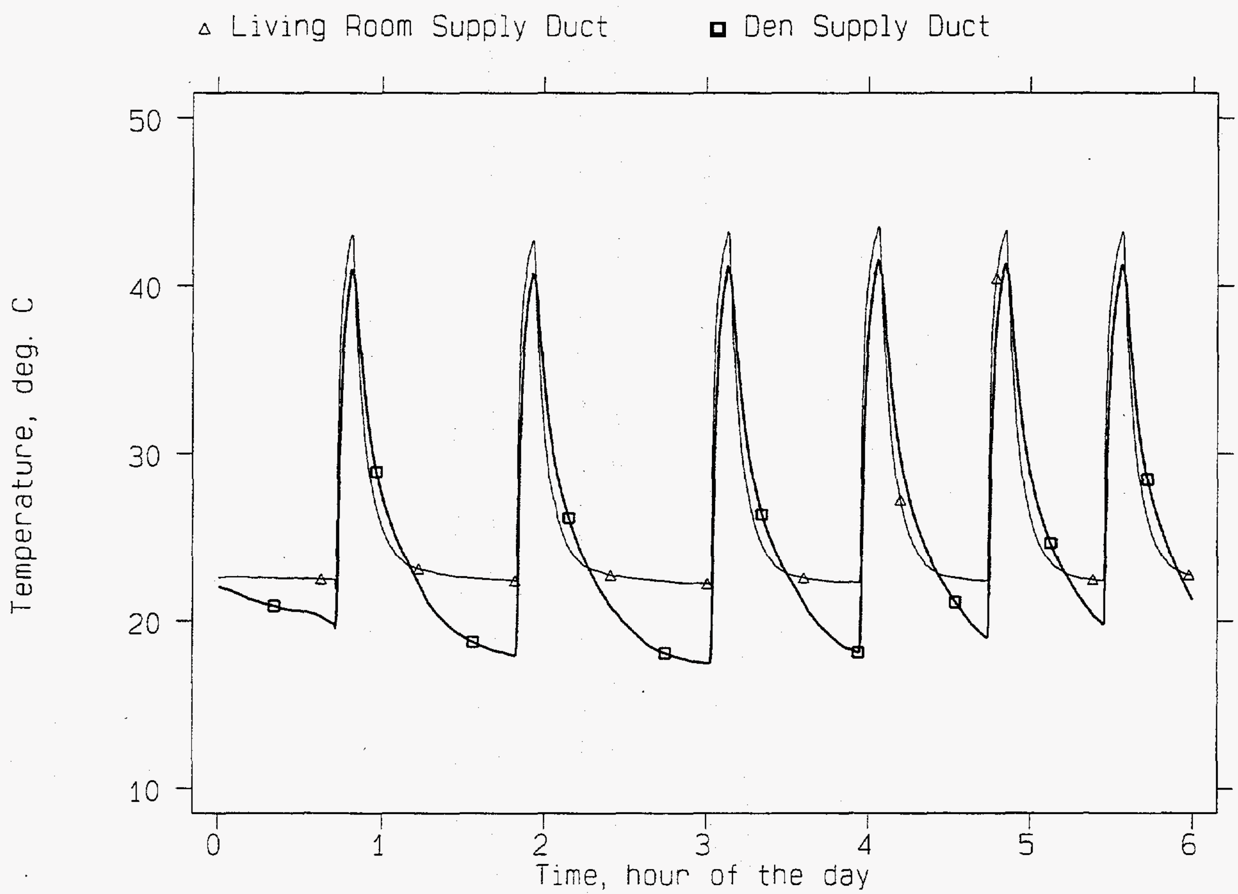

FIGURE 3. Supply-register temperature variations during normal system cycling during heating. One register decays to attic temperature during off cycle, whereas the other register decays to room temperature, suggesting a thermosiphon flow loop. Data from pilot house.

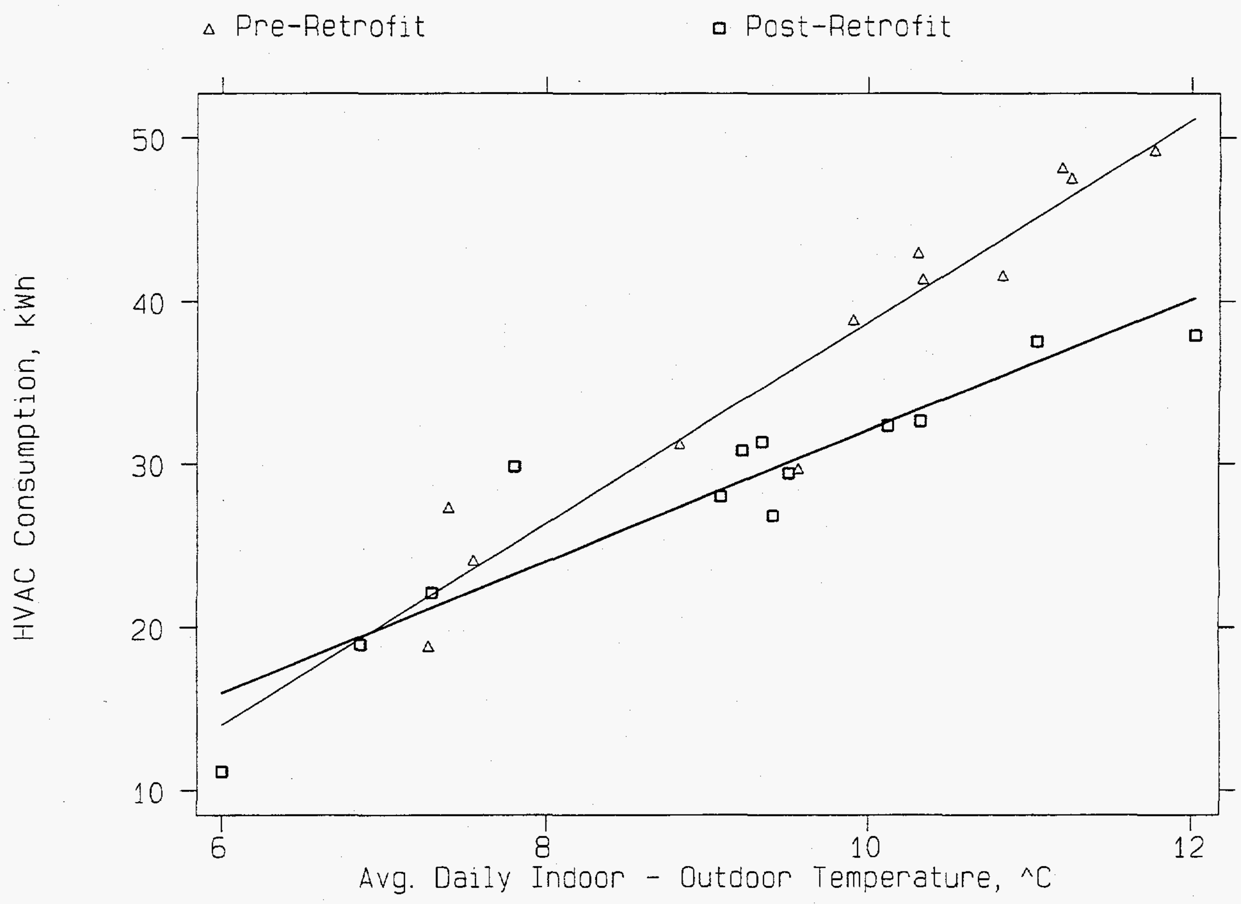

FIGURE 4. Daily heat-pump energy use as a function of average indoor-outdoor temperature differential before and after duct retrofit. Pre-retrofit regression line slope is 6 kWh/day °C ($R^2 = 0.92$), and whereas post retrofit is 4 kWh/day °C ($R^2 = 0.86$). Data for House 6.