Measured Efficiency of Forced-Air Distribution Systems in 24 Homes

Larry Palmiter and Paul W. Francisco, Ecotope, Inc.

This paper presents the results of field measurements of heating efficiency for 24 all-electric homes with central forced-air distribution systems. The base sample of 22 homes consisted of homes with more than 50% of the ductwork in unconditioned spaces, which is a common configuration in homes in the Western and Southern states. The remaining two homes had the furnace in the conditioned space and all ductwork in interior partitions. This provided a comparison with the other 22 homes, as well as a validity check on the coheat efficiency method. All of the tests were done during the 1991-92 and 1992-93 heating seasons.

The field tests were designed to measure the heat delivery efficiency and system efficiency of the 24 homes. Because the effects of increased infiltration during fan-off times and differential pressurization due to door closure are not included, the system efficiency given here should be taken as an upper limit on the actual efficiency under these weather conditions.

The temperature difference to the outside averaged 33 ‘F. The heat delivery efficiency averaged 56% for the 22-home base sample and 67% for the interior ductwork homes. The base sample averaged 71% system efficiency, while the homes with all interior ducts had a 98% average system efficiency.

Six of the homes, selected to have at least 400 cfm duct leakage to outside at 50 Pa, subsequently underwent a duct leakage retrofit. These retrofits resulted in an average reduction of duct leakage to outside of 70 %, and an average reduction in heating energy of 16%.

Introduction

In recent years it has been recognized that residential forced-air distribution systems with a significant portion of the ductwork located in unconditioned spaces will incur substantial thermal losses. One of the primary sources of these losses is duct air leakage. Current air sealing techniques can greatly reduce duct leakage, thus reducing the heating system energy losses. An increasing number of studies from different parts of the United States have evaluated the magnitude of typical thermal losses, and some analyses of the effects of duct system retrofits have been made. Of these we cite only those most pertinent to the present study.

Parker [1989] reviewed the impact of forced-air distribution on infiltration and space heat consumption on electrically-heated homes in the Pacific Northwest. Data were analyzed for 108 control (conventional) homes heated with baseboard systems and 91 control homes heated by forced-air electric furnaces. The homes with baseboard heat had 41% less tracer-based measured infiltration than did the homes with forced-air electric furnaces, and the annual space heat consumption, normalized by floor area, was 21% less for baseboards than for forced-air electric furnaces. This implies a forced-air electric furnace duct efficiency of 79% relative to baseboard heating systems.

Modera [1989] gave an overview of the impacts of duct system leakage on both infiltration and thermal loads. Cummings et al. [1990] studied the energy used for air-conditioning by 24 Florida homes before and after duct repairs were made. A decrease in energy use of 18% was found after the repairs were performed. Davis and Roberson [1993] found that repairing duct leaks in 18 Arkansas homes reduced duct leakage by 74% and reduced heating energy by 20% in 14 gas furnace systems and 31% in 3 heat pump systems.

Robison and Lambert [1988] measured the duct leakage in approximately 20 homes in Oregon and estimated that duct leakage caused a 12% average efficiency loss in these homes. Conduction losses were not considered. After performing duct sealing retrofits on these homes the estimated efficiency loss due to duct leakage was reduced to 9.7%, a 20% improvement. The duct leakage to outside was reduced by 33% as a result of the retrofits.

Guyton [1993] retrofit two of four identical apartments in a multi-family building in Martinsburg, West Virginia to have all ducts within the conditioned space. The energy use was measured for these four apartments for a full year. The units with all ducts inside used 33.8% less energy for heating and 71% less energy for cooling. This implies a heating efficiency prior to the retrofit of 66% and a pre-retrofit cooling efficiency of 29%.

This paper presents a summary of the results from a more detailed study conducted on 24 houses in the northwestern United States [Olson et al. 1993]. This study used an innovative technique based on temperature controlled coheaters to measure the system efficiency of the ductwork of central forced-air electric heating systems (furnaces and heat pumps) under typical Northwest winter conditions. Because the electric resistance elements in these systems are 100% efficient, the measured system efficiency is for the distribution system only. Although the homes measured were all-electric, gas-heated homes in the region have duct systems that are essentially the same in terms of percentage in unconditioned space, insulation levels, and quality of installation. It is therefore likely that the distribution system efficiencies are comparable, although the higher supply temperatures produced by gas furnaces would result in a somewhat higher distribution efficiency, and the efficiency of the gas furnace would have to be factored in.

There are three basic categories of homes with regard to the energy losses of residential forced-air distribution systems. The first category is homes with the air handler and all or a significant portion of the ductwork located in unconditioned spaces. These are the homes where large energy losses were expected. The second category is homes where the air handler and all of the ductwork are located within the conditioned space, i.e., no ductwork in exterior walls, floors, or ceilings. It was expected that these homes would have small energy losses. The third category is homes with the air handler and a significant portion of the ductwork in a partially conditioned space, or in an unconditioned space not insulated from the conditioned space. This category includes many homes with basements and also homes with unvented crawl spaces with perimeter insulation. It is difficult to define or measure the distribution system efficiency in these cases for a variety of reasons, such as thermal mass effects and the definition of allowable basement temperatures.

The primary purpose of this study was to quantify by direct field measurement the energy losses due to forced-air distribution systems with a significant portion of the ductwork located in unconditioned spaces. This was a pilot study designed to address the question of whether these losses were large enough to justify further study and remedy. Due to limited resources, it was decided to focus the study on the homes where energy losses would be of the most consequence and also amenable to clearcut definition and measurement. Homes in the third category were excluded, as well as those with multiple air-handlers or other problematic features. Since it was anticipated that homes with all ductwork located within the conditioned space would have small losses, proportional representation of this category in the sample would have been a waste of research effort; however, two homes were selected in this category in order to confirm the anticipation and also to verify the coheat technique. The other 22 homes were all selected from the first category (the initial screening was based primarily on the occupant's response to whether 50% of the ductwork was in an unconditioned space).

It is important to be clear that this study does not purport to be a random sample of the regional stock of all-electric homes with forced-air distribution systems. It is a sample of the population of homes in which at least 50% of the ductwork was in unconditioned spaces, exterior to the envelope insulation. The sample was further restricted to homes in which system efficiency would be relatively easy to define and measure. Location of the air handler and some of the ductwork in unconditioned spaces is a common in practice in the region, particularly in newer homes (including many utility subsidized energy efficient homes). Although the homes which met the criteria were not randomly selected, the authors believe the measured efficiencies are broadly representative of such homes.

Fourteen of the homes in the base sample had the air handler in the garage, four had the air handler in the crawl space, and the remaining four had the air handler inside the conditioned space. Ten of these 22 homes had electric furnaces while the remaining twelve had heat pumps. Two of the twelve heat pumps were ground coupled; the other ten were air-to-air. The heat pumps were run in resistance-mode only as if they were electric furnaces. A separate one-time test, not discussed in this paper, was made with only the compressor running to determine the heat pump COP for these homes. The two homes with all ducts interior had electric furnaces, and all of the ducts were metal.

A variety of supply duct types, locations, and levels of insulation were found in the base sample of 22 homes. Fourteen of the supply duct systems were metal, six were flex, and the other two were a mixture of metal and flex. The median R-value for the 22 homes was R-7. Several houses had R-values in excess of R- 10. Two of the homes which had R-11 insulation had been retrofit with heat pumps by a local utility. Two others with R-11 were located in Eugene, Oregon, where a minimum of R-11 is required. All of the homes had insulated supply ducts. The majority of the supply ductwork in these homes was in the crawl space. Seven homes had all of the supply ductwork in the crawl space, and the average for the 22 homes was 74% of the supply ducts in the crawl space. Only three homes had supply ducts in the attic. One of these homes had all of the supply ductwork in the attic, while the other two had less than 50% in the attic. Twelve homes had some supply ductwork inside the conditioned space, with an average of 18% of the supply ducts interior for the 22 homes.

Also presented is a summary of the results of tests performed on six of these homes both before and after duct air sealing retrofits were made [Palmiter et al. 1994]. Five of the houses retrofit for this study were in the Puget Sound region. The remaining house was located in Eugene, Oregon.

Measurement Techniques

The testing began in the winter of 1991-92 and was completed the following winter. The complete test protocol required about 30 hours including set-up and take-down. The protocol and instrumentation are given in detail in Olson et al. [1993]; here we only outline some of the most pertinent aspects. The occupants were paid a small incentive to vacate the home overnight, so as not to interfere with the tests, and to allow more rapid setup.

The field tests were designed to measure two standard criteria of delivery efficiency as defined in Chapter 29 of the 1992 *ASHRAE HVAC Systems and Equipment Handbook* [ASHRAE 1992]. These are the heat delivery efficiency and the system efficiency. The heat delivery efficiency is the useful heat delivered to the space through the supply registers divided by the power input to the furnace. It is calculated only when the air-handler fan is on. The system efficiency allows for the fact that, in some circumstances, a significant portion of the heat losses from the supply air are recovered as useful heat. One typical instance of this is air leakage from the supply ducts to the conditioned space. Also, when uninsulated supply ducts run in interior partitions, there are large heat losses to the wallboard. During the furnace offcycle this wallboard cools to the interior such that most of this heat is recovered. The system efficiency is defined as total useful heat delivered to the space divided by the furnace power. Both efficiency measures must be calculated over an integral number of furnace cycles under steady cycling conditions. The most notable feature of the protocol was the technique for measuring system efficiency. One of the advantages of this method is the determination of the system efficiency by means of a single overnight test. This is particularly useful for the evaluation of duct retrofits, since the test can be done immediately before and after the retrofit.

The basic concept is to alternate between heating the home with the furnace and heating it with portable fan-forced electric heaters. The homes were divided into 6-12 control zones, in each of which the datalogger controlled the coheaters to provide the same average temperature during the coheating as that measured during the furnace cycling. The alternating coheat and furnace periods were each about 1.5 hours duration. About 10 hours of 10-second time resolution data were taken at each home. The system efficiency was calculated for each period by comparing the time-averaged power for the period with the mean of the two adjacent coheat or furnace periods. Only the second half of each coheat and furnace period was used, so as to reduce transient effects from heat stored in the duct system.

In addition to the interior air temperatures used for control, we measured each individual supply and return air temperature, and outdoor, crawl space, attic, and garage air temperatures. True power was measured at the mains with two precision Hall-effect clamp-on power meters. During the tests, all lights and appliances were disconnected to minimize the base load. The registers were left open during the coheat part of the test; therefore any extra infiltration due to duct leaks appeared in the load for the coheaters.

In addition to these tests a number of one-time measurements were made. Flow hoods were used to measure the air flow through the supply and return registers. These were corrected to standard cubic feet per minute (scfm) at an air density of 0.075 lbm/ft^3. The useful heat delivered by a register is calculated by multiplying the flow by the heat capacity and the temperature difference between the supply register and the interior air. The heat delivery efficiency was then calculated by summing the heat delivered over all registers and dividing by the furnace power.

The house leakage was measured with a blower door. The total house leakage was determined with all registers fully open. A second test was done with all registers sealed, The difference of these is a measure of duct leakage. This method will underestimate the amount of duct leakage if there is significant leakage from the ducts to the interior. Just before the second season of tests, we acquired a commercial duct tester which was used to directly measure the duct leakage for the last 10 homes. Comparison with the blower door subtraction method for these homes showed the bias to be significant. The mean correction factor for these homes was applied to the earlier duct leakage results.

Efficiency Results

A summary of some of the most pertinent results is given in Table 1. A much more detailed analysis is given in Olson et al. [1993]. The table is set up to facilitate a direct comparison between the base sample of 22 homes and the two homes with all interior duct work. The outdoor temperatures for the base sample averaged 39°F yielding an inside-outside temperature difference of 33°F. Note that the temperatures of the crawl space and garage where ducts and the air handler were most frequently located were considerably higher than the outdoor temperature. This effect was noted in all of the homes and throughout the winter. The temperature difference from indoors to the crawl space was about 18°F and from indoors to the garage was about 21°F, about 2/3 of the temperature difference to outside. This will reduce the heat losses from the ducts by about the same factor.

The next section of Table 1 lists some of the characteristics of the heating system as operated under the test conditions. The static pressures in the supply and return plenums averaged about 50 Pa or 0.2 inches of water, with individual furnaces varying from 3 to 200 Pa. The distributions of the supply and return static pressures for the base sample are shown in Figure 1. These plots show

Table 1. Average Results of Heating System Tests on 24 Homes

		Base Sample (n=22)		All Interior Ductwork (n=2)	
		Average	Std. Deviation	Average	Std. Deviation
Site Characteristics					
Year Built		1983	9	1985	5
Floor Area	[ft^2]	1610	383	2386	463
Temperatures					
Outdoor Temperature	[F]	39.2	8.3	29.3	4.3
Indoor Temperature	[F]	72.5	2.1	70.0	0.6
Delta T (in - out)	[F]	33.2	7.7	40.8	3.7
Crawl Space Temperature	[F]	54.5	4.6	--	--
Garage Temperature	[F]	51.7	6.4	--	--
System Characteristics					
Supply Plenum Pressure	[Pa]	47.4	34.1	37.5	2.1
Return Plenum Pressure	[Pa]	58.6	48.9	47.5	0.7
Supply Register Flow	[scfm]	862	154	818	95
Return Register Flow	[scfm]	813	193	763	159
Pressure Across Bedroom Door	[Pa]	5.0	2.6	9.2	0.2
Full Furnace Power	[W]	13476	4567	15648	498
Fan-On Furnace Power	[W]	10972	4008	10166	1460
Average Cycling Power	[W]	4439	1656	4014	7
Air Handler Fan Power	[W]	451	150	485	21
Percent Fan Ontime	[%]	42.8	16.2	39.9	5.8
Air Leakage at 50 Pa					
Total House Leakage to Outside	[cfm]	2226	1083	2211	1572
Total House Leakage to Outside	[ACH]	9.8	3.5	7.8	6.9
Duct Leakage to Outside	[cfm]	435.6	278.9	20.5	24.7
Leakage Percent of Total	[%]	19.5	7.5	0.7	0.6
Efficiency Results					
Heat Delivery Efficiency	[%]	56.2	10.4	66.8	14.1
System Efficiency	[%]	71.0	7.6	97.9	1.6
System Efficiency Loss	[%]	29.0	7.6	2.2	1.6
Power Loss	[W]	1276.1	664.2	86.5	65.8

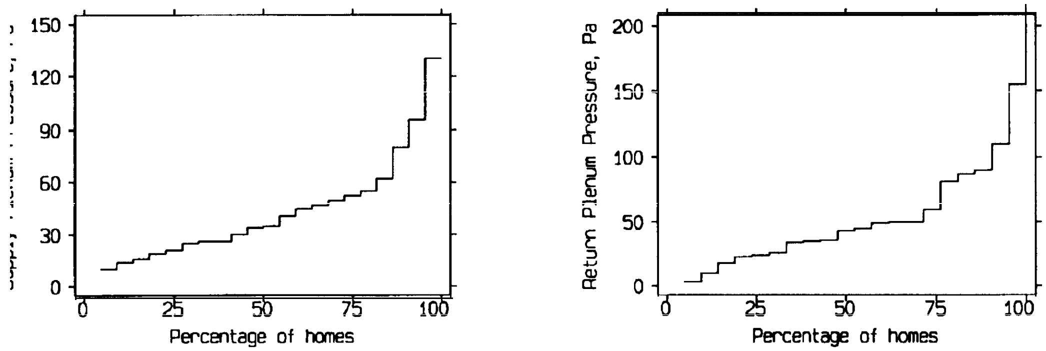

Figure 1. Distributions of Supply and Retum Plenum Pressures

the cumulative percentage of homes with pressures less than the value on the y-axis. These pressures are important because, in conjunction with the measured leakage at 50 Pa, they determine the amount of air leakage from the duct system when the air handler operates.

Most of the homes had one return register per floor and 12-14 supply registers. The return air from rooms lacking returns is forced to flow under any closed doors, thus pressurizing the room and depressurizing the main body of the home. This effect was not measured in this study; the tests were done with all interior doors open. As an indicator of the magnitude of this effect we measured the differential pressure across the master bedroom door with the door closed and the air handler on. The average value was about 5 Pa which would, in a typical case, indicate that the bedroom was pressurized by about 4 Pa relative to outside and the bulk of the home was depressurized by about 1 Pa relative to outside. One of the authors has shown in another study that differential pressurization of this magnitude can result in more than doubling the infiltration rate of the home [Palmiter and Bond 1991].

The full furnace power is the measured power draw of the furnace with all elements on, including the power required by the fan. The fan-on furnace power is the measured value of the furnace power (including fan power) during the part of the cycle when the fan is on. On average there is a reduction from a full furnace power of 13476 W to 10972 W when the fan is on, or about 19%. This is due to the operation of the element sequencers. The air handler fan and control power averaged 451 W, with some efficient heat pumps as low as 170 W and some large older units at nearly 800 W. Most of the fan power goes directly into the air stream as heat. This helps serve the heating load but exacerbates the cooling load. The fan power takes on special significance with the increasing popularity of electronic air cleaners (it is recommended to run the fan continuously) and the use of the fan as part of a ventilation strategy. Continuous fan operation would consume about 3900 kWh per year.

The electrical heating elements in nearly all electric forced-air systems are operated by sequencers. Typically, when the thermostat calls for heat, nothing happens for 10 seconds, then the air handler fan and one or two elements come on; after another 20 to 60 seconds another element comes on, etc. When the thermostat is satisfied similar sequencing operates in reverse. The fan goes off simultaneously with the last element. The time delays and the number of elements per stage were quite variable from one furnace to the next. This sequencing has two important consequences; it makes it impossible to use a runtime monitor to measure the furnace energy, and it can have a noticeable impact on the distribution system efficiency. Sequencing up in the beginning will lower the distribution efficiency and result in delivering cool or cold air to the home. Conversely, the sequence down will tend to improve the efficiency since it allows some of the heat stored in the ductwork to be scavenged. Operating the fan for an additional minute or two as in gas furnaces would further improve the efficiency. It is interesting to note that the largest electric furnace in the sample, rated at 25 kW, had no sequencers; all elements and the fan operated simultaneously.

The average cycling power is the time average of the furnace power (including fan power) during an integral number of complete cycles. This is the actual power input and heat output of the device. The last row in the system section of Table 1 gives the percent fan ontime which averaged about 43% for the base sample.

The two major sources of efficiency loss in forced-air distribution systems are conduction loss through the sides of the pipes to colder surroundings and air leakage. While the importance of conduction losses has long been recognized and most regions have minimum insulation standards, air leakage in residential duct systems has been ignored until recently when it has received increasing interest as a potential major opportunity for energy savings. One way to quantify the leakiness of houses and ducts is to measure the flow at some fixed pressure difference, typically 50 Pa.

The total house leakage is the combined leakage to outdoors of the house envelope and the duct system. This averaged about 2200 cfm at 50 Pa for both the base sample and the interior duct sample. In terms of air changes per hour (ACH), the base sample averaged 9.8 ACH while the interior duct homes, being larger, averaged 7.8 ACH. The distribution of total house leakage is shown in the left plot of Figure 2.

The duct leakage to outside averaged 436 cfm or about 20% of the total house leakage for the base sample, based on duct tester and corrected blower door subtraction measurements. The duct system thus increases the natural infiltration rate of the home by about 25% over what it would have been without the ducts. This is a noticeable indirect heating load increase, about 400-600 kWh per year. Note the very low leakage to outside for the interior duct homes, at only 20 cfm or 0.7% of the total. It is important to verify this for a larger sample size. The distribution of duct leakage to outside for the base sample is shown in the right plot of Figure 2, which shows that one home with extraordinary leakage may have strongly influenced the mean value. The median (at 50% of homes) was about 415 cfm with 25% of the homes above 534 cfm and 25% of the homes below 243 cfm.

The last section of Table 1 summarizes the efficiency results. The heat delivery efficiency averaged 56% for the base sample and 67% for the homes with all interior ducts. In both cases, a large fraction of the output of the furnace disappears before reaching the registers.

The system efficiency, based on the coheat measurements, is our best estimate of the overall efficiency of the distribution system because it includes the effects of duct air leakage to the inside and the heat lost from ducts to interior walls and floors. However, it does not include the effect of increased natural infiltration during fan-off times, thermosiphoning in the duct system during fan-off times, or the effects of differential pressurization due to door closures. All of these effects will decrease the effective overall efficiency of the distribution system. The system efficiency should therefore be taken as an upper bound; the actual efficiency in the occupied home will be somewhat less. For the homes with heat pumps, there are additional important interactions between the duct losses and the heat pump that may result in further efficiency losses.

The system efficiency averaged 71% for the base sample, corresponding to an efficiency loss of 29%. This means that with electric furnaces the homes used about 1.41 times more energy for space heat than they would have used if maintained at the same temperatures by electric baseboards. These are large losses; in fact, they are of comparable magnitude to the total savings from many space heat conservation programs. The system efficiencies varied widely from home to home. The distribution of system efficiencies and efficiency losses are shown in Figure 3, from which it can be seen that about 25% of the homes had system efficiencies greater than 77% (losses less than 23%) and about 25% of the homes had system efficiencies less than 66% (losses greater than 34%). The homes in the last category are attractive targets for retrofit with large potential savings. Comparison of the heat delivery and system efficiencies shows a recovery of about 34% of the initial duct losses for the base sample homes and about 94% recovery for the all interior case.

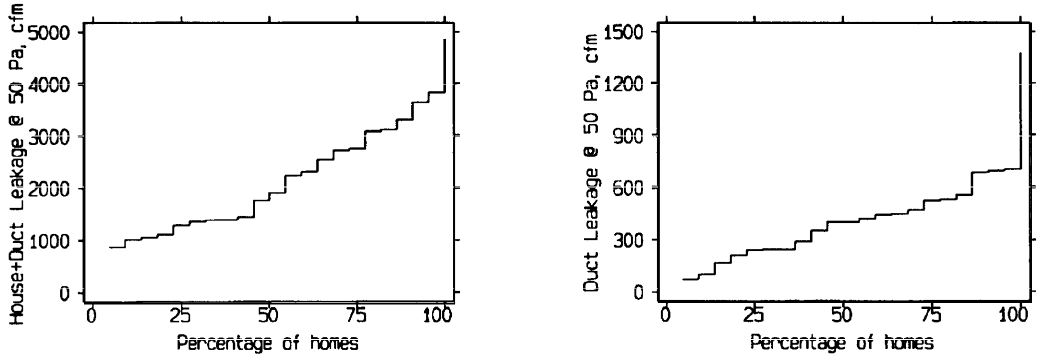

Figure 2. Distributions of Whole-House Leakage (including ducts) and Duct Leakage to Outside at 50 Pa

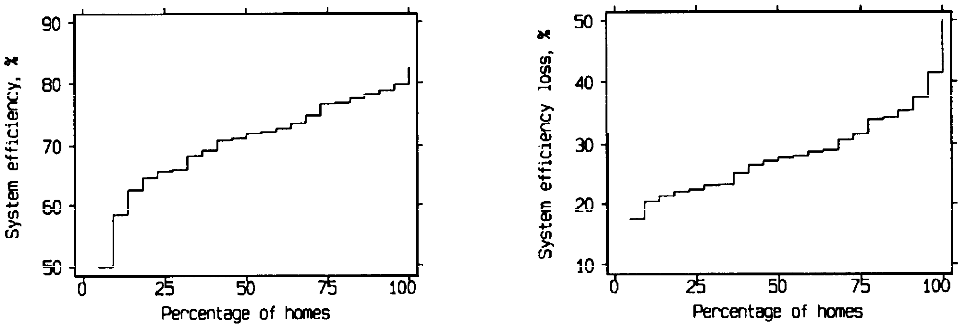

Figure 3. Distributions of System Efficiency and System Efficiency Loss

The two interior duct homes had an average system efficiency of 98%, for a loss of only 2%. This is consistent with the very low measured air leakage to outside and indicates that the conduction loss to outside is also very small. As this result has potentially major policy implications for new home construction standards, it is important to verify it on a larger sample of homes.

Fractional performance indices like efficiency and efficiency loss can sometimes be misleading because the economic cost/benefit analysis of energy use depends on the absolute energy amounts, not on the percentage. For instance, the home with largest cycling power was not the one with the lowest efficiency and the home with the highest efficiency was not the one with lowest cycling power. Other things being equal, homes with larger heating loads offer larger financial benefits for a given efficiency improvement. The power loss (under the test conditions) averaged about 1276 W for the base sample and only 86 W for the all interior duct homes. These numbers can be compared with the average cycling power of 4440 W and 4014 W respectively.

Retrofit Results

Aggressive duct retrofits were performed on six of the homes in the base sample. These six homes were selected to have at least 400 cfm leakage from the ducts to outside at 50 Pa. Additional insulation was also placed into a couple of the homes, but the focus was on air leakage repairs. A full set of tests was performed on the homes after the retrofits were completed and compared to the pre-retrofit results. The primary results are summarized in Table 2. Note that the column titled “Change” is an actual difference between pre- and post-retrofit results. This includes the efficiencies, where the change is actual percentage points. The relative improvement is provided in the column labeled “% Change.” For the efficiencies the percentage change is given as the reduction in required space heat.

The repairs greatly reduced the air leakage at 50 Pa in these homes. The first row of Table 2 shows that whole-house leakage at 50 Pa (including ducts) was reduced by an average of 17%, from 2821 cfm to 2352 cfm. Total duct leakage (leakage to outside plus leakage to inside), shown in the second row of Table 2, was reduced by 57%, from an average of 764 cfm before retrofits to 331 cfm after retrofits. The majority of this improvement was in duct leakage to outside, which was reduced by 70% from 541 cfm to 161 cfm. The left and right sides of Figure 4 show the reduction in duct leakage to outdoors for each individual house and as an average in percentage and in cfm, respectively. Note that a large percentage reduction does not necessarily correspond to a large reduction in cfm, because a small percentage reduction in very leaky ducts can result in a larger cfm reduction than a large percentage in a tighter duct system.

Duct leakage to indoors, shown in the fourth row of Table 2, was reduced by 23% from an average of 222 cfm to 170 cfm. Duct leakage to inside has little impact on the system efficiency and the overall energy loss, but may result in a low heat delivery efficiency. The left and right sides of Figure 5 show the reduction in duct leakage to inside for each home and as an average measured as a percentage and in cfm, respectively. Again, a large percentage reduction does not necessarily correspond to a large cfm reduction.

The fifth row of Table 2 shows the improvement in the heat delivery efficiency due to retrofits. Retrofits resulted in a 16.1% reduction in the apparent required space heating energy, which does not take into account the heat that is reclaimed from duct leaks to inside. The system efficiency, which does take the heat from leaks to inside into account and is shown in the sixth row of Table 2, increased from an average of 69% before retrofit to an average of 83% after retrofit. This translates to a 16.4% average reduction in the actual space heating energy needed by the homes.

Table 2. Average Retrofit Effects for Six Homes

		Pre	Post	Change	% Change
Whole-House Leakage at 50 Pa	[cfm]	2821	2352	469	16.6
Total Duct Leakage at 50 Pa	[cfm]	764	331	432	56.6
Duct Leakage to Outside at 50 Pa	[cfm]	541	161	380	70.3
Duct Leakage to Inside at 50 Pa	[cfm]	222	170	52	23.3
Heat Delivery Efficiency	[%]	56.3	67.1	10.8	16.1[(a)]
System Efficiency	[%]	69.2	82.8	13.6	16.4[(b)]
Efficiency Loss	[%]	30.8	17.2	13.6	44.1
Power Loss	[W]	1751	990	762	43.5

(a) This is the apparent reduction in required space heating energy, as measured by the heat delivered through the registers with the fans on under test conditions.

(b) This is the actual reduction in required space heating energy under test condtions including the recovery of duct losses.

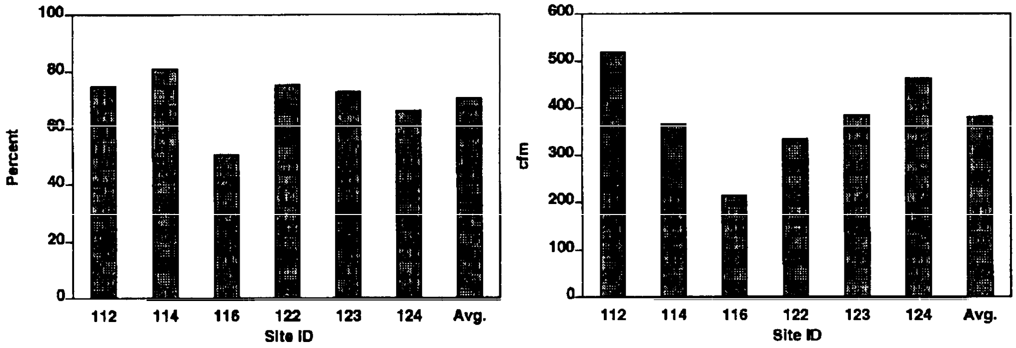

Figure 4. Reduction in Duct Leakage to Outside at 50 Pa

The system efficiency loss, which is the system efficiency subtracted from 100 %, is shown in the seventh row of Table 2. Before retrofits the six homes averaged 31% efficiency loss. This was reduced to 17% after retrofit, an average reduction of 44%. Multiplying the system efficiency loss by the average cycling power of the furnace gives the actual power loss. This is shown in the final row of Table 2 expressed in watts. The retrofits resulted in a 44% average reduction in power loss, from 1751 W before retrofit to 990 W after retrofit. This is very important since, as noted previously, efficiency measured in percentage can be misleading and it is the power loss that determines the actual economic impacts. Figure 6 shows the energy loss for each home and as an average. The left side shows the reduction in system energy loss in terms of percentage decrease in efficiency loss, while the right side depicts the reduction in system energy loss in terms of the actual power loss reduction. As with the heat delivery and system efficiencies, a large percentage reduction does not necessarily correspond to large power loss reductions.

Findings and Conclusions

In discussing the test results, it should be kept in mind that the base sample homes were deliberately selected to have the air handler and at least 50% of the ductwork in unconditioned spaces. Also, the homes chosen for retrofit had at least 400 cfm of duct leakage to outside. The variation in air-tightness and insulation levels of duct systems is large, as can be seen from the standard

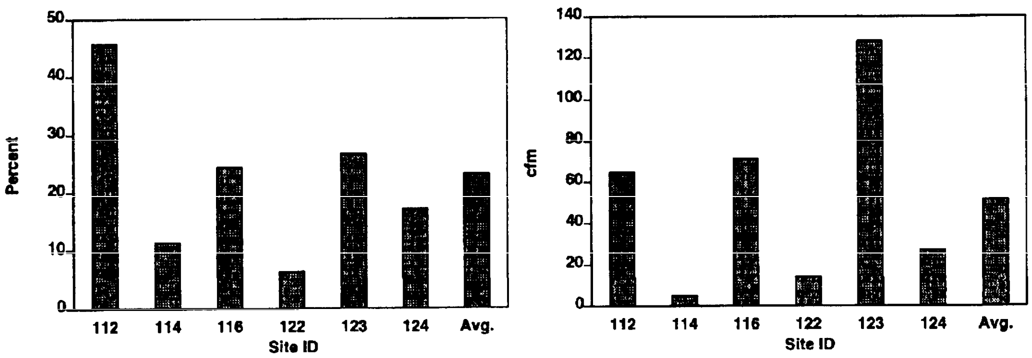

Figure 5. Reduction in Duct Leakage to Inside at 50 Pa

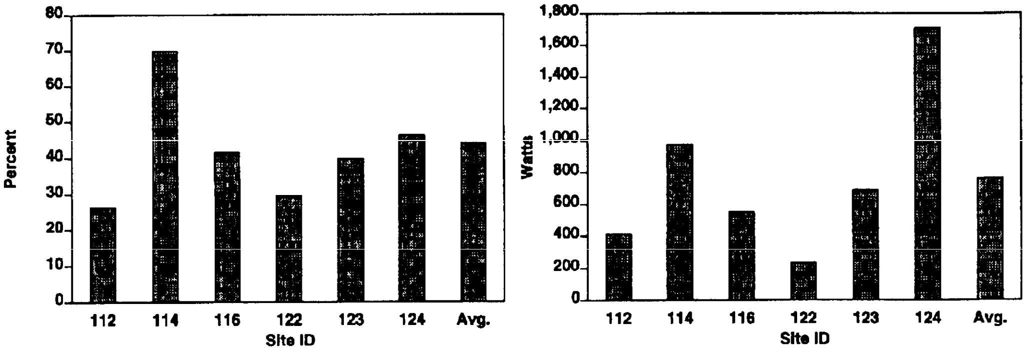

Figure 6. Reduction in System Efficiency Losses Due to Duct System Repairs

deviations. An effective approach to dealing with distribution systems will require the development of quick and inexpensive screening criteria to identify those homes which have large potential savings. Duct retrofitting is not a measure which can be cost-effectively applied across the board to all forced-air distribution systems.

As noted, the energy loss of 30% for the base sample is of comparable magnitude to the total savings from the combined envelope efficiency measures (improved insulation, glazing, and air sealing) in many utility programs. The overall potential for the region is large due to the common occurrence in the Northwest of homes like those in the sample.

A number of the test homes were newly constructed under utility-subsidized energy-efficiency programs. The duct air leakage to outside and the system efficiency loss for these homes were as large or larger than those of the older homes, despite much better duct insulation.

The tests identified air leakage as a major loss mechanism. For the base sample homes it is estimated that, on average, about half of the losses were due to air leakage and the other half to conduction losses. In addition, the duct leakage resulted in a 25% increase in the natural infiltration rate. This energy loss was not included as an efficiency loss. Because many of the homes were new and energy efficient, the levels of duct insulation were higher than would be typical, which tends to increase the percentage of the total loss that is due to air leakage. In the homes with the largest energy losses, the dominant mechanism was always air leakage. Tightness testing and air-sealing will be important techniques in addressing this problem.

Many of the air leakage problems are due to careless installation perhaps exacerbated by a very competitive market and the virtual absence of any type of inspection. For example, about one in eight homes had a disconnected supply duct lying on the crawl space floor. There was virtually no use of duct tape or other types of air sealing even though the uniform mechanical code requires all ductwork be substantially airtight.

The heat delivery efficiency averaged 56% for the base sample and 67% for the interior ductwork homes. Due to recovery of cycling losses, air leakage to the interior, and offset of loads caused by heating of buffer zones, the system efficiency was higher at 71% and 98%, respectively. For the base sample the recovery of losses was 34% and for the interior ducts 99%. This shows that heat delivery efficiency is not an adequate measure of energy impacts, especially for homes with interior ductwork.

The homes with all interior ducts had a system efficiency of 98%, which means that almost all of the duct losses were recovered as useful heat. This is potentially a very important finding, which should be verified by measurements on additional homes. If this high efficiency is indeed typical of such systems, retrofit measures would be superfluous. Requiring the air handler and all ductwork to be in the conditioned space may be an effective alternative to additional restrictions, such as air sealing or additional duct insulation, in new construction.

The air-sealing retrofits resulted in significant savings. The duct leakage to outdoors in the six retrofit homes was reduced by an average of 70% from 541 cfm to 161. The six homes had an average pre-retrofit system efficiency of 69% and a post-retrofit system efficiency of 83%, corresponding to a 16% average decrease in required space heating energy under test conditions. Looked at another way, the retrofits reduced the energy losses by 44%. Although the sample is very small, the results suggest that current duct retrofitting techniques can significantly reduce distribution system losses, provided the homes are screened to ensure adequate retrofit potential.

It should be noted that the techniques used in these retrofits were very aggressive, and required special training in repair methods, advanced leakage diagnostics, and skilled use of blower doors, duct testers, and micromanometers. The pressure pan technique discussed by Davis and Roberson [1993] was extremely useful in identifying the location of major leaks. The training material developed by Cummings et al. [1993] was invaluable.

Acknowledgments

This heating system study was sponsored by the Bonneville Power Administration through the Washington State Energy Office, Michael Lubliner, Project Manager. The fieldwork was performed by Joseph Olson and Bob Davis, Ecotope, Inc. Tami Bond and Michael Geffon, Ecotope, assisted in the data analysis.

The retrofit study was funded by the Electric Power Research Institute and Puget Sound Power & Light Company, John Kesselring, Project Manager. The retrofits were performed by Scott Finley of Energy Options Northwest with help from Olson and Davis. John Tooley of Natural Florida Retrofit supervised the retrofit work at one of the homes. John Proctor of Proctor Engineering Associates supervised the retrofit work at two additional homes. We thank them for sharing their wealth of field experience. We also thank Mark Modera of Lawrence Berkeley Laboratory for his many useful comments and suggestions throughout the duration of these projects.

References

ASHRAE. 1989. *ASHRAE Standard 62-1989: Ventilation for Acceptable Indoor Air Quality.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

ASHRAE. 1992. 1992 *ASHRAE HVAC Systems and Equipment Handbook,* Chapter 29. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta.

Cummings, J. B., J. J. Tooley, N. Moyer, and R. Dunsmore. 1990. “Impacts of Duct Leakage on Infiltration Rates, Space Conditioning Energy Use, and Peak Electrical Demand in Florida Homes.” *Proceedings of the ACEEE 1990 Summer Study on Energy Efficiency in Buildings,* Volume 9, pp. 9.65-9.76. American Council for an Energy-Efficient Economy, Washington, D.C.

Cummings, J. B., J. J. Tooley, and N. Moyer. 1993. *Duct Doctoring: Diagnosis and Repair of Duct System Leaks.* Florida Solar Energy Center, Cape Canaveral, Florida. (Draft).

Davis, B. E., and M. Roberson. 1993. “Using the “Pressure Pan” Technique to Prioritize Duct Sealing Efforts: a Study of 18 Arkansas Homes.” *Energy and Buildings,* 20:57-63.

Guyton, M. L. 1993. “Measured Performance of Relocated Air Distribution Systems in an Existing Residential Building.” *ASHRAE Transactions,* Vol. 99, Part 2. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Modera, M. P. 1989. “Residential Duct System Leakage: Magnitude, Impacts and Potential for Reduction.” *ASHRAE Transactions,* Vol. 96, Part 2. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Olson, J. R., L. Palmiter, B. Davis, M. Geffon, and T. Bond. 1993. “Field Measurements of the Heating Efficiency of Electric Forced-Air Systems in 24 Homes.” Prepared for the Washington State Energy Office under Contract No. 90-05-12.

Palmiter, L., and I. A. Brown. 1989. "Northwest Residential Infiltration Survey: Analysis and Results." Prepared for the Washington State Energy Office under Contract No. 88-24-01.

Palmiter, L., and T. Bond. 1991. *Measured and Modeled Infiltration: A Detailed Case Study of Four Electrically Heated Homes.* Electric Power Research Institute Report CU-7327, Palo Alto, California.

Palmiter, L., J. R. Olson, M. Geffon, and P. W. Francisco. 1994. *Measured Efgiciency Improvements from Duct Retrofits on Six Electrically-Heated Homes.* Ecotope, Inc., Seattle, Washington.

Parker, D. S. 1989. "Evidence of Increased Levels of Space Heat Consumption and Air Leakage Associated with Forced Air Heating Systems in Houses in the Pacific Northwest." *ASHRAE Transactions*, Vol. 96, Part 2. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Robison, D. H., and L. A. Lambert. 1988. "Field Investigation of Residential Duct Leakage." Prepared for the Oregon Department of Energy under Contract No. 90023.