Field Measurements of Efficiency and Duct Effectiveness in Residential Forced Air Distributions Systems

Jump, D.A.

1996-08-01

LBL-38537
UC-1600

Field Measurements of Efficiency and Duct Effectiveness in Residential Forced Air Distributions Systems

D.A. Jump, I.S. Walker, M.P. Modera

Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720 USA

August 1996

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy of the U.S. Department of Energy, Office of Building Technologies, Existing Buildings Energy Research Program, under Contract No. DE-AC03-76SF00098.

LBL# 38537
UC-1600

In Proc. 1996 ACEEE Summer Study, August 1996, Asilomar, CA

Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced air Distribution Systems

David A. Jump, Iain S. Walker and Mark P. Modera
Lawrence Berkeley National Laboratory
Berkeley, California

SYNOPSIS

Field tests were performed on duct systems in 24 houses pre- and post-retrofit to determine the potential savings due to sealing and insulating the duct system.

ABSTRACT

Forced air distribution systems can have a significant impact on the energy consumed in residences. It is common practice in U.S. residential buildings to place such duct systems outside the conditioned space. This results in the loss of energy by leakage and conduction to the surroundings. In order to estimate the magnitudes of these losses, 24 houses in the Sacramento, California, area were tested before and after duct retrofitting. The systems in these houses included conventional air conditioning, gas furnaces, electric furnaces and heat pumps. The retrofits consisted of sealing and insulating the duct systems.

The field testing consisted of the following measurements: leakage of the house envelopes and their ductwork, flow through individual registers, duct air temperatures, ambient temperatures, surface areas of ducts, and HVAC equipment energy consumption. These data were used to calculate distribution system delivery efficiency as well as the overall efficiency of the distribution system including all interactions with building load and HVAC equipment. Analysis of the test results indicate an average increase in delivery efficiency from 64% to 76% and a corresponding average decrease in HVAC energy use of 18%. This paper summarizes the pre- and post-retrofit efficiency measurements to evaluate the retrofit effectiveness, and includes cost estimates for the duct retrofits. The impacts of leak sealing and insulating will be examined separately.

INTRODUCTION

It is common practice in many locations to put forced-air-system ductwork outside the conditioned envelope. Typical duct locations are attics, crawlspaces and garages. Putting ducts in these non-conditioned areas increases the potential for energy losses from the duct system because the ducts are exposed to a harsher environment and energy lost from the ducts is outside the conditioned envelope of the building. Previous studies (e.g., Cummings et al. 1990; Modera 1993; Palmiter and Francisco 1994; Parker et al. 1993 and Proctor 1991) have shown losses on the order of 35% are typical in residential construction. These losses contribute to large energy bills for home owners and to large peak demands for utilities.

Some previous studies have examined the impact of duct retrofits; for example,

- Palmiter and Francisco made pre- and post-duct system retrofit measurements in six houses and found a 70% reduction in duct leakage post-retrofit and a 16% reduction in heating energy consumption.
- Cummings et al. performed pre- and post-duct retrofit measurements in 24 houses. They found an average energy reduction of 18% at a retrofit cost of about $200 per house.

In the current study, duct systems were retrofitted by sealing leaks and adding insulation. These measures reduced energy loss by reducing heat conduction through duct walls and reducing loss of conditioned air through holes in the ducts. The objective of this study was to evaluate the retrofit effectiveness of each of these measures (including any interaction between the retrofit measures) and to determine possible energy savings due to retrofitting. Also, by determining the cost of the retrofits, an economic evaluation of the retrofit procedures could be performed. The results of this study also provided additional baseline information on the magnitude of duct losses.

Twenty four houses in Sacramento, California were used in this study. Sacramento has hot dry summers with a 2.5% design dry bulb temperature of 37°C (98°F) and a mean coincident wet bulb temperature of 21°C (70°F). The winters are mild, with a 2.5% design temperature of 0°C (32°F). The houses had varying energy usage and had floor areas raging from 78 m^2 (840 ft^2) to 372 m^2 (4000 ft^2). There was a variety of equipment tested, with 13 air conditioners, eight heat pumps (one house had three heat pumps), three gas furnaces and two electric furnaces. Almost all of the ducts were located in attics and the majority were made of flexible plastic duct.

These houses were monitored during pre- and post-retrofit periods to determine distribution system and equipment performance. Retrofits consisted of adding extra insulation to the exterior of the ducts (added insulation was foil backed 50 mm (2 in) thick, nominally RSI 1 (R-6)) and using metal foil backed butyl tape and mastic to seal duct leaks.

By examining a wide range of houses, this study revealed a wide range of potential savings from retrofitting. The diagnostic procedures performed for this study could be used to select houses with the greatest potential benefit from retrofitting the duct system. Preliminary results from a subset of the test houses in this study were presented previously by Jump and Modera 1994. Jump and Modera focused on duct leakage and conduction losses. The current paper expands on this previous study to concentrate on delivery and overall system efficiency in all the houses, and also provides estimates of the fraction of losses attributed to leakage or conduction.

FIELD TESTING

Tests performed in the field consisted of two types:

1. Diagnostic tests of building and duct system characteristics.
2. Approximately two weeks of monitoring of characteristic temperatures, weather and HVAC power consumption in both pre- and post-retrofit periods.

More detailed descriptions of the field tests can be found in Jump and Modera 1994. In this paper we will present an overview of the test procedures in order to provide a context for the experimental results.

Diagnostic Tests

The diagnostic tests were performed to determine building and duct system parameters of interest in energy calculations. These measured parameters were considered invariant during system operation. The following measurements were performed for the diagnostic testing:

1. House pressurization test to determine exterior envelope leakage. This test was a slightly modified version of ASTM 779 1991.
2. Register air flows. These flows were measured with a modified flow capture hood and calibrated fan as described in Jump and Modera 1994.
3. Fan flow. The air flow through the fan was measured using a constant injection tracer gas technique. Some fan flows were measured with a fan assisted flow capture hood method. System air leakage flow during operation was determined directly from the measured fan and register air flows.
4. Duct system characteristics, including the number and location of registers, duct location, duct shape (round, rectangular), duct material (flex duct, sheet metal or duct board), duct diameter and length and air handler location.
5. Equipment characteristics such as type of equipment (A/C, gas furnace, heat pump), heating/cooling capacity, air handler rated flow, and location within the building.
6. House characteristics such as floor area, number of stories, floor plan.

Two week measurements

Measurements were made over a two week period so as to capture changing weather conditions and system cycling effects in both pre- and post-retrofit periods. These measurements were made by installing monitoring equipment in the test houses and using a computer based automatic data acquisition system to store the data. Air temperatures were measured with fast-response thermistors, while electric power was measured with clamp-on current meters. The measurements included:

1. Register temperatures: Used together with the measured register air flows to calculate energy supplied to the conditioned space during fan operation.
2. Plenum temperatures (and relative humidity for air conditioners): Used together with measured fan air flows to calculate energy output by the equipment and input to the ducts.
3. Ambient temperatures: These include outside air temperature, and the temperature of air surrounding the ducts (this is the attic air for most houses in this study).

Energy consumed by equipment: This was electrical power consumed by the air handlers, and either electrical power for air conditioning, heat pumps and electric furnaces, or natural gas consumed by gas furnaces.

RESULTS

The overall system performance is characterized by the normalized power consumption given by:

$$\frac{P}{\left(T_{in} - T_{out}\right)} \tag{1}$$

where P is the energy consumed during a system cycle, T_{in} is the indoor temperature and T_{out} is the ambient temperature. The normalized power consumption is calculated for each system cycle, using values of P integrated over the cycle.

The following relationships are used to describe duct system performance (for convenience, only the relationships for heating systems are given).

Delivery efficiency (η_{del}) is the ratio of energy supplied to the conditioned space through the registers (E_{del}) to the energy input to the duct system from the equipment (E_{in}) while the fan is operating. Note that the energy supplied to the conditioned space is the net energy and includes energy removed by the return side of the system (i.e., it is not just the energy in the air coming out of the supply registers). These definitions are the same as in the proposed ASHRAE standard 152P.

$$\eta_{del} = \frac{E_{del}}{E_{in}} \tag{2}$$

where

$$E_{in} = M_e Cp\left(T_{sp} - T_{rp}\right) \tag{3}$$

$$E_{del} = \left(M_e - M_s\right)Cp\left(T_{sreg} - T_{in}\right) - \left(M_e - M_r\right)Cp\left(T_{rreg} - T_{in}\right) \tag{4}$$

and M_e is the measured flow through the system fan, M_s is the supply leakage, M_r is the return leakage, T_{sp} is the supply plenum temperature, T_{rp} is the return plenum temperature, T_{sreg} is the mass flow weighted supply register temperature, T_{rreg} is the mass flow weighted return register temperature, and Cp is the specific heat of air.

Equipment efficiency (η_{equip}) is the ratio of energy supplied to the duct system (E_{in}) to the energy consumed by the equipment (E_{equip}). Both E_{in} and E_{equip} include fan power.

$$\eta_{equip} = \frac{E_{in}}{E_{equip}} \tag{5}$$

In order to isolate leakage losses from conduction losses an assumption must be made about the leakage location. The two options examined here are:

1. All the leaks were at the plenum. This assumption had the potential for overestimating the leakage losses at the expense of conduction losses.

2. The leaks were evenly distributed along the length of the duct system
The following analysis used monitored temperatures to calculate F_{sl} once assuming all supply leaks lost air at the supply plenum temperature, and calculated F_{sl} again assuming supply leaks lost air at an average duct temperature. The options for estimating the appropriate temperature difference for calculating F_{sl} were:

Option 1: All leaks were at the plenum. F_{sl} is calculated using (T_{sp}-T_{in}) in Equation 8.

Option 2: Leaks distributed over duct system. F_{sl} is calculated using $\frac{T_{sreg} + T_{sp}}{2} - T_{in}$ (instead of (T_{sp}-T_{in})) in Equation 8.

Table 1 summarizes the calculated fractional supply leakage and conduction losses calculated using the above two options. In Table 1, the fractional change in F_{sl} (ΔF_{sl}) and F_{sc} (ΔF_{sc}) are given by:

$$\Delta F_{sl} = \frac{100\left(F_{sl}(\mathrm{Option1}) - F_{sl}(\mathrm{Option2})\right)}{F_{sl}(\mathrm{Option1})} \quad \mathbf{(6)}$$

$$\Delta F_{sc} = \frac{100\left(F_{sc}(\mathrm{Option1}) - F_{sc}(\mathrm{Option2})\right)}{F_{sc}(\mathrm{Option1})} \quad \mathbf{(7)}$$

Because the temperature changes from the plenum to the registers are not very large in these systems (typically 3° C), the assumption of duct leak location did not have a large impact on the test results. Averaged over all the systems, there was a 9% difference in supply leakage loss between the two options (both pre- and post-retrofit). In Table 1 it was assumed that all the change in leakage losses would appear as conduction losses in order to estimate the effect of the leak location on conduction losses. Averaged over all the duct systems, there was a 9% preretrofit and 4% post-retrofit difference in supply conduction loss between the two options. Given the simplification of the calculations and analysis allowed by assuming all the leaks are at the plenum the above differences are acceptable.

The fraction of energy lost due to supply leaks (F_{sl}) was therefore estimated by assuming that all the leaks are at the plenum, and is given by:

$$F_{sl} = \frac{M_s Cp\left(T_{sp} - T_{in}\right)}{E_{in}} \quad \mathbf{(8)}$$

The fraction of energy lost due to supply conduction was given by:

$$F_{sc} = \frac{\left(M_e - M_s\right)Cp\left(T_{sp} - T_{sreg}\right)}{E_{in}} \quad \mathbf{(9)}$$

Table 1. Comparison of Methods for Calculating Supply Leakage Losses

	PRE-retrofit		POST-retrofit	
Temperature difference options	Option 1 (plenum leaks)	Option 2 (distributed leaks)	Option 1 (plenum leaks)	Option 2 (distributed leaks)
Temperature Difference for Leakage Losses	17.1 C	15.5 C	17.9 C	16.4 C
F_{sl}, Fractional Supply leakage loss	17.6 %	16 %	7.9 %	7.2 %
ΔF_{sl}, Fractional Change in F_{sl}	9 %		9 %	
F_{sc}, Fractional Supply conduction loss	15.8 %	17.3 %	15.7 %	16.4 %
ΔF_{sc}, Fractional Change in F_{sc}	9 %		4 %	

Because the temperature of air leaking into the return ducts was generally unknown, the return leakage and conduction losses are combined into a single term for fractional return losses (F_{rloss}), such that the total losses plus the energy delivered to the conditioned space by the duct system add up to the energy supplied to the duct system:

$$F_{rloss} = \frac{M_e C_p (T_{rp} - T_{in})}{E_{in}} - \frac{(M_e - M_r) C_p (T_{rreg} - T_{in})}{E_{in}} \qquad \textbf{(10)}$$

where T_{rreg} is the return register temperature and M_r is the return leakage mass flow. As a check, F_{rloss} should be equal to $1-\eta_{del} - F_{sl} - F_{sc}$.

Data Binning Procedure

In order to be able to compare systems between houses and between pre- and post-retrofit periods a binning procedure was used. The data were binned by indoor to outdoor temperature difference to minimize the effects of changes in operating conditions (duct ambient temperatures) and system loads. This binning method does not account for differences in solar gain or the effects of the thermal mass of the building.

In the original procedure proposed by Jump and Modera (1994) the energy consumption for each day was summed and the average indoor-outdoor temperature was calculated. Each day would then generate a value of energy consumed at a given load. Using regression analysis to estimate energy use at any temperature would allow comparisons between the pre- and post-retrofit periods even when the weather was not the same for both cases. Unfortunately, this system was found to be inadequate because:

- Two weeks of testing in each period did not provide enough data.

- The weather range for each two week period was narrow, but weather changes between pre- and post-retrofit were often large. This generated large extrapolation uncertainties.
- Small changes in average daily temperature were found over the two week test periods even when temperature changes through the day were large. This meant that it was difficult to determine correlations between energy use and system load (indoor-outdoor temperature).

The above limitations did not allow for comparisons between houses, nor for calculating the overall effects of the retrofits on the duct systems performance.

To address these limitations, a binning procedure was developed. The parameters monitored for each two week period were averaged over the cycle time of the equipment. The cycle time was defined as the period of time from when the equipment switched on to the next time the equipment switched on. Data for extremely long cycles (over two hours) were ignored in order to eliminate AC systems shutting down at night, heating systems shutting down during the day or interactions with the occupants of the houses. Also, houses with undersized equipment with very long on times were not analyzed with this binning procedure.

For each cycle, the power consumed by the equipment was integrated to obtain the system energy consumption. In addition, the measured air flow rates through the fan and registers were combined with the measured temperatures to determine the energy delivered by the equipment (by convention, this was negative for cooling) and the energy delivered by the registers to the rooms. With this information the equipment and delivery efficiencies were determined for each cycle. The calculated delivery efficiencies and normalized power consumption were then sorted into bins using the measured temperatures. The bins are 2° C wide and are represented by their middle temperature, i.e., the 20° C bin represents all temperatures between 19° and 21° C. The results given later are the average of all the cycles belonging to each bin. Using this cyclic averaging results in data bins covering a wide range of temperatures and allows variations due to weather conditions or retrofits to be observed more easily.

Diagnostic Results

These test houses are representative of typical California housing with an average floor area of 164 m^2 (1765 ft^2) and average system fans flows of 1700 m^3/hour (1000 cfm). The diagnostic results are summarized in Table 2. Note that the supply and return leakage flows are expressed as a fraction of the fan flow. These results show that the system fan flows are reduced by about four percent on average due to the added flow resistance caused by sealing the ducts. The average pre-retrofit leakage flows were 18% of fan flow for supplies and 17 % of fan flow for returns. The reduction in leakage due to the retrofits was about 10% of fan flow for supply ducts and 7% of fan flow for return ducts. These correspond to significant reductions in leakage flows: 55% of pre-retrofit supply leakage and 40% of pre-retrofit return leakage was sealed. There was a large range of fractional leakage flows from system to system, as shown in Table 2 and by the standard deviations being a large fraction of the mean value.

Table 2. Diagnostic Test Results and House Specifications

House	# Stories	Floor Area m^2	System Type*	Fan Flow m^3/hour		Supply Leakage % of Fan Flow		Return Leakage % of Fan Flow	
				Pre	Post	Pre	Post	Pre	Post
1	1	135	AC	1807	1654	22	11	22	15
2	1	158	AC	2756	2639	24	14	24	19
3	2	127	AC	1408		24	17	44	15
4	1	155	AC	1825	1780	24	15	13	11
5	1	78	AC	1754					
6	1	200	HP	2153		16	10	22	6
7	1	93	EF	1129		13	3	3	0
8	1	135	HP	1413		12	8	5	8
9_1	1	372	HP	1623		6	0	24	16
9_2			HP	1943		15	13	34	27
9_3			HP	1766		33	10	13	17
10	3	223	HP	1484	1468	26	10	26	1
11	2	186	HP	2354	2324	23	9	11	1
12	1	130	GF	841	817	19	20	0	6
13	2	132	HP	1972	1774	33	3	35	4
14	2	214	GF	2028	1966	21	5	0	1
15	1	155	GF	1207	1415	19	30	35	27
16	1	139	EF	1713	1666	11	5	4	4
17	2	177	AC	1793	1716	5	2	6	0
18	2	167	AC	1471	1458	29	0	15	6
19	2	156	AC	1466	1583	13	2	7	16
20	1	242	AC	1635	1213	38	6	26	24
21	1	158	AC	1293	1171	14	8	16	16
22	1	125	AC	1849	1582	7	0	22	14
23	1	114	AC	1691	1619	2	0	5	3
24	1	153	AC	1847	1813	6	3	3	2
Mean	-	**164**	-	**1701****	**1648**	**18**	**8**	**17**	**10**
St. Dev	-	**59**	-	**391**	**379**	**10**	**8**	**13**	**9**

* AC : air conditioning, HP : heat pump, GF : gas furnace, EF : electric furnace
**1724 for fans that were also tested post-retrofit

Binned Test Results

The binned data for each system was examined in order to find the bin that had the most cycles in both pre- and post-retrofit periods. For example, the data used for House 14 has $T_{in} = 22°$ C, $T_{out} = 10°$ C, $\Delta T = 12°$ C both pre- and post-retrofit. These particular temperatures had 31 cycles pre-retrofit and 33 cycles post-retrofit. Other temperature bins had a lower number of cycles pre- or post-retrofit. Only a single bin for both pre- and post-retrofit in each house provided the results shown in Table 3, which allowed an estimation of the effect of the retrofits to be made without biases due to changing weather conditions. On average, there were 28 cycles in each bin used in this analysis.

Table 3 summarizes the measured delivery efficiency, normalized power consumption and what fraction of the losses are attributed to supply leakage, supply conduction and return losses. Some of the return losses are negative because the return leakage and conduction energy flows acted to heat the air in the ducts (for heating) or cool the air in the ducts (for cooling) and therefore were a net benefit to the system energy balance. Some houses did not have complete measurements and are neglected in this analysis, and therefore they do not appear in Table 3. This reduces the number of houses compared pre- and post-retrofit to 17 out of the original 24.

Table 3. Pre- and Post-Retrofit Two Week System Test Results

House	Equipment Efficiency, η_{equip}		Delivery Efficiency, η_{del}, %		Fractional supply leak loss, %		Fractional supply conduction loss, %		Fractional return loss, %		Normalized power consumption, P/ΔT (W/K)	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
2	2.55	2.45	68	78	24	17	7	4	2	1	453	387
3	1.98	1.94	63	68	31	25	12	12	-6	-4	145	129
6	2.26	2.42	63	77	16	10	10	10	10	4	206	175
7	0.75	0.73	71	88	16	1	16	11	-1	0	367	200
8	2.2	2.05	62	72	14	9	18	14	7	5	99	89
10	2.76	1.69	57	74	34	15	12	15	9	-3	217	164
11	1.93	1.61	53	69	25	10	12	17	13	5	228	98
12	0.64	0.63	66	64	23	24	11	12	1	0	503	445
13	1.62	1.49	53	90	32	4	6	8	9	-1	120	108
14	0.96	0.94	46	57	23	6	34	40	-2	-2	700	634
17	1.87	1.94	85	87	1	2	9	15	5	-5	263	247
18	1.53	1.49	46	68	26	1	23	30	4	1	283	178
19	1.35	1.46	67	69	11	2	20	26	2	2	287	268
21	1	0.95	74	85	13	8	15	10	-3	0	348	326
22	20.6	1.53	68	85	6	0	17	19	9	-3	165	145
23	0.93	0.99	75	95	0	0	23	6	1	0	151	127
24	2.46	2.34	64	71	5	3	23	20	8	7	310	294
Mean	**1.7**	**1.6**	**64**	**76**	**18**	**8**	**16**	**16**	**4**	**0**	**285**	**236**

The following results are based upon averages over all systems:

- Pre-retrofit, the delivery efficiency was 64%. This increased to a post-retrofit value of 76% (an increase of 19% of the pre-retrofit value). There was a wide variability from house to house from a minimum change of 3% of pre-retrofit value to a maximum change of 68%. This indicates that diagnostic tests would be valuable in selecting houses that would receive maximum benefit from duct system retrofitting.
- The fraction of energy lost from supply leaks was 18% in the pre-retrofit period and decreased to 8% in the post-retrofit period. These supply losses correspond to the reduction in supply leakage flows from 18% of fan flow to 8% of fan flow. Note that despite precise agreement of the numbers, the correlation between leakage flow and energy losses is not exact because the retrofits changed air temperature within the ducts between pre- and post-retrofit periods, as well as leakage flows.
- The fraction of energy lost due to supply conduction was unchanged at about 16% of delivered energy for both periods. The conduction losses did not change significantly because the decrease in temperature difference between supply plenum and supply registers (indicating less energy loss) was balanced by an increase in supply duct flows because the

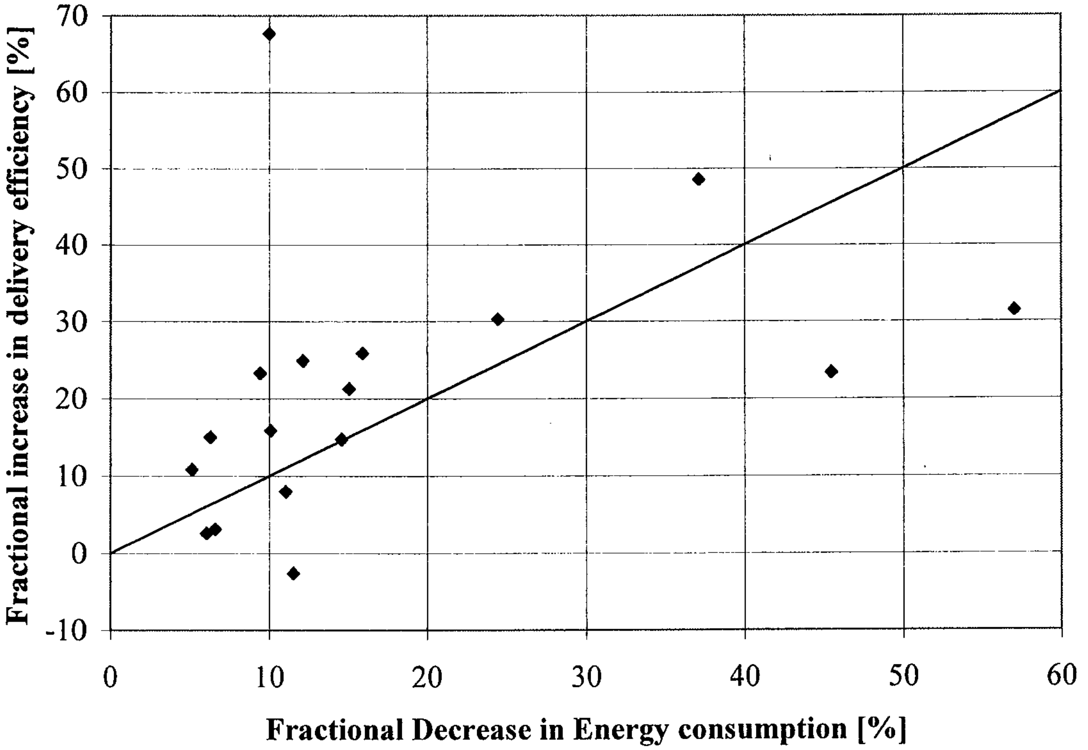
supply leaks have been sealed. Note that if ducts were sealed only, without adding extra insulation, the conduction losses would have increased.

- The return side losses were reduced from 4 % to about 0 % by the retrofit changes. Some systems had positive return losses and others had negative return losses. Note that the return losses combine both leakage and conduction effects. In general, the temperature differences between the air in the ducts and their surroundings are less for return ducts than supply ducts, and the impact of conduction losses and duct leakage is reduced. The exception is return duct leakage in hot attics in the summer, in which case the return leakage has a large effect on air conditioning performance. For example, an attic in a hot humid climate will have air with about twice the enthalpy of indoor air. Therefore a return leak equal to 10% of fan flow will increase the enthalpy of the air in the return plenum by 20%, with a corresponding increase in energy use for the A/C equipment.
- The COPs for heat pumps and air conditioners changed from 1.89 to 1.74 and the electric and gas furnace efficiencies changed from 0.78 to 0.77 before and after the retrofit. This result shows that the retrofits can have a slightly negative impact on the equipment operation. A combination of factors account for the reduced equipment performance including reduced system air flows, decreased ontime and changed operating temperatures for the coils.
- The average indoor-outdoor temperature difference was 10° C (18° F) both pre- and post-retrofit for the binned data given by Table3.
- The normalized power consumption (P/ΔT) was 285 W/K pre-retrofit and 236 W/K post-retrofit, a reduction of 18%.

The 19% increase in delivery efficiency, combined with a slight reduction in equipment efficiency and the same indoor-outdoor temperature difference leads to an 18% reduction in normalized power consumption. This result indicates that the change in delivery efficiency is a good indicator of system energy savings. Figure 1 illustrates how the change in delivery efficiency correlates to the change in normalized power consumption. The strong correlation between these parameters which shows that the change in energy consumption is mostly due to increased delivery efficiency. The increased delivery efficiency is due to the duct sealing and added insulation.

The range of normalized power consumption reduction was from 5 % (of pre-retrofit normalized power consumption) to 57 %, with a large variability from house to house. Diagnostic tests will therefore be important in selecting suitable houses for duct retrofits because some systems have the potential for large improvements and some systems do not. The selection of houses with large potential savings is important for both utilities and home owners in order to maximize the cost effectiveness of retrofits.

Figure 1. Use of Delivery Efficiency to Predict Reduction in Energy Consumption.



There was a trend of increasing improvement in delivery efficiency and reduction in normalized energy consumption with systems with larger pre-retrofit supply leakage. Therefore, supply duct leakage measurements can be used as a rough guide for selecting houses that will have the greatest benefit from duct retrofits. This does not imply that return leakage may be neglected. In other houses there may be greater return leakage than the houses used in this study. In addition, climate and duct location can both have significant impacts on the effects of return duct leakage. Return duct leakage interacts with supply duct leakage in system imbalance effects on building air infiltration and in systems with more supply duct leakage than return duct leakage, and there are also safety issues concerned with backdrafting of natural combustion appliances.

Retrofit Costs

A summary of the cost of the retrofits is shown in Table 4. The mean cost was $635 with a range of $335 to $1069. These costs do not include fixed costs per house for travel time, which would tend to reduce this variation. The costs were normalized with respect to the size of the duct system (surface area) and it was found that there remained a large variation from house to house. The standard deviation of these normalized costs was about 75% of the average cost. The costs were broken down into materials and labor for both sealing and insulating. Details of this breakdown are shown in Table 4.

Table 4. Cost of Retrofitting Duct Systems (dollars)

	Sealing				Insulating				Total
	Materials	Materials per m^2 duct	Labor	Labor per m^2 duct	Materials	Materials per m^2 duct	Labor	Labor per m^2 duct	
Mean	41	1.58	252	4.85	103	3.44	239	9.08	635
Standard deviation	15	1.1	108	9.5	61	1.89	122	6.81	216

The labor costs dominate over the materials cost (labor costs averaged 77% of the total retrofit cost), which is why there is a large range of costs from house to house independent of the size of the duct system. The labor costs reflect the time required to seal or insulate the system, which is due to ease of access to the duct system and of finding duct system leaks.

Given the mean cost of $635 and energy use reduction of 18%, an estimate of the cost effectiveness can be made. Houses with an annual energy bill of $572 would have a simple payback in 5 years or less. However, because there is a large variation in energy reduction and retrofit cost it would be prudent to perform diagnostic tests to determine the potential for energy savings for a house before retrofitting. Diagnostics should include a determination of the ease of access to the duct system because this is important in estimating the cost of the retrofits.

CONCLUSIONS

The reduction in energy consumption due to sealing and insulating the duct systems was about 18% on average. Most of this reduction in energy consumption was due to a 19% increase in delivery efficiency (i.e., the retrofit impact on building loads and on equipment performance was negligible). There was a large variation (5% to 57%) in energy consumption reduction and in retrofit costs from house to house, indicating that the energy savings and cost effectiveness of duct retrofits is highly system dependent, and that it would be prudent to have some simple diagnostic tests and inspections performed on duct systems before investing in duct retrofits. The most significant diagnostic would be to estimate supply duct leakage because sealing supply duct leaks tended to be the dominant factor in increasing delivery efficiency. A simple visual inspection could be used to determine ease of access and to look for large potential duct problems such as missing insulation or disconnected ducts.

For the houses tested in this study, the return losses were negligible. However, return losses cannot generally be ignored because the impact of return losses is highly dependent on climate and duct location.

The average cost of the retrofits was $635 and was dominated by labor costs (77% of the total). The range of costs was $335 to $1069 (a factor of three) and did not correlate with system size, showing that ease of access to the duct system was as important as system size in determining the cost of retrofits.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy of the U.S. Department of Energy, Office of Building Technologies, Existing Buildings Energy Research Program, under Contract No. DE-AC03-76SF00098.

The research reported here was funded in part by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor.

This work was also supported by the Sacramento Municipal Utility District, which identified all of the houses, interacted with the homeowners, acquired the retrofit contractors, and paid for the retrofits.

REFERENCES

ASHRAE Standard 152P (Proposed). *Standard Method of Test for Determining the Steady-State and Seasonal Efficiencies of Residential Thermal Distribution Systems*

ASTM Standard E779-87 1991. Test Method For Determining Air Leakage by Fan Pressurization. *ASTM Book of Standards*. American Society of Testing and Materials. 04.07.

Cummings, J.B., J.J. Tooley Jr., M. Moyer, and R. Dunsmore. 1990. "Impacts of Duct Leakage on Infiltration Rates, Space Conditioning Energy Use, and Peak Electrical Demand in Florida Homes". *Proc. ACEEE Summer Study 1994.* 9:65-76.

Jump, D.A., and M.P. Modera. 1994. "Energy Impacts of Attic Duct Retrofits in Sacramento Houses". *Proc. ACEEE Summer Study 1994.* 9:195-203.

Modera, M.P. 1993. "Characterizing the Performance of Residential Air Distribution Systems". *Energy and Buildings*. 20:65-75.

Palmiter, L, and P. W. Francisco. 1994. "Measured Efficiency of Forced-Air Distribution Systems in 24 Homes". *Proc. ACEEE Summer Study 1994.* 3:175-187.

Parker, D., P. Fairey, and L. Gu. 1993. "Simulation of the Effects of Duct Leakage and Heat Transfer on Residential Space-Cooling Energy Use". *Energy and Buildings*. 20 (2):97-114.

Proctor, J.P. 1991. *Pacific Gas and Electric Appliance Doctor Pilot Project: Final Report - Summer 1990 Activity.* Proctor Engineering Group. 5725 Paradise Dr. Corte Madera. Calif.