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Investigation of Air Distribution System Leakage and Its Impacts in Central Florida Homes

James B. Cummings, John J. Tooley, Jr., and Neil Moyer
Florida Solar Energy Center (FSEC)

FSEC-CR-397-91

1. ABSTRACT

Testing for air leakage in air distribution systems was done in 160 central Florida homes. Tracer gas tests found that infiltration rates were three times greater when the air handler was operating that when it was off, indicating that there are large leaks in the air distribution system. Infiltration averaged 0.91 air changes per hour (ach) with the air handler (AH) operating continuously and 0.28 ach with the AH off. Return leaks were measured by tracer gas and found to average 10.7% of AH total flow. House airtightness, in 99 of these homes, determined by blower door testing, averaged 12.7 air changes per hour at 50 Pascals (ACH50). When the duct registers were sealed, ACH50 decreased to 11.1, indication that 12.7% of the house leaks were in the air distribution system.

Duct leaks were repaired in 50 of the 160 homes. Blower door tests were done on these houses before and after repair. Before repair airtightness was 12.5 ACH50. After repair house ACH50 decreased to 11.2, indicating that 63.7% of the duct leaks were repaired. Infiltration tests were done before and after repair on 25 of these homes. Infiltration rates with the AH on decreased from 16.0% to 4.5% of total air handler flow.

Cooling energy use decreased as a result of duct repairs. Data was available for 46 of the 50 homes. Air conditioner energy use decreased by an average 17.2%, yielding estimated space conditioning energy savings of $110 per year. Duct repairs are a very cost-effective retrofit. At an average cost of $200 per home, duct repairs have a simple payback of less than two years.

Duct leaks have a dramatic impact upon peak electrical demand. While no peak demand data has yet been measured, theoretical analysis indicates that a 15% return leak from the attic can increase cooling electrical demand by about 90%. Detailed theoretical analysis of a winter Florida morning indicates that duct repairs in a typical, electrically heated Florida home reduce winter peak demand by about 1.6 kW per house at about one-sixth the cost of building new electrical generation capacity. Repair of ducts in 3 million Florida homes could reduce winter peak demand by 5000 megawatts, of 13% of the state's generating capacity. This effort would be very cost effective, since the generation capacity made available by duct repair would cost only abut one-third to one-eighth what new capacity would cost, depending upon type of generation facility.

2. INTRODUCTION

Duct leakage has been observed in many homes by the authors of this paper and others. Significant duct leakage was observed in the majority of the 370 homes they have tested with blower doors (Tooley and Moyer, 1989). They have also reported on duct leakage in about 25 homes, indicating that significant duct leakage has been found (Cummings, 1988; Cummings and Tooley, 1989; Cummings and Tooley, 1990). Other authors across the nation have detected air distribution systems (AD) leakage, as well. Infiltration rates n 31 Tennessee homes were found to be 77% higher when the air handler was operating (Gammage, et al., 1986). Tracer-gas-measured infiltration rates in 6 new Pacific Northwest homes were found to be 70% higher in those with forced-air systems during a four month winter period compared to those without forced-air heating systems. This indicates that leaking air distribution systems increased infiltration, since blower-door testing indicated they should only be 12% leakier (Parker, 1989). Blower door tests done on 20 homes n the Pacific Northwest found that about 10% of the house leak area was in the air distribution system (Robinson and Lambert, 1989).

3. PROJECT DESCRIPTION

A study was begun in the spring of 1989 to investigate air distribution system (ADS) leakage in central Florida homes. Testing was done using tracer gas to determine how much infiltration is caused by ADS leaks. Blower door tests were done to measure house and ADS airtightness. Duct repairs and cooling energy use monitoring were also done. (Note that the use of the terms "duct system" and "air distribution system" (ADS) are energy used interchangeably in this report. "Air distribution system" is the more accurate term since it includes the air handler (or furnace), return plenums, and supply plenums, which are not usually referred to as ducts).

Tracer gas infiltration testing has been done in a sample of 160 homes in order to detect ADS leakage. The housing sample was randomly selected. The only screening criteria used was that the house have a forced-air distribution system. It was also decided that the sample should fall into five groups, based primarily on air handler (AH) location. Therefore, 30 houses were selected in each of the following categories: (1) AH in the attic, (2) AH in a closet or utility room, (3) AH in the garage, (4) AH outdoor, and (5) HUD-code mobile homes. (Mobile homes normally have package units – air handler outdoors. Category (4) includes only site-constructed homes with package units).

ADS leakage was elevated by means of tracer gas testing, blower door testing, and visual inspection. Tracer gas tests were done once with the AH operating continuously (interior doors open) and once with the AH off. If the infiltration rate was higher when the AH was operating, then a high probability of duct leakage was indicated. If the infiltration rate was much higher (say three to five times higher) because of AH operation, the ADS leakage was strongly indicated.

Another measure of ADS leakage is the return leak fraction (RLF). This is the proportion of air returning to the AH which originates from outside the conditioned space. RLF is determined by measurement of tracer gas dilution from the return (in the room at the return register or registers) to a supply register. Tracer gas concentration is also measured in the attic (or other buffer zone) at the return leak site, in order to quantify the concentration of tracer gas in the dilution air. This method has proved to be accurate and repeatable method for quantifying leaks on the return side of the air distribution system. Supply leaks cannot be so quantified.

Infiltration tests were done using the tracer gas decay method and a portable infrared specific vapor analyzer. A 20 minute period was used to mix the tracer gas throughout the house using the AH as the mixer. In the test with the air handler operating, sulfur hexafluoride samples were taken every five minutes for 30 to 40 minutes (data collected at a minimum of 7 time increments) at the intake to the return register or registers (typically Florida homes have only one or two return registers). Mixing was maintained by the continuous operation of the AH.

In the tests with the air handler turned off, samples were taken every 10 minutes for a minimum of 50 minutes (data collected at a minimum of 6 time increments). Tracer gas measurements were again taken at the return registers. Mixing of the tracer gas was maintained by turning the air handler on for 1 or 2 minutes during each 10-minute period. A change in this test protocol was made after 110 homes were tested because duct leakage during the minute(s) of AH operation caused error in the result. As a result, natural infiltration is slightly overestimated in these 110 homes. On the last 50 homes, sampling was done at four distributed locations throughout the house, and the AH was not turned on at all during this test. These testing procedures are described in more detail in Cummings (1989).

Because of funding limitations, blower door tests were done on only 100 of these homes. These tests were done in the depressurization mode only. It is the belief of the authors that pressurization artificially opens up "holes" in the house, such as awning windows, exhaust fan dampers, etc., while depressurization generally pulls them closed. Fan air flow was measured at 5 to 8 house-to-outdoors delta-pressure points, generally across the range from 10 to 60 pascals (Pa). These tests were repeated with all the supply and return registers covered by paper and tape. These tests permit determination of house air leakage at 50 Pa (ACH50), and by subtraction, the proportion of the house leak (at 50 Pa) which is in the air distribution system.

Duct repairs were done on 50 of the 160 homes. Blower door and tracer as tests were repeated after repair. Air conditioner energy use was monitored for a period of approximately four weeks before repair and four weeks after repair. Monitoring was accomplished in the following manner. Watt-hour and run-time meters were installed on the air conditioner (AC). The house occupant was asked to record the run-time meter, the AC meter, and the whole-house watt-hour meter daily. In order to obtain comparable data, they were asked to maintain their thermostats at the same setting throughout the testing and take meter readings at about the same time each day. A weather station was installed to collect temperature, dew point temperature, solar radiation, and wind speed. Cooling energy use was normalized to weather by plotting "daily AC kWh" versus "daily average outdoor temperature".

4. PROJECT TEST RESULTS

Three different tests were performed to detect duct leakage: (1) tracer gas tests, (2) blower door tests, and (3) smoke test inspection. In each phase of testing, extensive evidence of duct leakage was found.

4.1 Tracer Gas Test Results

Infiltration tests revealed that duct leaks are large and widespread in central Florida homes. The average infiltration rate of the 160 homes tested was more than three times higher with the AH operating than when it was off. Figures 1 and 2 shows these results. The house infiltration rates averaged 0.91 ach when the AH was on, while only 0.28 ach when it was off.

4.1.1 Infiltration with air handler off

When the air handler is off, more than 50% of the homes have infiltration less than 0.25 ach while only 4% have infiltration greater than 0.75 ach. From this data it can be stated that natural infiltration is very low in Florida homes. Several considerations arise from this conclusion.

First, efforts to make the house envelope more airtight may not be cost-effective. Computer simulation of air conditioning and heating loads in Orlando, Florida using Thermal Analysis Research Program found that reduction of infiltration from 0.28 ach to 0.18 ach results in about $30/year energy use savings (Cummings and Tooley, 1990). This assumes that infiltration air comes from outdoors, as opposed to attic, garage, or crawl space. Even if much of the airtightening were in the attic and annual energy savings were $50, the added effort of airtightening would probably be marginally cost-effective.

Figure 1. Tracer gas infiltration rates in 154 homes with the air handler off. Average = 0.28.

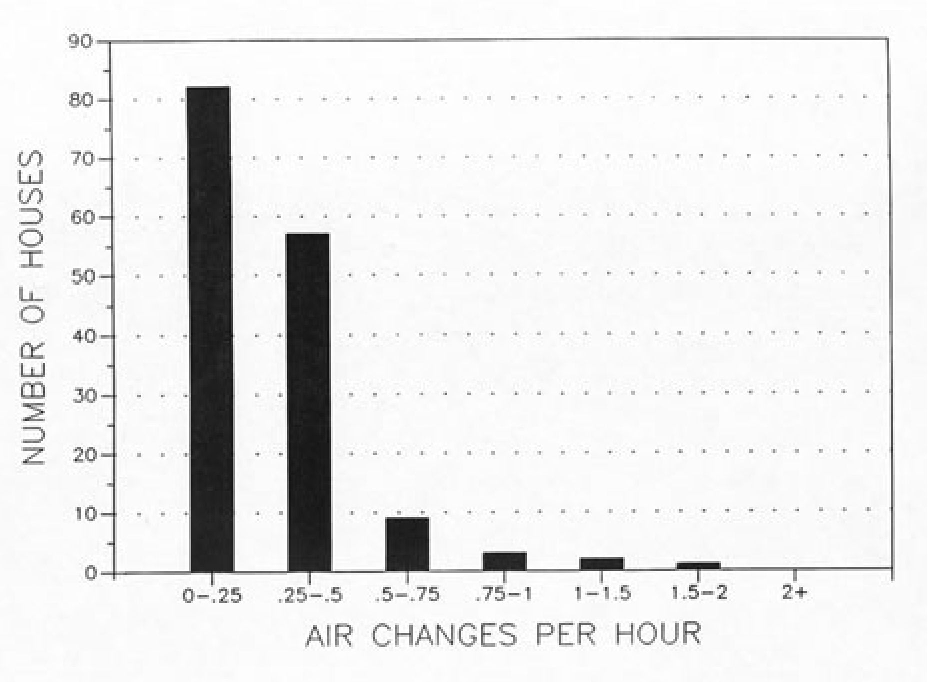
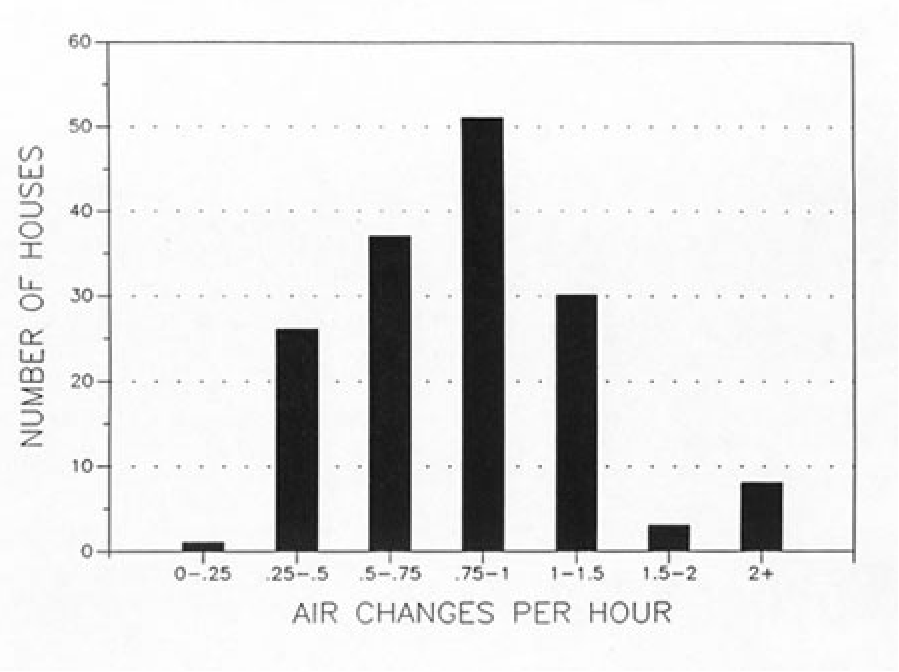


Figure 2. Tracer gas infiltration rates in 156 homes with the air handler on. Average = 0.91.



Second, further tightening may make indoor air quality worse. ASHRAE 62-1989 calls for 0.35 ach (or greater depending upon occupancy) for residences. Therefore, making homes tighter would not be recommended from the occupant health point of view.

It should also be noted that our measurements overestimate natural infiltration. There are two reasons for this. First, all tests were performed during the summer (April through October) hours of 9 A.M. to 5 P.M.. Because daytime winds in Florida are typically stronger than nighttime winds, measured natural infiltration probably over predicts actual annual average infiltration. Second, the air handler was used one or two minutes of each 10-minute sample period to provide mixing in 110 of the 160 homes. Air distribution system leaks cause elevated infiltration during these one to two minute periods, and they therefore overestimate natural infiltration.

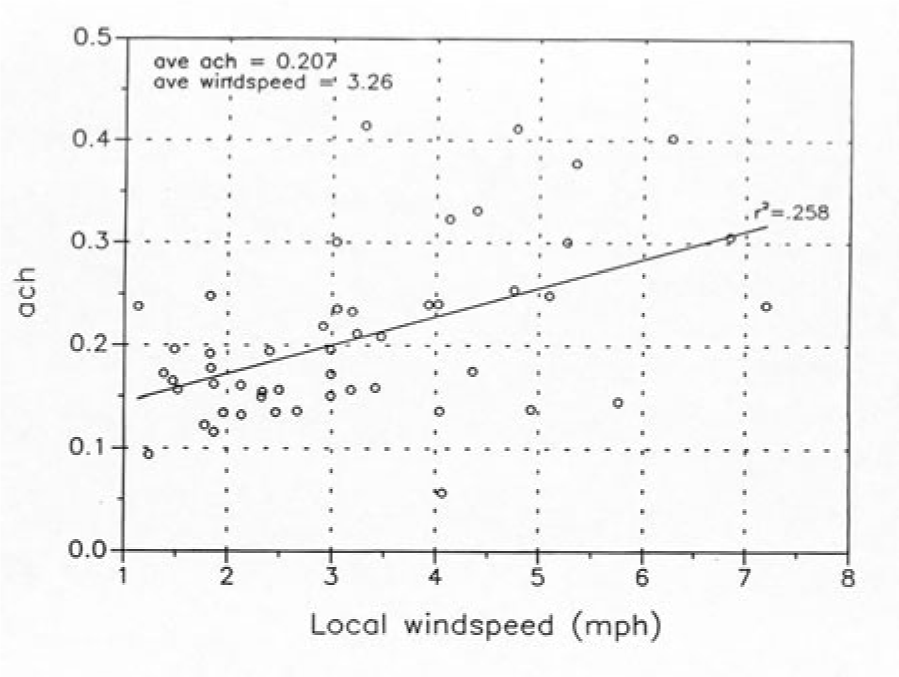
Since our measurements overestimate natural infiltration, the question can be raised, “What is the average annual natural infiltration rate for Florida homes?” Is it 0.25 ach? Or 0.22 ach? The answer will of course be speculative, but there may be some value in exploring this question. Comparison of wind speeds during the day and night is instructive. Wind speed from the Lakeland weather station averaged 5.3 MPH during the hours of 9 A.M. to 5 P.M., compared to 4.3 MPH for the entire day. Wind speed for the entire day is therefore 20% lower than for the testing hours of 9 A.M. to 5 P.M.. If a relation between wind speed and infiltration can be found, then an estimate may be made of daily infiltration rates.

Insight concerning wind speed impacts upon infiltration rates may be found in a study of 50 new homes (less than 5 years old) in Central Florida (Cummings, Moyer, and Tooley, 1990). Even though these homes are much more airtight (ACH50 = 7.3) and have lower infiltration rates (achon = 0.21) than the 99 home sample from this study, they show a pattern of increased infiltration with increased wind speed from which we may approximate a relation between test-period infiltration and daily infiltration (Figure 3). The plot contains a best-fit line for wind speed and infiltration. The average wind speed (measured on site using a 7 feet tower) during the tests was 3.3 MPH. If we look at the infiltration rate corresponding to a wind speed 20% lower, namely 2.6 MPH, we find that infiltration is 0.19 ach, or 10% lower. If we extrapolate this to the test results from our 160 house study, the measured natural infiltration of 0.28 ach would be reduced to 0.25 ach. If some adjustment is made for AH operation during the tests (which increased infiltration because of duct leaks), we might assume annual, natural infiltration of around 0.22 ach.

An additional piece of evidence concerning overall infiltration also comes from the same 50-house study. A 17-house subset of these 50 occupied homes had 7-day PFT (perfluorocarbon tracer) tests performed (Cummings, Moyer, and Tooley, 1990). The PFT tests provide a view of infiltration over the entire day-to-night spectrum. Seven-day infiltration averaged 0.17 ach, compared to 0.21 from the 80-minute tracer gas tests. PFT infiltration is 20% lower than that measured during the short tracer gas tests. When it is considered that the air handlers operated 27% of the time and caused average 0.44 ach infiltration when operating, then the PFT results actually are 36% lower. If we extrapolate this to the 160 sample in this study, overall infiltration would drop from 0.28 ach to 0.18 ach.

The preceding discussion does not resolve the question of what average annual infiltration rates. It does, however, suggest that overall natural infiltration rates in Florida homes may be in the range of 0.20 to 0.25 ach. In any case, Florida homes are already quite tight, and further tightening may lead to occupant health problems.

Figure 3. Tracer gas measured "natural" infiltration (air handler and all exhausts turned off) in 50 homes versus wind velocity measured by 7 foot tower on site. (Source: Cummings, Moyer, and Tooley, 1990)



It also suggests that if all ADS leaks are repaired, some homes may have increased indoor air quality problems. This does not, however, constitute a strong argument for not repairing ADS leaks. There are two major reasons why duct leaks should be repaired. First, while they provide ventilation, they also draw pollutants into the house; from the garage, crawl space, attic, and soil. While repair of duct leaks may decrease house ventilation, they may improve indoor air quality, on balance, because they reduce pollution entry rates.

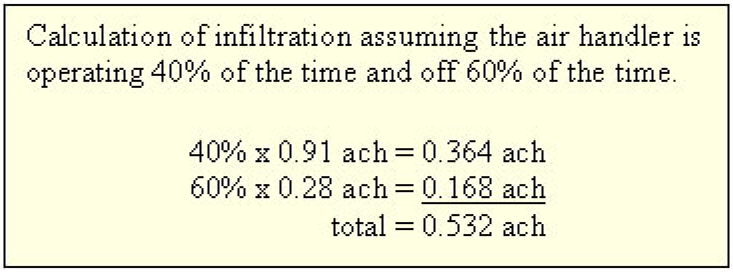
Second, the energy penalties resulting from duct leaks are generally much greater than infiltration from the outdoors, which is the most desirable source for ventilation air in terms of air quality. Supply leaks greatly increase energy use because they leak air that is highly conditioned (hotter than room air in the winter and colder than room air in the summer). In addition, in many cases they depressurize the house, causing air to be drawn in from the attic (among other places) and thereby increasing the cooling energy penalties. Return leaks generally cause higher energy use than ventilation air from outdoors, because a large fraction of return leaks are drawn from the attic of the garage, which locations have hotter air than outdoors.

For both indoor air quality and energy use reasons, duct leaks should be repaired. If additional air is required to maintain good indoor air quality (after some attempt has been made to remove pollution sources), then alternative means should be implemented to bring in air from outdoors, perhaps on a daily schedule which would minimize energy and peak demand impacts.

4.1.2 Infiltration with air handler on

When the air handler is operating, infiltration rates are much higher (see Figures 1 and 2). On the average, the infiltration rate with the AH on was 0.91 ach, or 225% greater than the natural infiltration rate. While more than 80 homes had infiltration rates less than 0.25 when the AH was off only 1 of 160 homes had infiltration less than 0.25 ach when the AH was on. Only 6 homes had achoff greater than 0.75 ach, while 92 had achon greater than 0.75 ach.

As can be seen from these numbers, duct leakage dominates infiltration in Florida homes. If we assume 40% air handler operation time (based on run-time from 50 monitored homes), then the daily average infiltration rate would be 0.54 ach (see calculations below). Duct leaks increase overall infiltration by 90%. If we assume that average natural infiltration is actually lower than measured (because nighttime winds in Florida are lower), say 0.22 ach, then overall infiltration would be 0.50 ach, and ADS leaks increase infiltration by 125%.

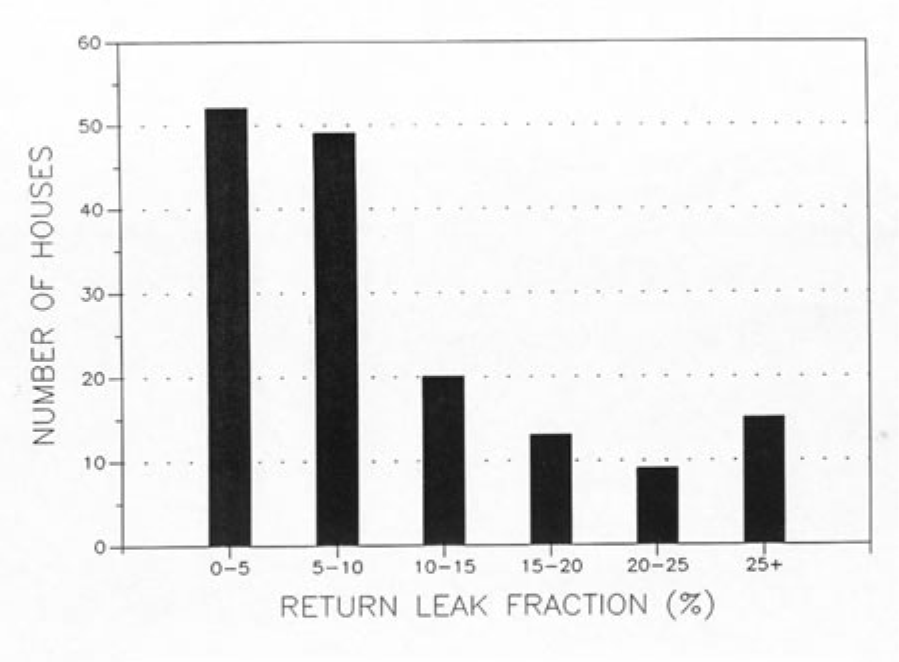


Calculation of infiltration assuming the air handler is operating 40% of the time and off 60% of the time.

40% x 0.91 ach = 0.364 ach
60% x 0.28 ach = 0.168 ach
total = 0.532 ach

Return leaks were found to be dominant in the majority of homes based on visual inspection. Tracer gas tests were used to determine the size of return leaks. The return leak fraction (RLF) was measured in each home with the AH operating (Figure 4). Sixty-seven prevent were found to have return leaks equal to or greater than 5% of the AH total air flow. Thirty-six percent have greater than 10% RLF. The average for 160 homes was 10.7% RLF.

Figure 4. Return leak fraction (RLF) in 158 homes measured by tracer gas dilution. Average = 10.7%.



4.1.3 Low natural infiltration rates are reasonable

To some readers, 0.28 ach natural infiltration may seem lower than expected. The following observations are offered as an explanation for low infiltration in Florida homes. “Natural” infiltration is driven by pressure differentials caused by wind and thermal stack. Florida wind speeds are lower than in other parts of the country. Stack effect is small because: (1) temperature differences (indoors minus outdoors) are less than 15ºF most hours of the year, (2) homes are typically short (one story), and (3) concrete slabs (greater than 90% of homes) and block walls (greater than 80% of homes) do not offer many inlets for stack infiltration.

Infiltration testing from other projects indicate that these low natural infiltration rates are reasonable. Natural infiltration in 50 new (less than five years old) Florida homes was 0.21 ach (Cummings, Moyer, and Tooley, 1990). A sample of 9 Florida homes averaged 0.22 ach (Cummings, 1988). Another sample of 12 Florida homes averaged 0.26 ach (Cummings and Tooley, 1989). A sample of 5 Florida homes averaged 0.14 ach (Cummings and Tooley, 1990). Infiltration measured in other states is similar as well. In Tennessee, 31 homes averaged 0.44 ach with the air handler off and 0.78 ach with the air handler on (Gammage, et al., 1986). In 55 new homes in the Pacific Northwest, infiltration measured over a four-month winter period averaged 0.24 ach, in homes which did not have forced air space conditioning.

4.2 Blower Door Test Results

Blower door tests were performed on 100 homes. ACH50, the ventilation rate of the house when depressurized to 50 Pa, averaged 12.7 (Figure 5). When the supply and return registers were sealed by means of paper and tape, ACH50 dropped to 11.1 indicating that holes in the ADS system account for 12.7% of the total house air leakage at 50 Pa pressure (Figure 6). Since the duct system is less than 1% of the volume of the house, it is remarkable that is contains such a large proportion of the leak area of the house. This indicates significant problems in ADS construction which must be addressed.

Figure 5. House airtightness (ACH50) measured by blower door in 99 Florida homes. Average = 12.7 ACH50.

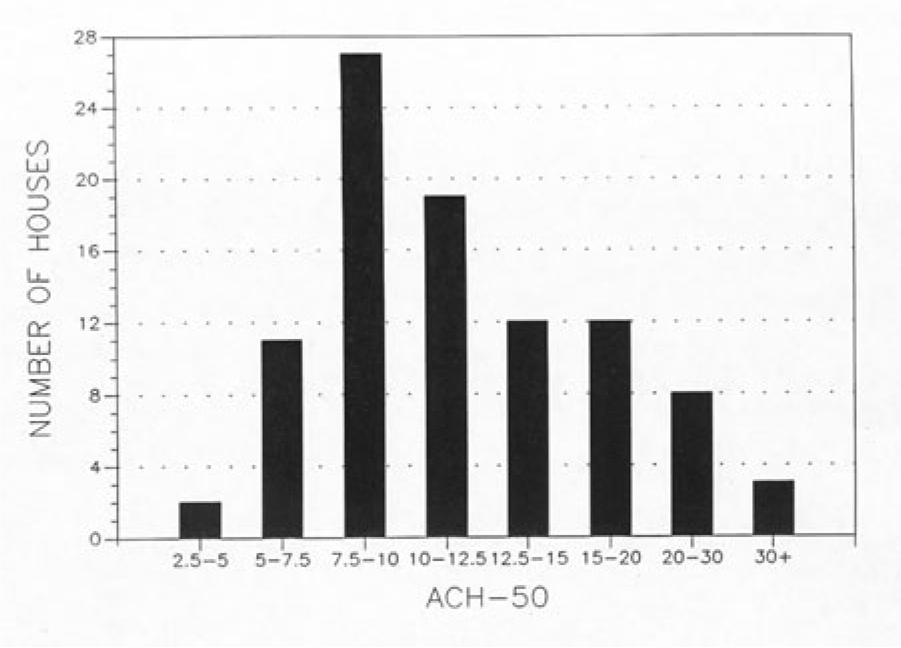
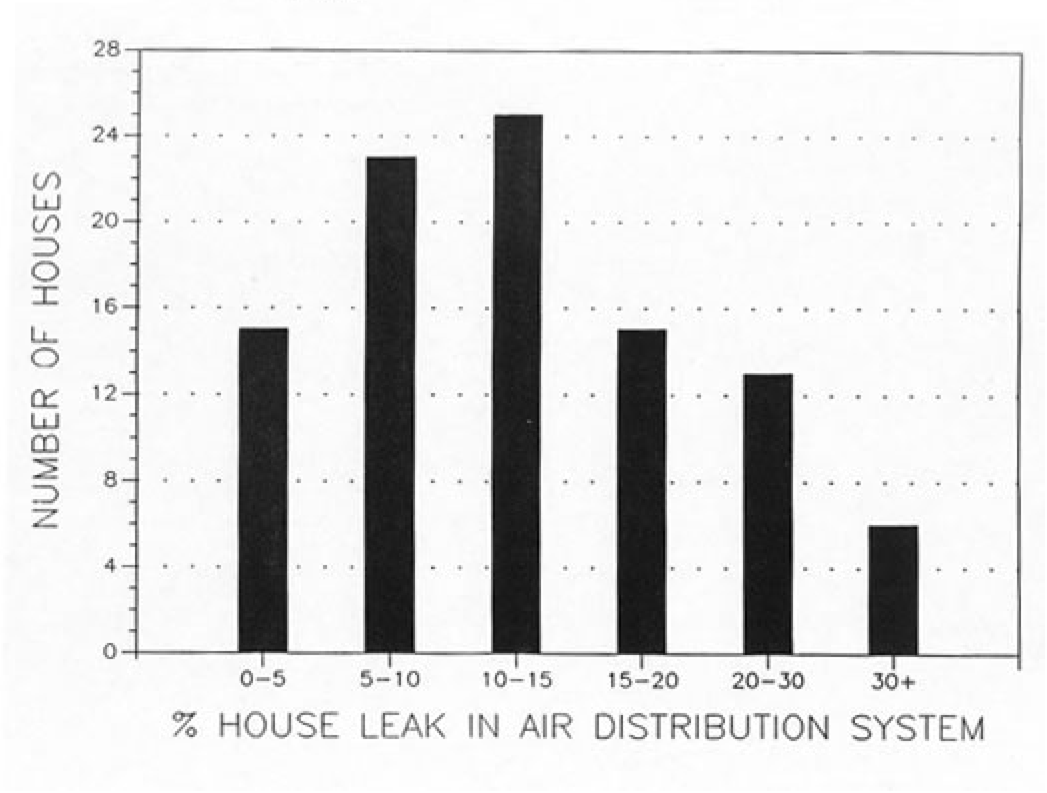


Figure 6. Percent of house air leakage at 50 pascals which is located in the air distribution system of 95 homes, determined by blower door. Average = 12.7%



The significance of leaks in the duct system becomes more important when it is considered that most of the ADS system is under an order of magnitude greater pressure differential than the remainder of the house. The air distribution system is commonly under pressure most of the time. It is interesting to note that the 12.7% of the house leaks located in the duct system account for 70% of the infiltration when the AH blower is on.

The 100 homes which had blower door tests have slightly greater duct leakage than the larger sample of 160 homes, based on comparison of tracer gas test results. Infiltration with the AH on was 1.04 ach in these 100 homes compared to 0.91 ach for the 160 homes. RLF is 12.9% compared to 10.7%. Infiltration with AH off is 0.31 ach compared to 0.28 ach.

Blower door tests indicate that house airtightness is a function of age (Figure 7). Older homes are leakier. Homes built in the last 10 years have ACH50 of about 8 while those over 20 years old have an average ACH50 of about 16.

4.3 Air Handler Location

Variations in house airtightness, duct airtightness, infiltration rates, and return leakage can be seen for various air handler locations. The five air handler categories are attic, closet, garage, package, and mobile home. Table 1 table summarizes the results for the 98 homes which had complete blower door tests.

Figure 7. House airtightness (ACH50) as a function of age, measured by blower door in 95 Florida homes. Average = 12.7 ACH50.

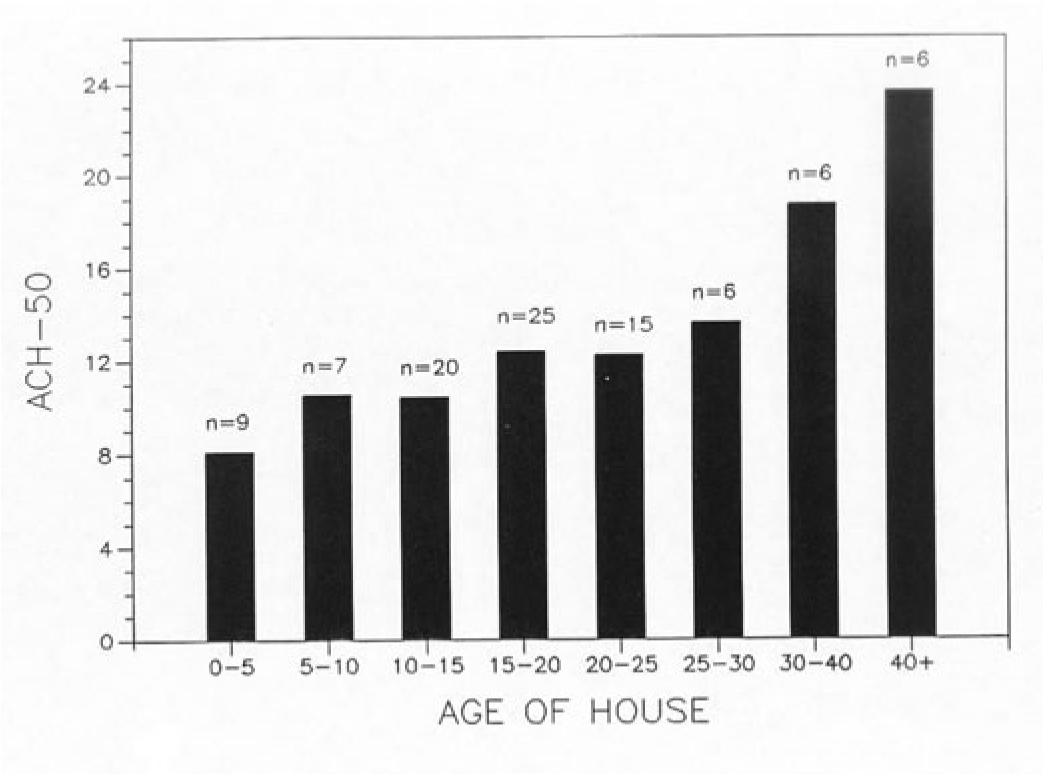


Table 1. House airtightness and tracer gas measured infiltration rates in 98 homes which had complete blower door tests by air handler location.

		Blower Door		**Tracer Gas**		
Location	**Sample Size**	**House ACH50**	**Leak % in Duct**	**AH off ach**	**AH on ach**	**RLF**
attic	20	14.7	13.0%	0.27	0.95	14.8%
closet	18	12.1	12.4%	0.30	0.93	12.0%
garage	21	8.9	13.7%	0.29	0.90	11.5%
package	17	12.2	13.0%	0.39	1.26	16.8%
mobile	22	14.0	12.0%	0.36	1.14	10.3%
tot / avg	98	12.7	12.7%	0.32	1.03	12.9%

Blower door tests reveal that all air handler locations have duct leakage. The proportion of the house leak area which is in the air distribution system is similar among the five categories, all in the range of 12% to 14%. Tracer gas test results indicate that mobile homes and homes with package air handlers have greater air distribution system leakage, shown by higher infiltration rates with the air handler on. Attic and package units have greater return leakage, on average. Since the samples are only in the range of 17 to 22 houses, the variations among types are not statistically significant.

Tracer gas tests for the larger sample of 160 homes show a similar pattern to that in the 98 house sample. Air handler induced infiltration is again highest in the package and mobile home samples. Return leaks are substantially higher only in the package unit homes.

Table 2. Tracer gas measured infiltration rates in 160 homes by air handler location.

		Tracer Gas		
Location	**Sample Size**	**AH off ach**	**AH on ach**	**RLF**
attic	42	0.25	0.81	9.8%
closet	31	0.30	0.82	9.0%
garage	30	0.24	0.82	10.1%
package	28	0.32	1.16	16.3%
mobile	29	0.33	1.00	8.7%
total	160	0.28	0.91	10.7%

4.4 Smoke Test Inspection

Visual inspection of duct leaks was done in two ways. First, with the blower door in place, the house was pressurized to about 15 Pa. Using a smoke stick (titanium tetrachloride) each supply and return register was checked (with the AH off) to see if smoke would pass into it, and at what velocity. If the smoke did not enter the grill, or entered it slowly, then little or no leak was located in nearby ducts. However, if the smoke "raced" into the register, then leakage existed in the ducts nearby. Second, the duct system was inspected with the AH operating (blower door off). All connections, ducts, plenums, and air handlers were inspected for leaks, either with the smoke stick or by feeling by hand.

Return leaks are estimated to be about twice as large as supply leaks in site-built homes, based on the homes we have inspected. The reason this is an estimate is because we have no direct method for measuring supply leakage. Return leaks can be measured fairly precisely with tracer gas. The estimate that supply leaks are about one-half that of return leaks is based upon visual inspections alone.

Return leaks in mobile homes are large, but not as large as supply leaks. It is estimated that supply leaks are larger than return leaks in more than two-thirds of mobile homes.

4.4.1 Description of return leaks in site-built homes

Return leaks are found in the following locations, listed in order of magnitude, based on visual inspection (remember that return leak here refers to the fraction of air coming from outside the house):

1. Return plenums: The return plenum is most frequently also the support platform for the air handler unit. While it is usually lined with fiberglass duct board for sound deadening and insulation, it is typically not airtight. Commonly, the construction is such that the plenum is framed or joined into the walls in the garage, closet, or utility room in which they are located. These walls are not airtight because they have framing gaps and often are used as chase ways for plumbing and wiring. Air is drawn through these walls from the attic, garage, crawl space, or outdoors into the return air system. Dropped ceilings or soffits are also frequently framed onto the walls that adjoin the support platform/return plenum, thus enlarging the leak pathways. Leaks in the return plenums commonly range from 5% to 25% of the total air handler air flow.
2. Return register connections: Commonly the wall penetrations where a return register connects to a return plenum or duct is not sealed, and consequently air can be drawn through the wall cavity from the attic, crawl space, garage, or outdoors into the return air stream.
3. Air handler cabinets: Air handlers leak at panel cracks. Through use and abuse the panels become bent and more leaky. Penetrations in the cabinet for electrical, Freon, and condensate lines create additional leak sites. The filter door frequently is not tightly sealed. Electronic air filters often create large return leaks where they are attached to the air handler. In addition, the seal between the air handler and the return plenum is often not adequately sealed.
4. Return ducts: In a small proportion of homes, return ducts have become disconnected from registers, plenums, or other ducts, creating large leakage.
5. Chase lines: Chases carrying Freon and condensate lines from outdoors to the air handler through the concrete slab usually terminate in the return plenum and often are not sealed. Consequently they are pathways for infiltration because they are under substantial depressurization. The quantity of infiltration air is generally very small. Its impact upon radon and other soil gas entry may be very great in some cases.

4.4.2 Description of supply leaks in site-built homes

Supply leaks are found in the following locations, listed in order of magnitude, based on visual inspection:

1. Supply plenums: Supply plenums often have major leaks at the connection of the plenum to the air handler or furnace cabinet. This leakage usually occurs because of failure of tape adhesion. Frequently the air handler/supply plenum is located so close to adjacent walls that sealing is difficult, which points to the need for clearance around air handlers, plenums, and ducts.
2. Supply box (boot): The connection of supply duct to supply register frequently leaks. Typically the box is simply slipped over the flanges of the register and no seal is applied. These leaks are very common, but they are commonly small to moderate in size in a majority of homes, and large in a small proportion.
3. Flex duct connections: Flex duct connections typically leak. These leaks are mostly small to moderate. They commonly occur where the flex duct joins to duct board. They occur because care is not taken to apply sealant thoroughly to a number of leakage points which exist at this junction.
4. Supply duct leaks: Flex duct often has small leaks resulting from tears in plastic linings which develop because of rough treatment. In a small number of cases, the plastic outer liner has disintegrated because of exposure to sunlight. Duct board ducts sometimes leak because the closure system (usually tape) fails, resulting in small, medium, and infrequently very large (grater than 30% of total air flow) leaks.

4.4.3 Description of return duct leaks in HUD-code mobile homes

Return leaks are generally smaller than supply leaks in mobile homes. The most dominant return leaks are listed below, in order of estimated leak magnitude.

1. Package unit cabinet air leakage: Commonly the cabinet bottom rusts out creating openings. Because the leak sites are located near the blower, the leak air flow is large. In a significant number of cases the wall separating the evaporator and condenser coils has rusted out. This creates large energy problems since hot air from the condenser coil can be drawn into the return air stream. Even when there is no rust, penetrations and cracks in panels cause small to moderate leakage.
2. Central return box leak: Where the return duct meets the house floor, there is a return plenum box which is a central return. This commonly leaks to adjacent walls or where it connects to the floor.
3. Flex duct connections: Flex duct connections at the air handler, return plenum box, or duct to duct connections often leak small to moderate amounts, and in rare cases where these connections totally separate, the leaks may be extremely large.
4. Subfloor space as return plenum: In a few cases, the space between the floor and the pan is used as a return plenum. Since this area is not airtight from the outdoors, large leakage occurs.

4.4.4 Description of supply duct leaks in HUD-code mobile homes

Supply leaks are found in mobile homes in the following locations in order estimated leak magnitude.

1. Supply arm seals: The joint between the main supply trunk and the metal shafts to the floor are typically not sealed and produce moderate to large leaks into the Subfloor area.
2. Supply duct to floor connections: In nearly all cases there is no positive, airtight seal between the supply arm and the floor. The metal duct is usually only stapled to the Subfloor material. Consequently, there are often large leaks at these junctions.
3. Leaks at the end of supply trunk lines: In a significant minority of mobile homes, the ends of the supply trunk lines have not been sealed and may cause large supply air leaks.
4. Misalignment of supply registers: In a few cases the supply duct does not line up with the floor register. This creates large supply leaks, since the connection to the floor is not airtight.
5. Flex duct connections: Leaks in the flex duct connecting the air handler to the main supply trunk line. Connections at the air handler, the trunk line, or at a connection of two flex duct sections often have small to moderate leaks. In rare cases these connections totally separate causing nearly complete performance degradation of the space conditioning system.

4.5 Duct Repairs Impacts in 50 Homes

Duct leaks were repaired in 50 homes. The impact of these repairs upon the following variables was measured: infiltration rate with the air handler operating, the return leak fraction, house airtightness, the proportion of the ADS leak area which was repaired, and cooling energy use.

4.5.1 Impact of duct repair upon infiltration

Infiltration rates were measured before and after ADS repairs. The results are summarized in Table 3 for the first 25 homes which were repaired in 1989. Results for the second 25 homes (repaired in 1990) are available only for “before repair”. Infiltration rates “after repair” are unavailable because of equipment failure. Since post-repair tests are unavailable for the second 25 homes, the following discussion of infiltration and return leaks relate only to the first 25 homes.

Because of duct repair, infiltration with the AH on decreased from 1.10 ach to 0.54 ach. It is interesting to note that duct repairs, which decreased house leak area by 10.7% (ACH50 decreased from 12.3 to 10.9), caused a 53% reduction in infiltration with the air handler operating. Perhaps more significantly, infiltration with the air handler on was reduced 66% of the way to the natural infiltration rate of 0.25 ach. RLF was reduced 73%, from 15.8% to 4.4%.

Table 3. Infiltration Rates and Return Leak Fraction (RLF)
in 25 Homes Before and After Duct Repairs.

	Before Repair			**After Repair**				
	achoff	**achon**	**RLF %**	achoff	**achon**	**achon % red.**	**RLF %**	**RLF % red.**
1- CRO	.39	.99	14.5	.17	.27	72.7	2.7	81.3
2- KET	.33	.95	22.4	.16	.25	73.6	3.9	82.5
3- KAL	.15	.96	7.0	.19	.35	63.5	3.3	52.8
4- MER	.19	.88	26.1	.16	.49	44.3	2.4	90.8
5- RAI	.49	1.36	21.6	.13	.42	69.1	1.8	91.6
6- STA	.10	.99	15.4	.15	.49	50.5	2.7	82.4
7- SWA	.10	.97	6.6	.81	.83	14.4	3.0	54.5
8- VIE	.10	1.33	15.4	.27	.82	38.3	8.0	48.0
9- BRI	NA	2.12	0.0	.64	1.50	42.3	4.7	0.0
10- CAR	.49	.72	8.8	.27	.38	47.2	0.0	100.0
11- CUS	NA	.88	10.0	.19	.44	50.0	0.0	100.0
12- GAG	.46	1.45	29.1	.62	1.19	17.9	15.3	47.4
13- GRU	.10	.98	10.3	.36	.47	52.0	1.1	89.3
14- GUD	.32	.77	10.9	.24	.49	36.4	8.5	22.0
15- HUG	.30	1.29	16.8	.08	.16	87.5	0.5	97.0
16- HUT	NA	1.15	22.5	.05	.33	71.3	5.2	76.9
17- JON	.18	1.45	15.2	.15	.56	61.4	7.4	51.3
18- LAM	.07	1.26	36.1	.10	.68	46.0	13.4	62.9
19- LAU	.16	1.21	45.5	.23	.31	74.3	5.4	89.5
20- PEN	.14	.74	5.8	.13	.51	31.1	4.8	17.2
21- PET	.38	.76	4.0	.11	.48	36.8	0.0	100.0
22- PET	.10	1.07	19.5	.08	.44	58.8	4.2	78.4
23- RID	.16	.89	7.2	.42	.72	19.1	7.9	0.0
24- SUT	.44	1.20	23.0	.23	.31	74.2	3.5	84.8
25- WES	.24	1.16	0.7	NA	.52	55.2	1.1	0.0
AVE.	.245	1.10	15.78	.248	.536	51.3	4.43	71.9

1 Return leak fraction is the proportion of the air returning to the air handler which originates outside the house.

4.5.2 Impact of duct repairs upon house and ADS airtightness

Blower door tests results are summarized in Tables 4 and 5 for before and after repair. In the 48 which had complete blower door tests, ACH50 averaged 12.5, which is similar to 12.7 for the larger sample of 98. While overall house airtightness is similar to the larger sample, duct leakage is larger in these 48 homes than in the larger sample. The proportion of the whole-house leakage at 50 Pa which is in the air distribution system is 15.6%, compared to 12.7% in the sample of 98. Tracer-gas-measured infiltration with the air handler on averaged 1.07 ach (compared to 1.04 ach for the 98 and 0.91 ach for the sample of 160), and the RLF averaged 15.7% (compared to 12.9% for the 98 and 10.7% in the 160 house sample).

Repair of duct leaks reduced ACH50 in these 48 houses by 9.9%, from 12.5 to 11.2. This reduction in ACH50 of 1.23 indicates that 64% of the duct leak area was sealed.

4.5.3 Impact of duct repair upon cooling energy use

Air conditioner energy use was analyzed for these 50 homes. In one home the air conditioner failed during the test period, making analysis impossible. In three others, the quality of meter reading was too low to make the data useable. In the remaining 46, cooling energy use was reduced from an average 40.6 kWh/day to 33.6 kWh/day, or an average 17.2% reduction per home. Savings ranged from a low –4.0% (energy use rose by 4 percent) to a high of 44.6%. The distribution of cooling energy savings is presented in Figure 8.

Table 4. House Airtightness, Duct Airtightness and Cooling
Energy Use In 25 Homes Before and After Duct Repair.

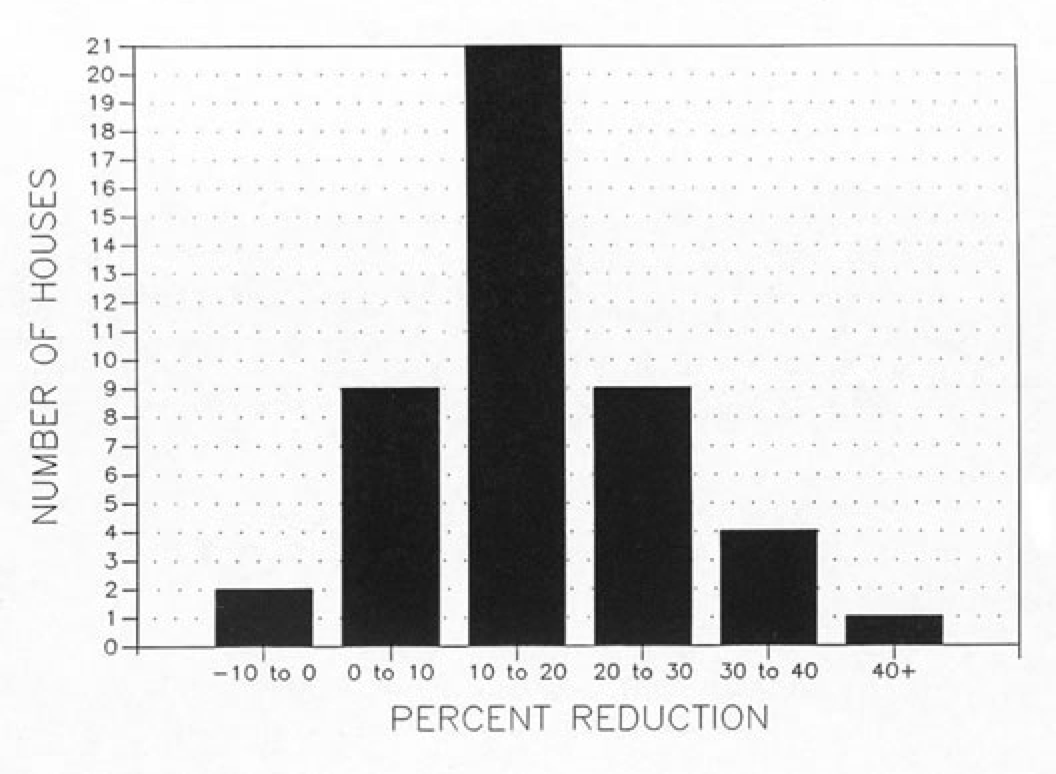
	Before Repair			After Repair			Cooling Energy kWh		
	ACH50 Total	ACH50 w/o Ducts	ACH50 Reduc %	ACH50 Total	ACH50 % Reduc.	% Leaks Repair	Before Repair	After Repair	% Reduc
1-CRO	10.6	10.0	5.9	9.5	10.9	100.0	83.9	68.5	18.4
2-KET	5.3	4.5	15.4	4.6	12.5	81.6	35.6	26.1	26.7
3-KAL	6.8	6.4	5.3	6.6	2.1	39.6	28.0	26.9	4.2
4-MER	13.9	8.9	35.8	10.5	24.6	68.7	25.2	13.9	44.6
5-RAI	10.1	9.1	10.0	9.3	7.5	75.0	31.7	26.4	16.4
6-STA	8.4	6.9	17.8	7.5	10.4	58.4	35.1	30.0	14.4
7-SWA	11.7	8.6	26.9	9.5	19.2	71.3	NA	NA	NA
8-VIE	11.4	9.6	16.0	9.9	12.5	78.1	17.4	15.3	12.0
9-BRI	35.6	32.5	8.7	33.4	6.1	70.1	58.5	56.4	3.5
10-CAR	19.4	17.5	10.1	18.5	4.9	48.5	29.6	23.3	21.4
11-CUS	9.3	8.9	4.6	8.9	4.3	93.4	41.2	38.8	5.8
12-GAG	22.1	19.9	9.9	20.2	8.5	85.8	48.4	43.0	11.1
13-GRU	13.1	11.4	12.8	12.1	7.7	60.1	57.1	54.6	4.5
14-GUD	6.4	4.9	23.5	5.9	8.8	37.4	56.8	38.1	33.0
15-HUG	10.3	9.0	12.4	9.1	11.4	91.9	41.3	34.1	17.4
16-HUT	6.6	4.1	38.9	4.9	26.3	67.6	25.1	17.7	29.5
17-JON	7.8	5.2	33.3	6.4	18.8	56.4	53.3	46.5	12.7
18-LAM	10.4	9.5	8.6	10.2	1.7	19.7	25.9	22.3	13.9
19-LAU	8.8	7.9	10.2	8.1	7.9	77.4	52.8	38.9	26.2
20-PEN	7.8	5.4	30.4	5.8	26.0	85.5	54.0	38.6	28.4
21-PET	10.0	8.5	15.0	9.1	9.7	64.6	36.5	33.9	7.2
22-PET	7.2	NA	NA	6.7	8.3	NA	27.7	23.0	16.8
23-RID	25.0	23.4	6.5	24.6	1.8	51.2	62.2	55.0	11.6
24-SUT	8.1	6.6	18.8	7.2	10.9	57.9	44.8	36.7	18.0
25-WES	16.3	15.3	6.0	15.4	5.1	85.0	20.0	13.4	33.3
AVE.	12.10	10.58	16.0	10.95	10.72	67.7	41.3	34.2	18.0
1 This ACH50 is with all supply and return registers covered by paper and tape.									

Table 5. House Airtightness, Duct Airtightness, and Cooling Energy Use in 24 Homes Before and After Duct Repair.

Before Repair				After Repair			Cooling Energy kWh		
	ACH50 Total	ACH50 1 w/o Ducts	ACH50 Reduc. %	ACH50 Total	ACH50 % Reduc.	%Leaks Repair	Before Repair	After Repair	% Reduc.
1-AUG	17.2	15.8	8.0	15.5	10.0	100.0	24.7	21.4	13.4
2-BLA	11.5	9.5	17.3	10.8	6.8	39.2	33.5	28.2	15.8
3-BOR	9.8	8.7	10.9	9.7	1.5	13.8	38.9	34.6	11.1
4-BOY	11.8	10.5	11.4	11.3	4.9	43.1	19.6	19.4	1.1
5-CAR	12.0	10.5	12.5	11.3	5.9	47.0	NA	NA	NA
6-DEN	9.0	7.9	12.6	8.5	6.3	49.8	28.8	29.4	-2.2
7-GRI	4.6	3.6	21.8	4.0	12.3	56.5	42.3	36.8	13.0
8-HAN	6.8	6.1	9.5	6.5	4.5	47.4	26.9	24.1	10.5
9-HEF	16.8	14.0	16.4	14.5	13.4	81.6	41.0	32.4	21.0
10-HER	15.1	13.8	8.5	13.8	8.6	100.0	42.5	34.3	19.4
11-HUT	14.5	12.5	13.6	13.7	5.8	42.7	41.8	43.5	-4.0
12-KIN	14.2	7.1	49.8	9.1	35.4	71.1	50.0	30.6	38.9
13-LAV	13.5	10.5	22.4	12.3	9.1	40.5	19.8	14.6	26.3
14-MAX	NA	NA	NA	NA	NA	NA	38.7	32.5	16.0
15-PAR	9.3	7.7	18.2	8.1	12.9	71.0	31.5	30.9	2.0
16-PAR	13.1	12.1	7.0	12.5	4.2	59.6	38.3	28.2	26.4
17-SCI	12.3	10.8	12.2	12.0	3.1	25.7	27.7	21.1	23.8

18-SCH	17.1	14.6	14.7	17.2	-.3	-1.8	35.1	34.7	1.2
19-SHA	18.0	13.9	22.8	14.4	20.0	87.5	NA	NA	NA
20-SME	14.6	12.5	14.5	13.2	10.0	68.9	44.0	41.5	5.7
21-SWA	22.3	19.2	14.0	19.8	11.6	82.4	40.1	32.2	19.4
22-THA	12.2	9.1	25.5	9.5	22.8	89.2	62.7	38.0	39.4
23-TUR	11.4	9.5	17.1	9.6	15.6	91.5	95.7	78.2	18.3
24-WUE	8.3	6.0	27.3	7.1	14.3	52.2	41.3	35.1	14.8
AVE.	12.9	10.7	16.9	11.5	10.4	60.2	39.3	32.8	16.5
1 This ACH50 is with all supply and return registers/grills covered by paper and tape.									

Figure 8. Reduction in cooling energy use resulting from repair of air distribution system leaks in 46 homes. Average reduction = 17.4%.



In eight homes, energy savings were less than five percent. These cases were examined to see why savings were low. In two instances, energy savings were small because the initial duct leakage was small. Therefore, small energy savings were expected. In one, repairs reduced 7% return leak to 3.3%, and energy use was reduced 4.2%. In another, which had almost no duct leakage (achon = 0.35 and RLF = 4%), energy savings was 2.0%.

In other cases it was found that some of the duct leaks were inaccessible or unrepairable, so complete repair was not possible. In one case, which experienced only 3.5% energy savings, the majority of the large supply leaks were in inaccessible portions of an attic addition. In another case, a package air handler was badly rusted, and no repair of the air handler leaks could be made. A change-out of that air conditioner (about $1500) would solve the majority of those large duct leaks.

A number of homes were not included in the sample for repair because their ducts were inaccessible. The majority of these were new mobile homes with supply ducts in the ceiling. Because there is no attic space, access to duct leaks in this ceiling cavity is impossible, short of removing the ceiling. Since these ducts cannot be accessed and the duct leaks therefore cannot be located and repaired, this type of construction, in effect, makes the duct leaks permanent. Careful assessment should be made of all building practices which restrict access to ducts, plenums, and air handlers.

It is our recommendation that building energy codes require access and clearance around these components of the air distribution system. Precedence for this is in the Southern Building Code Congress International, Inc. building code, which Florida has adopted. It requires a minimum of one access to the attic so that various mechanical and utility systems may be serviced. The air distribution system clearly is a system which requires servicing and repair in a large majority of homes.

In two cases "short-circuiting" of supply to return leaks may have been occurring. By "short-circuiting" we mean the supply and return leaks are in close proximity, so much of the supply leak air is drawn back into the system through the return leak. In one mobile home which showed only 1% energy savings, supply leaks were discharging into the pan/sub-floor area from which the return leak was also drawing. In one attic-air-handler home which experienced 4% increase in energy use, supply leaks were dumping into a space below the air handler where the return leak was also drawing much of its air. This "short-circuiting" may partially account for that fact that energy savings were near zero.

In one other case where energy use actually increased by 2% and in another case where energy use decreased by 4.5%, no explanation could be found for the lack of savings, since significant leaks were repaired. It is possible that there were lifestyle, occupancy, or equipment changes in the home which could explain the lack of savings. In general, however, there seemed to be reasonable factors explaining the lack of energy savings in six of the eight homes which had less than 5% energy use reduction.

Five homes experienced greater than 30% energy savings (Figure 8). The greatest was 44.6% reduction. In this case there was a 26.2% return leak, nearly all of which was from the attic. If the air conditioner had been sized larger, the savings would have been even greater since the air conditioner, before repair, could not meet the cooling load during most afternoons. While the house thermostat was set at 79ºF, the house temperature often rose to 82ºF and above. It is suspected that energy savings were smaller than would have otherwise occurred in at least 10 of these homes because the air conditioner was unable to meet cooling loads caused by large duct leaks.

Comparison of energy use before and after repair was done in the following manner. A least-squares first-order best fit was made for the daily AC kWh verses average daily temperature. From these best fit lines, energy use before and after repair was determined at the average summer temperatures of 81.3ºF and 81.8ºF in Brevard and Polk counties, respectively. Plots for eighteen houses are presented in Figures 9, 10, and 11.

It is estimated that the average cost of duct repair in these 50 homes was about $200. With average energy savings of 7.0 kWh/day, cooling season savings of $85 could be expected. Including heating season savings of perhaps $25, duct repairs would have a simple payback of less than 2 years.

4.5.4 Energy savings by air handler location

Energy savings by air handler location is presented in Table 6. Some observations can be made. Energy use appears to be significantly higher in homes with attic air handlers both before and after repair. Attic AH houses used 30% more cooling energy (before repair) than the other four groups collectively. Following repair, attic AH houses used 35% more cooling energy than the others.

Table 6. Impact of duct repair upon house airtightness, air distribution systems air tightness, and cooling energy use by air handler location.

		Before			**After**			
Locat.	**#**	**ACH50**	**%inDuct**	**kWh/d**	**ACH50**	**%Rep'd**	**kWh/d**	**%red.**
attic	8	15.8	19.2%	49.9	14.2	62.8%	42.6	14.7%
closet	10	12.4	14.3%	44.1	11.2	63.1%	37.1	15.9%
garage	10	10.2	15.2%	34.1	9.2	67.0%	28.3	17.3%
p'kage	10	9.7	18.5%	39.2	8.8	49.5%	31.9	18.6%
mobile	10	14.9	14.8%	36.2	13.3	66.2%	30.6	17.2%
tot/avg	48	12.5	15.7%	40.6	11.2	61.7%	33.6	17.2%

Figure 9. Measured cooling energy use before and after repair of air distribution system leaks in six Florida homes. (Source: Cummings, Tooley, Moyer, and Dunsmore, 1990)

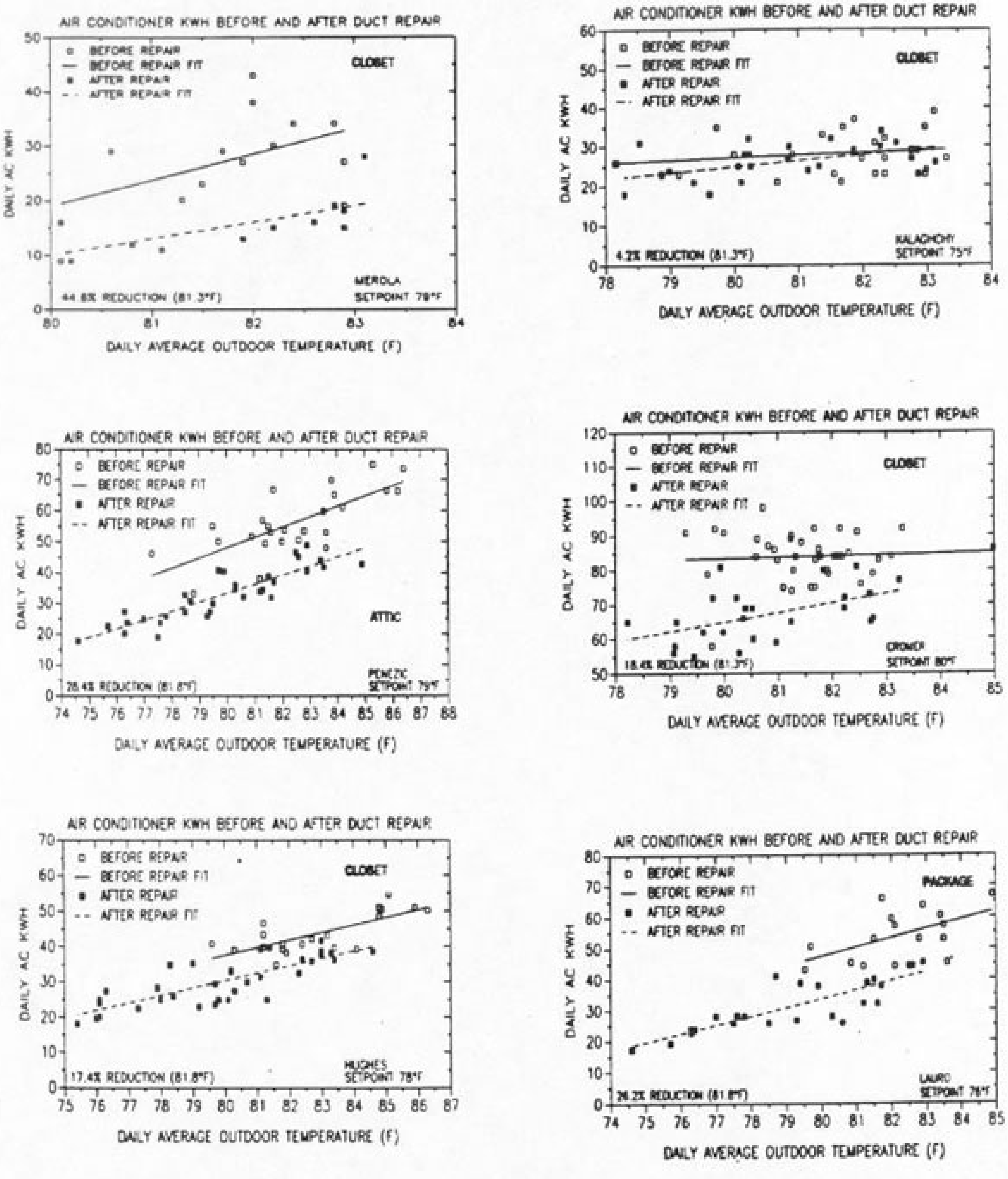
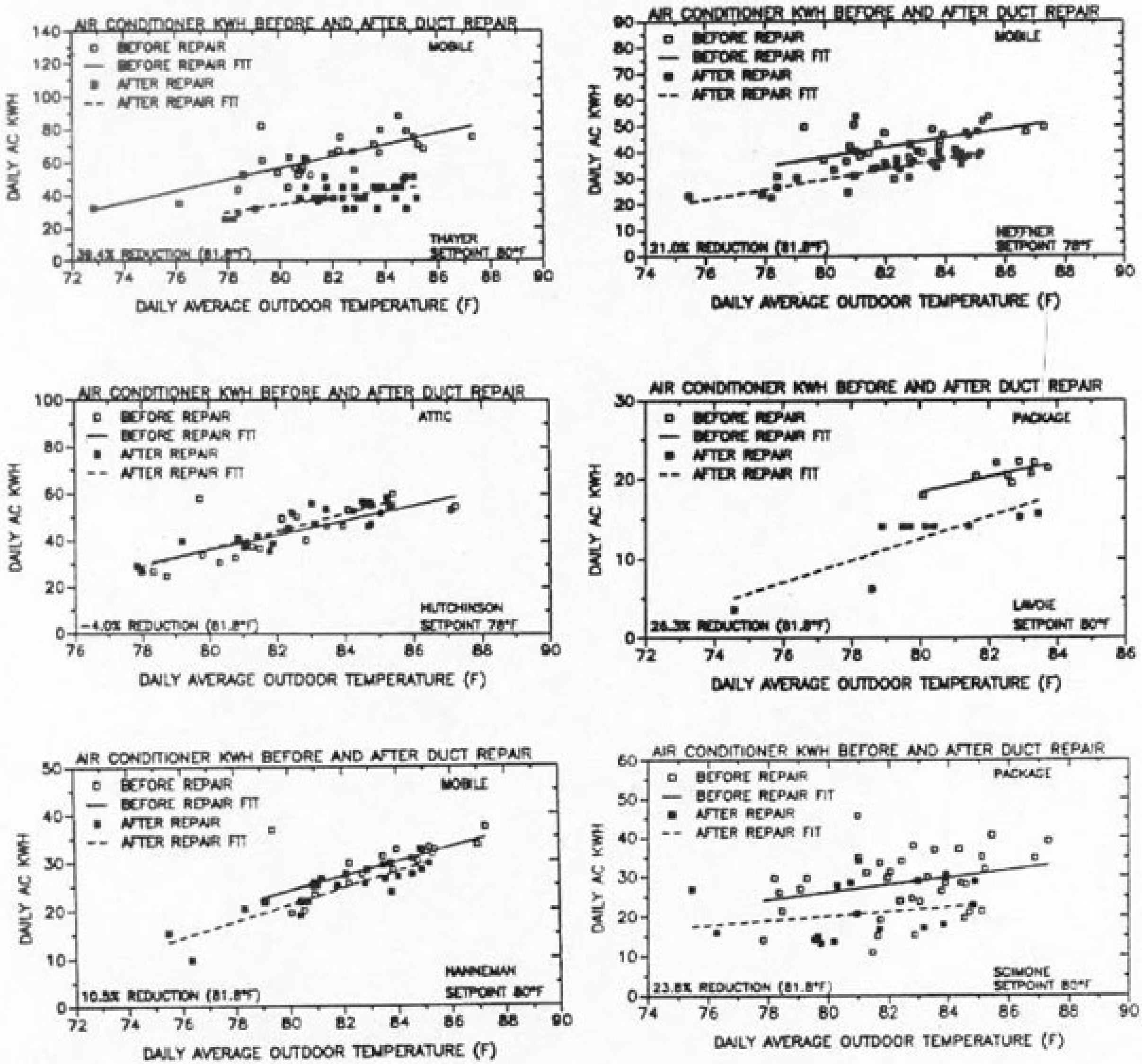


Figure 10. Measured cooling energy use before and after repair of air distribution system leaks in six Florida homes.



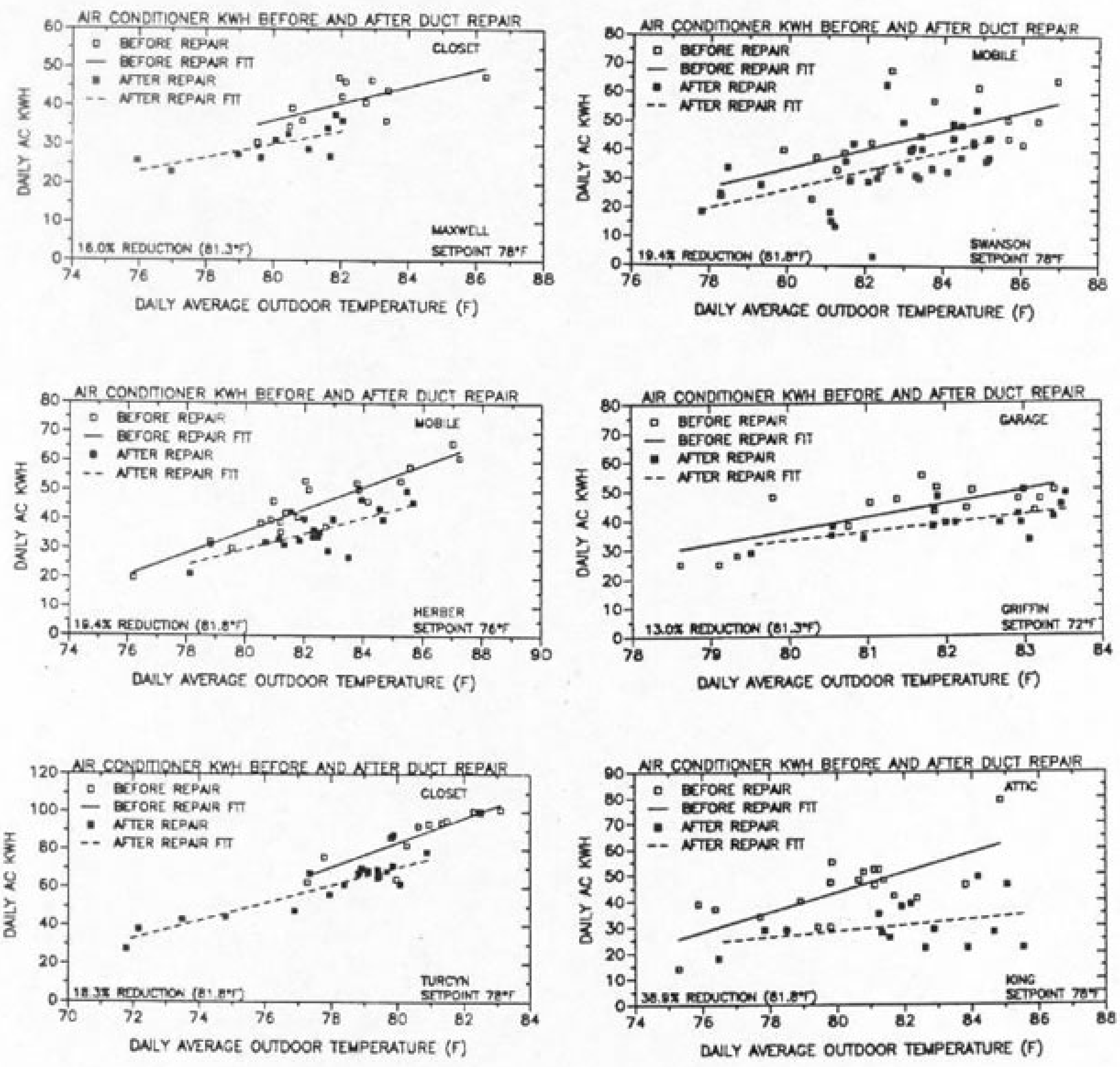


Figure 11. Measured cooling energy use before and after repair of air distribution system leaks in six Florida homes.

Garage AH houses used 32% less cooling energy than attic AH houses. This observation is even more significant when it is considered that garage AH houses are 20% larger than attic AH houses. Thermostat settings were essentially equal in the two groups of houses, 78.9ºF for the garage AH houses and 79.0ºF for the attic-AH houses. After adjusting for house size, homes with AH in the attic used 75% more cooling energy than homes with AH in the garage. While the sample sizes are too small to say that the findings are statistically conclusive, this data does suggest that attic AH houses are substantially more inefficient. The cause may be greater conductive and infiltration heat gains, since more of the air distribution system is located in the hot attic. Further study on a larger sample should be useful in verifying these findings, and determining the cause.

It can also be noted that all categories experienced about 65% duct repair based on blower door tests, expect package units, which had only 50% repair. In spite of this, package systems experienced greater than average energy use reduction. A possible explanation for this anomaly may be found in the fact that the leaks for these package systems were closer to the air handler fan and therefore were under greater pressure differential. Because of the greater delta-pressure, the amount of leakage would be greater.

5. DUCT LEAK IMPACTS UPON PEAK ELECTRICAL DEMAND

The impact of duct leakage upon peak electrical demand is greater than upon total energy use. The reason for this is that two factors are at a maximum during the utilities peak demand period – the air handler operation time and the temperature of the air brought into the house. While an air conditioner may operate 30% to 40% over an average day, during the hottest hours of the hottest day, the AH may be run 80% or more of the time. In addition, the outdoor temperature and especially the attic temperature are at their greatest extreme from the house interior temperature.

Figure 12 shows the impact of return duct leaks from the attic upon AC energy efficiency ratio (EER). Since the utility's summer peak occurs at about 5 P.M., when the attic is likely to be 120ºF and have a dewpoint temperature of about 85ºF, a 14% return leak can reduce the effective capacity and EER of the system by 45%. A 30% return leak can completely overwhelm the capacity of the system, causing the temperature in the house to rise. The total increased electrical demand in many homes is limited by the capacity of the air conditioner. If air conditioner capacity were unlimited, the peak demand impact of duct leaks on the summer peak would be much larger.

Duct leak impacts on demand are illustrated in Figure 13. Measured infiltration and air conditioner performance are shown before and after repair of a 30% return leak. The infiltration rate with the air handler operating decreased nearly 75% from 1.15 ach to 0.30 ach as a result of the repairs. Temperature drop from return (measured in the room at the register) to supply increased from 7ºF to 16ºF, indicating a 130% increase in net, sensible cooling capacity. Put another way, air conditioner capacity and efficiency were reduced by about 55% as a result of drawing 104ºF attic air into the return air stream. It is interesting to note that the room temperature was 87ºF before repair, even though the air conditioner was insufficient to maintain the setpoint. Afterwards, the house could be easily cooled with the air conditioner cycling normally.

Figure 12. Degradation in air conditioner efficiency (Energy Efficiency Ratio) when various sized return leaks draw hot air from the attic, assuming the room is 78°F and attic air is 120°F.

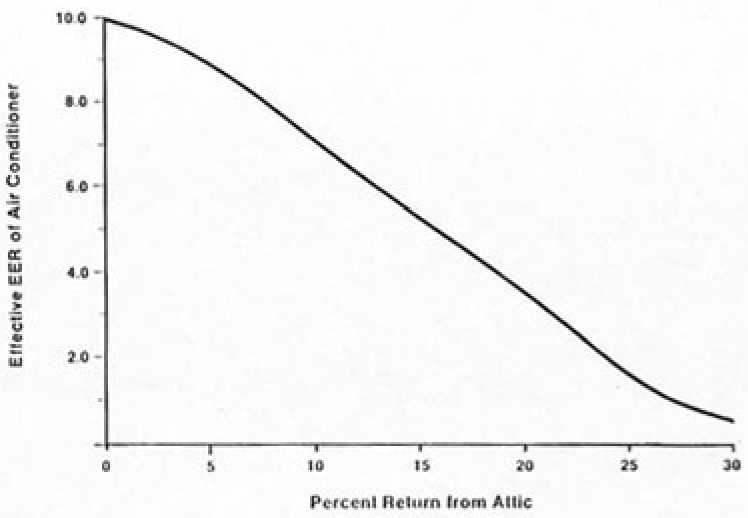
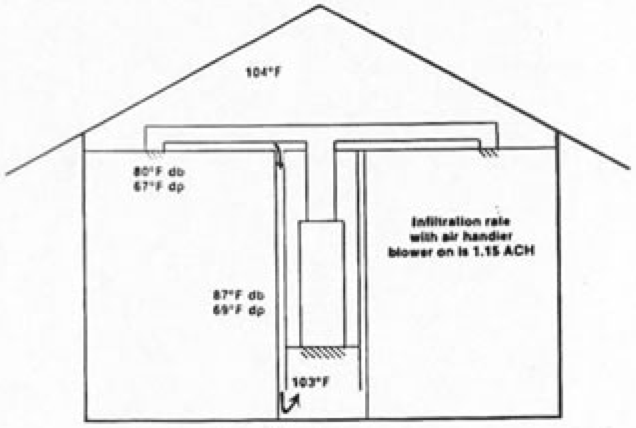
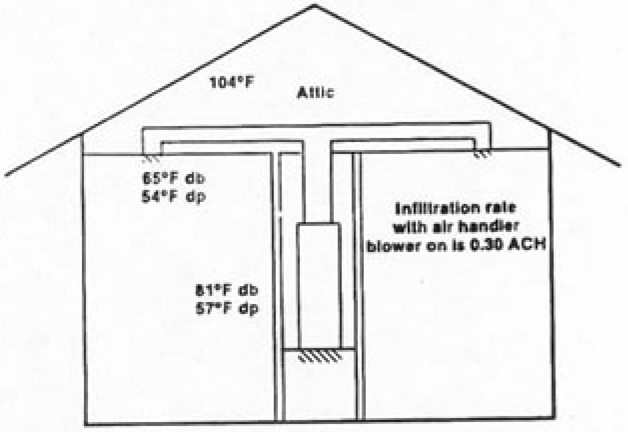


Figure 13. Impact of a 30% return leak from the attic upon the house infiltration rate and air conditioner performance. Air distribution system leaks increase infiltration by a factor of four and reduce sensible cooling capacity by 56%.



Before



After

Duct leak impacts upon winter peak electrical demand are much greater than summer peak electric demand. The reason for this is that a large proportion of heating is done by electric resistance heat strips. In addition, the heating capacity of heat pumps is generally exceeded on the coldest winter mornings, so added load created by duct leaks are met by electric resistance backup.

5.1 Theoretical Analysis of Peak Demand Impacts for Typical House

Theoretical analysis of duct leak impacts upon peak electrical demand in a typical house on a winter morning is presented in Table 7. The purpose of this analysis is to obtain a “ballpark” estimate of the magnitude of duct leak impacts on peak demand. The assumptions of the analysis are:

- A natural infiltration rate of 0.35 ach. This is higher than the 0.28 ach measured in our sample houses because we assume that wind and stack affects are greater on this winter morning.
- An indoor temperature of 72ºF and an outdoor temperature of 30ºF.
- Fifty CFM duct leakage interacts with natural infiltration to produce 80 CFM of infiltration. 100 CFM duct leakage is assumed to create pressures which overwhelm natural forces so that natural infiltration is near zero and combined infiltration (natural + mechanical) is equal to 100 CFM.
- The floor area of the typical house is 1500 ft². Construction is concrete slab, R-19 attic, R-4 block walls, and 120 ft² of single pane windows.
- House heating load is 25,000 Btu/hr after internal generation of 1500 Btu/hr is subtracted, and assuming no duct leaks.

- The house has a 2.5 ton heat pump (sized for cooling load) with a COP of 2.47 and heat output of 23,000 Btu/hr at 30ºF.

Table 7. Increased heating load (Btu/hr) and kW demand from a heat pump with electric strip heat backup as a result of return and supply duct leaks on a Florida winter morning.

Duct Leak CFM	House ACH	Infil Load 1	Duct Leak Added Load	Total Load	Heat Strip Load	Heat Strip kW	Total kW	Act ² COP	Eff ³ COP
Return Leaks									
0	.35	3136	-	25000	2000	.59	3.31	2.21	2.21
50	.40	3584	448	25448	2448	.71	3.43	2.17	2.14
100	.50	4480	1344	26344	3344	.98	3.70	2.09	1.98
150	.75	6720	3584	28584	5584	1.64	4.36	1.92	1.68
200	1.00	8960	5824	30824	7824	2.29	5.01	1.80	1.46
250	1.25	11200	8064	33064	10064	2.95	5.67	1.71	1.29
300	1.50	13440	10304	35304	12304	3.61	6.33	1.63	1.16
Supply Leaks									
0	.35	3136	-	25000	2000	.59	3.31	2.21	2.21
50	.40	4915	1779	26779	3779	1.11	3.83	2.05	1.91
100	.50	7385	4249	29249	6249	1.83	4.55	1.88	1.61
150	.75	11552	8416	33416	10416	3.05	5.77	1.71	1.27
200	1.00	16520	13384	38384	15384	4.51	7.23	1.56	1.01
250	1.25	22154	19018	44018	21018	6.16	8.88	1.45	0.82
300	1.50	28294	25158	50158	27158	7.96	10.68	1.38	0.69

1 Calculation of house heat lead resulting from return leak infiltration assumes that the house temperature is 72ºF and the outdoor temperature is 30ºF. Calculation of house head load from supply leak infiltration assumes that the average temperature rise across the coil varies from 24ºF to 47ºF, depending upon the amount of strip heat required, so the air lost to the outdoors is considerably warmer than house air. The heat pump has a heating capacity of 23,000 Btu/hr at 30ºF outdoor temperature, a 2.72 kW demand, and a 1000 CFM blower.

² Actual heat pump COP is based on the total load, including the load caused by the duct leaks.

³ Effective heat pump COP is based on the original house heating load (25,000 Btu/hr), not including the load caused by the leaks.

Because the heating load of the building is greater than the capacity of the heat pump, the AH will run constantly and the electric resistance strip heat will cycle on and off to meet the load. Table 7 shows the infiltration heating load, the kW demand, and the effective COP of the heating system caused by the return and supply duct leaks. A 30% return leak causes a 90% increase in electrical demand. A 30% supply leak causes more than 200% increase in electrical demand. This same supply leak reduces the effective COP of the heat pump by 69%, from 2.21 to 0.69. The infiltration heating load caused by supply leaks is greater than for return leaks because the air lost from the house is hotter. It should be pointed out that the greater the duct leaks, the hotter the supply air will be, since the duct leaks cause the strips to cycle a greater proportion of the time.

This analysis underestimates impacts in some ways and overestimates impacts in other ways. Underestimation occurs because the state-wide average outdoor temperature on this peak winter day should be about 20ºF instead of 30ºF. A recent example of a recent cold period was Christmas 1989, when it was 30ºF in Miami, 20ºF in central Florida, and 10ºF in north Florida. Consequently, the peak demand would be about 25% greater than indicated in this analysis if 20ºF was assumed.

Additionally, evaporative cooling from moisture in furnishings is not considered. Evaporative cooling is an important variable in determination of heating loads, but is not easily quantified. This cooling occurs in the following typical scenario. Houses are being ventilated during typical winter weather of 65ºF at night and 80ºF during the day, with fairly high humidity. (Even if the house is not being ventilated, the humidity level in the house will be high, unless the occupants have been air conditioning.) Household furnishing and building materials have adsorbed and stored a good deal of moisture. When the cold front arrives, the house is closed up, trapping the moisture inside. As lower dewpoint air infiltrates the home, moisture is desorbed from the furnishings causing evaporative cooling, which may add on the order of 1500 Btu/hr to the total heating load.

Overestimation of heating load occurs because some of the air drawn from buffer zones, such as attic, garages, and crawl spaces, is not as cold as outdoors. Interactions of supply and return leaks in the same zone, also previously preferred to as “short-circuiting”, are not considered as well. This analysis also assumes that all of the duct leaks have been repaired, when in actual fact 70% to 80% is a realistic expectation. On balance, factors which underestimate may cancel, so the conclusions should be “in the ball-park”.

5.2 Project State-wide Demand Reduction

Table 8 presents an analysis of the potential reduction in winter peak electrical demand and the associated construction costs for new generation capacity in the whole state of Florida. The following assumptions apply to this analysis:

- The distribution of duct leaks in the approximately 3 million electrically heated Florida homes (which also have duct systems) is the same as we have found in our sample of 160 homes. The supply leak estimates are based upon visual inspections in these and over 400 additional homes.
- The kW demand reduction for each duct leak size is derived from Table 7.
- The cost of duct repair is based on the few schedule of $40/man-hour.
- The cost of new electrical generation capacity is $700/kW. In actual practice, new capacity can vary in the range of $250/kW to $2000/kW for combustion generation facilities.
- In determination of the combined reduction in demand from return and supply repairs, the total reduction is less than the sum of the two. This is because return leaks do not create added load when supply leaks are larger than the return leaks. The reason for this is that supply leaks depressurize the house and this depressurization then draws in outdoor air to make up for that “pumped” out of the house by the supply leak. As an example, if we have a 1500 ft^2 house with a large supply leak of 200 CFM, and no return leak, the infiltration rate will be about 1.0 ach. If the return of 100 CFM develops, the house infiltration rate will continue to be about 1.0 ach. Because the mix and interaction of return and supply leaks is difficult to assess, the total demand reduction at the bottom of Table 8 is an estimate based on only half of the return leak repairs producing demand reduction.

Table 8. Potential reduction in statewide winter peak electrical demand resulting from repairing duct leaks in three million electrically heated homes in Florida.

duct leak%	**housing units (x1000)**	**repair Cost (x10 6)**	**demand reduction kW/house**	**demand reduction mW**	**capacity value (x10 6)**
Return Leaks					
2	1100	$55.5	0.05	55	$38.5
7	805	$60.4	0.26	209	$146.3
14	585	$58.5	0.92	538	$376.6
25	510	$76.5	2.36	1204	$842.8
Total	3000	$250.4	0.67	2006	$1404.2
Supply Leaks					
3	450	$36.0	0.31	140	$98.0
7	1800	$180.0	0.91	1638	$1146.6
14	600	$90.0	2.22	1332	$932.4
25	150	$34.5	5.57	836	$585.2
Total	3000	$340.5	1.32	3946	$2762.2
Return and Supply Leaks Combined					
Total	3000	$590.9	1.65	4949	$3464.3

1 The proportion of duct leaks in Florida’s 3,000,000 electrically heated homes is extrapolated from test results on 100 homes.[2] This assumes that only ½ of the calculated demand reduction due to return duct leaks is counted. This assumption is made because repair of return duct leaks does not reduce the heating load when supply leaks are larger than the return leaks.

The result of this analysis shows that repair of duct leaks can dramatically reduce Florida’s winter electrical peak demand (most of Florida’s utilities are winter peaking, though much of their demand management programs focus largely on the summer peak). At a typically cost of $200, duct repairs produce a 1.6 kW peak demand reduction per house, which has a new-plant construction value of about $1100.

Total peak demand reduction from repairing ducts in 3 million homes in Florida is estimated at 5000 megawatts, or about 13% of the state’s nameplate generation capacity. These duct repairs are a very cost-effective means of “building” new generating capacity. The cost f duct repair is estimated at $600 million and the avoided cost of new capacity is about $3.5 billion. So repairing duct can produce generating capacity at about one-sixth the cost of new construction. This “new” capacity produced by duct repairs has another advantage to the consumer – the electricity provided from duct repairs cost the consumer nothing.

6. IMPORTANCE OF DUCT REPAIR TRAINNG

It is important to emphasize the necessity of training for those involved in the diagnosis and repair of duct leaks. There are several reasons why this training is essential. First, it is difficult to identify air leak sites in the air distribution system without instruction and necessary tools. If diagnosticians do not have the skills and equipment to find a wide variety of leak sites, then the repairs will yield substantially less energy savings than the potential. This could contribute to failure of duct repair programs, and loss of a great opportunity for saving energy resources, generation capacity, and our environment.

Second, and most important, repair of duct leaks has associated health and safety risks for home occupants. Return leaks draw in air from garages, crawl spaces, and attics which often contain products which are hazardous to our health. These products include radon, herbicides, pesticides, gasoline and oil products, chemicals, other products stored in garages, and fiberglass particles and pesticide powders from the attic. It is important to be able to identify return leak sites and know how to repair them completely.

In cases where there is combustion equipment in the room (garage, utility room, etc.) where the return leak is located, combustion and fire hazard exist. Depressurization of these rooms can cause back-drafting of flue gases into the house, and in some cases flame roll-out from gas water heaters. Research has identified that back drafting of water heaters and furnaces can begin with pressures as low as –3 Pascals. Flame roll-out from combustion water heaters can begin at 12.5 Pascals (Kao, Ward, and Kelly, 1988).

Depressurization of as much as –37 Pa has been measured in Florida homes as a result of exhaust fan and clothes dryer operation. Depressurization of as much as –12 Pa in a garage and –6 Pa in a utility room has been observed a result of return leaks (Cummings, Tooley, and Moyer, 1990). The potential for carbon monoxide poisoning from backdrafting and fire from flame roll-out is great. If the repairs are not made successfully and completely, then “the last man out” may be held responsible.

An even more disturbing scenario exists. We may make changes to the house which actually create health hazards. One example, where the initial condition is not dangerous, is a garage which has large supply and return leaks. The garage is experiencing neutral pressure, because depressurization cased by the return leak is offset by the pressurization created by the supply leak. However, if the repair person incorrectly diagnosis the duct leak problem, or for some other reason repairs only the supply leak while ignoring the return leak, then the garage will become depressurized when the air handler operates. If there is a gas water heater in the garage, backdrafting of flue gases (which may then drawn into the return leak) or even flame roll-out may occur, creating serious danger.

Another example of duct repair impacts is the following. Let’s say that when the interior doors in the house are closed, the main portion of the house is depressurizes to –3 Pa. This is a commonly observed pressure. In this family, all the interior doors are closed during the night. This house has a fireplace and a gas water heater within the house. A potential problem exists because this –3 Pa depressurization can pull glue gases down the water heater flue and smoke down the fireplace chimney under low draft conditions, such as during start-up and burn-down. However, previous to the duct repairs there has never been a problem because the ADS has had a large return leak which produces +4 Pa pressure, causing the main body of the house to be +1 Pa when the doors are closed. The next time a fire is built in the fireplace, the repair agency may get a call from the customer that his house is full of smoke. He wants to know what you did to his house.

A number of other scenarios exist which could cause inconvenience or danger to occupants and therefore require careful analysis. Each of them points to the need for repair and diagnostic personnel to go through a comprehensive training program which familiarizes them with how house systems interact, and which interactions may create problems.

In summary, it is essential that those responsible for diagnosing and repairing duct leaks understand how to identify the leaks accurately and efficiently. It is even more important that they understand house pressures, know how to measure them, and understand that the house is a system and that duct repairs may impact the operation of other house systems.

7. CONCLUSIONS

Forced air distribution systems in Florida are leaky. Blower door tests found that on the average nearly 13% of the leak area of the house is in the duct system. These leaks cause the average infiltration rate of the sample of 160 homes to increase more than threefold when the air handler is turned on.

Return leaks occur in the following locations in order of magnitude: return plenums, wall penetrations at registers, air handler cabinets, return duct connections, and chase lines. Supply leaks are found in the following locations in order of magnitude: the junction of the supply plenum to the air handler, supply duct connections, supply box to register connections, and air handler cabinet leaks. Supply leaks are dominant in mobile homes. The largest leak sites are in the connection of the short supply arms to the main trunk, and where the supply arms attach to the floor.

These duct leaks create enormous energy waste. On the average, cooling energy use decreased by 17.2% in the 46 homes which were repaired. If we assume that repairs actually stopped about 70% of the duct leaks, then it can be projected that duct leaks increase total cooling and heating energy use in Florida residences, by about 33%.

Energy use reduction was fairly equally distributed across the four groups of houses – four air handler locations and mobile homes – ranging from 15% for attic AH homes to 19% for garage AH homes. Mobile homes were close to average for energy savings and fraction of house leak area in the air distribution system, however they had significantly higher mechanical and natural infiltration rates.

Repair of air distribution system leaks is a very cost-effective retrofit. Based on our measured savings, cooling season energy savings in an average Florida home from duct repair would be about $85. Heating season savings might be $25. At an average cost of $200 per home, duct repairs have a simple payback of less than two years, and a rate of return on investment of greater than 30%. Since the typical cost of duct repair for mobile homes is about 40% less than for site-built homes, or $120, repair of ADS in mobile homes represents an outstanding opportunity for cost-effectively reducing energy use and peak electrical demand.

Duct leak impacts upon peak electrical demand are even more dramatic than for energy use. The reasons for this are 1) the air handler is operating at its maximum (and thus, AH induced infiltration is at a maximum) during peak demand periods and 2) the air brought into the house is at its greatest temperature extreme during the utility’s peak demand period. Based on theoretical calculations, a 15% return leak from the attic can increase air conditioning electrical demand by about 90%, and reduce the effective capacity and efficiency of the air conditioner by 45%.

Winter peak demand impacts from ADS leaks are greater than summer peak demand impacts. There are two reasons for this. First, when heat pumps run out of capacity, electric resistance backup kicks in to meet the added load caused by duct leakage. By contrast, air conditioners do not have “strip cooling” backup, so demand is limited to the compressor capacity. Second, most of the added heating load created by duct leaks is met by electric resistance which has a COP of 1.0, compared to air conditioner COP of greater than 2.0. So each increment of heating load adds at least twice as much to the utility’s demand as cooling load.

Repairing duct systems is an excellent means to provide “new” capacity to the electrical generation system. Calculations indicate that a typical $200 duct repair should reduce the winter peak by about 1.6 kW, which has an avoided capacity construction cost of about $1100. Repair of duct leaks statewide could yield 5000 megawatts of freed-up generation capacity at approximately one-sixth the cost of building new power plants.

Since the peak demand impacts are largely based on theory, it is essential that research be done on a large sample of homes to assess both winter and summer peak. This could be done by recording time-of-day space conditioning demand over a one- or two-year period, with duct repair at the midpoint of the monitoring period. This data will be helpful in assessing the impact of ADS repair programs on utility energy sales and generation needs.

Some recommendations follow from these findings. Utilities should consider beginning duct repair programs. Training programs should be developed to train appropriate trades people in duct leak diagnostics, duct leak repair, and methods of constructing airtight air distribution systems. Building/energy codes need to be revised and strengthened to ensure that new homes will have airtight duct systems which last the life of the building.

It is important to emphasize the necessity for training those involved in the diagnosis and repair of duct leaks. There are several reasons why this training is essential. First, it is difficult to identify air leak sites in the air distribution system without instruction and necessary tools. If diagnosticians do not have the skills and equipment to find the large leak sites, then repair will yield substantially less energy savings than is possible. This could contribute to failure of duct repair programs.

Second, and most important, repair of ADS leaks has associated health and safety risks for the home occupants. Return leaks drawing in air from garages, crawl spaces, and attics may contain products which are hazardous to health, such as radon, various air pollution products stored in garages, and fiberglass particles from attic insulation. It is important to be able to identify return leak sites and know how to repair them completely. In cases where combustion equipment is located in the room where the return leak is located (garage, utility room, etc.), combustion and fire hazard exist. Depressurization of these rooms can cause back-drafting of flue gases into the house, and in some cases flame roll-out from gas water heaters. The potential for carbon monoxide poisoning and fire is great.

All of these points emphasize the need for education and training of those groups responsible for ensuring airtight and durable ducts in new construction and the repair of ducts in existing homes.

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APPENDIX

Following are infiltration test results for 160 central Florida homes. Infiltration rates were determined by tracer gas testing. This testing technique measures the decay rate of a tracer gas (sulfur hexafluoride) to determine the house infiltration rate. House airtightness was determined for 99 of these homes using a blower door.

Infiltration was measured twice. One test was with the air handler turned off (ach off). This can be thought of as the "natural" infiltration rate of the house. The second test was done with the air conditioner air handler operating continuously (ach on). Elevated infiltration with air handler operation indicates that duct leakage is creating significant infiltration. The return leak fraction (RLF) is determined during this test, by measuring the decay in tracer gas concentration from return to supply. RLF is the fraction of air returning to the air handler when originates from outside the conditioned space.

House airtightness was measured by blower door. The house was depressurized and the amount of air leaking into the house was measured (it is equal to the flow rate through the blower door). House airtightness is expressed as ACH50, which is the air changes per hour at 50 pascals depressurization.

The blower door test was repeated with all supply and return registers covered by paper and tape, thus, eliminating the leak area located in the air distribution systems. The "percent in the ducts" is determined by subtraction of these two blower door tests.

The data are separate into three groups of approximately 50 houses each. The first 50 are houses that were repaired. Test results for "after repair" are presented in Tables 3, 4, and 5 of the report. Energy use reduction from duct repair is also presented in these three tables.

The second 49 houses had racer gas and blower door tests, but were not repaired. The final 61 houses had tracer gas tests but no blower door test. Averages for each group, and running averages are presented.

Housing description data are presented. Construction type is block (B), frame (F), or mobile home (M). County is Brevard (B), Polk (P), and Orange (O). Air handler location (AHloc) is attic (A), closet (C), which also includes utility rooms, garage (G), package (P), and mobile home (M). All mobile homes are package units, but are listed as (M).

Infiltration rates and house airtightness in 50 homes which were repaired (data for before repair).

House	Age	Const	Co.	AHloc	area ft²	ach off	ach on	RLF	ACH50	% in duct
1-CRO	21	B	B	C	2977	0.39	0.99	14.5	10.6	5.9
2-KET	1	B	B	G	1986	0.33	0.95	22.4	5.3	15.4
3-KAL	3	B	B	C	1700	0.15	0.96	7.0	6.8	5.3
4-MER	8	B	O	C	2200	0.19	0.88	26.1	13.9	35.8
5-RAI	4	B	P	G	1400	0.49	1.36	21.6	10.1	10.0
6-STA	6	B	B	G	1934	0.10	0.99	15.4	8.4	17.8
7-SWA	9	B	B	G	1277	0.10	0.97	6.6	11.7	26.9
8-VIE	22	B	B	G	1521	0.10	1.33	15.4	11.4	16.0
9-BRI	40	B	P	A	1812	NA	2.12	0.0	35.6	8.7
10-CAR	17	B	P	C	1175	0.49	0.72	8.8	19.4	10.1
11-CUS	13	B	P	A	1700	NA	0.88	10.0	9.3	4.6
12-GAG	25	B	P	C	2172	0.46	1.45	29.1	22.1	9.9
13-GRU	25	B	P	G	2000	0.10	0.98	10.3	13.1	12.8
14-GUD	17	B	P	P	1672	0.32	0.77	10.9	6.4	23.5
15-HUG	20	B	P	C	1650	0.30	1.29	16.8	10.3	12.4
16-HUT	28	B	P	P	1327	NA	1.15	22.5	6.6	38.9
17-JON	15	B	P	P	2100	0.18	1.45	15.2	7.8	33.3
18-LAM	20	B	P	C	1175	0.07	1.26	36.1	10.4	8.6
19-LAU	16	B	P	P	2050	0.16	1.21	45.5	8.8	10.2
20-PEN	15	B	P	A	1723	0.14	0.74	5.8	7.8	30.4
21-PET	11	B	P	C	1035	0.38	0.76	4.0	10.0	15.0
22-PET	3	B	B	G	1400	0.10	1.07	19.5	7.2	NA
23-RID	41	F	P	A	1275	0.16	0.89	7.2	25.0	6.5
24-SUT	20	B	P	P	1341	0.44	1.20	23.0	8.1	18.8
25-WES	38	B	P	G	1148	0.24	1.16	0.7	16.3	6.0
26-AUG	6	M	P	M	840	0.22	1.15	9.6	17.2	8.0
27-BLA	19	M	P	M	1392	0.15	0.87	11.2	11.5	17.3
28-BOR	16	B	P	P	1879	0.11	1.01	10.4	9.8	10.9
29-BOY	15	M	P	M	1382	0.19	0.73	13.9	11.8	11.4
30-CAR	17	B	P	A	2262	0.01	0.94	30.6	12.0	12.5
31-DEN	23	B	P	P	1600	0.00	0.72	2.9	9.0	12.6
32-CRI	1	F	B	G	1890	0.12	0.92	27.1	4.6	21.8
33-HAN	13	M	P	M	1350	0.17	0.72	3.4	6.8	9.5
34-HEF	17	M	P	M	1296	0.46	0.91	3.6	16.8	16.4
35-HER	5	M	P	M	784	0.37	0.91	16.1	15.1	8.5
36-HUG	28	B	P	A	1659	0.27	0.73	12.9	14.5	13.6
37-KIN	12	F	P	A	1624	0.13	1.48	57.6	14.2	49.8
38-LAV	20	F	P	P	936	0.36	1.25	35.0	13.5	22.4
39-MAX	35	B	B	C	1100	0.40	0.91	23.0	NA	NA
40-PAR	38	B	B	G	1420	0.58	0.86	9.7	9.3	18.2
41-PAR	17	B	P	C	2000	0.10	0.35	4.0	13.1	7.0
42-SCI	23	B	P	P	1400	0.18	1.00	20.4	12.3	12.2
43-SCH	17	M	P	M	720	0.79	2.14	16.8	17.1	14.7
44-SHA	17	M	P	M	1125	0.29	4.26	62.0	18.0	22.8

45-SME	20	B	P	P	1296	0.42	0.94	17.8	14.6	14.5
46-SWA	15	M	P	M	1440	0.87	1.43	3.6	22.3	14.0
47-THA	12	M	P	M	1368	0.72	2.35	1.3	12.2	25.5
48-TUR	4	B	P	C	1656	0.40	0.83	27.7	11.4	17.1
49-WUE	23	B	P	A	1682	0.35	NA	NA	8.3	27.3
50-TRA	16	B	P	G	2499	0.18	1.11	20.5	NA	NA
AVG.	17				1567	0.29	1.14	16.9	12.5	16.4

AH – A: attic, C: closet, G: garage, P: package, M: mobile
Co(unty) – B: Brevard, P: Polk, O: Orange
Const(ruction) – B: block, F: frame, M: mobile home
RLF – return leaks fraction (%)

Infiltration rates and house air tightness in 49 homes which were not repaired.

House	**Age**	**Const**	**Co.**	**AHloc**	**area ft²**	**ach off**	**ach on**	**RLF**	**ACH50**	**% in duct**
1-HOB	17	B	P	P	2040	0.28	0.62	7.1	7.6	18.4
2-BAT	15	B	P	A	1800	0.38	0.70	8.2	7.8	10.3
3-BLU	21	B	B	G	2150	0.39	0.80	21.0	8.3	14.1
4-BRY	39	F	P	G	1229	0.23	1.27	7.3	17.1	3.0
5-BUR	18	B	P	G	2100	0.18	0.58	1.5	10.1	7.2
6-CAB	2	F	P	G	2800	0.24	0.78	0.4	4.0	3.9
7-CHA	10	B	B	G	2000	0.81	0.98	9.9	10.0	10.9
8-JON	15	B	P	A	2400	0.10	0.96	50.0	9.9	32.9
9-DEC	3	B	B	C	2220	0.14	0.87	10.3	8.2	2.5
10-DUN	60	F	P	A	1250	0.55	0.84	1.2	18.8	1.1
11-FLO	37	B	P	A	1863	0.03	0.73	10.6	13.5	5.0
12-HAR	27	B	P	P	1400	0.26	0.56	6.6	17.0	3.5
13-HEN	26	B	B	C	1500	0.36	0.93	2.4	11.6	5.8
14-HUG	11	B	B	G	1500	0.32	0.85	7.3	7.5	17.8
15-HUT	28	B	P	A	1674	0.43	0.99	17.2	15.0	9.1
16-LAB	19	F	P	A	1000	0.30	0.40	10.3	26.5	5.3
17-MAR	6	B	B	G	1200	0.32	0.73	10.2	6.9	16.7
18-MAT	31	B	P	A	1543	0.28	1.68	12.0	20.5	12.5
19-MAY	24	B	C	C	1590	0.41	0.58	5.1	9.8	29.9
20-MOR	25	B	B	C	2800	0.14	1.56	6.2	NA	19.0
21-MOS	25	B	P	C	3500	0.54	0.82	7.1	8.1	1.7
22-McK	22	B	P	P	1619	0.18	1.29	25.9	9.3	20.2
23-PER	52	B	P	A	1800	0.18	0.71	4.5	12.9	16.9
24-RIC	17	B	B	G	1754	0.35	0.52	7.8	5.3	20.3
25-ROB	24	B	P	P	1104	1.80	2.84	15.5	10.6	11.1
26-ARM	20	B	B	C	1200	0.22	1.15	9.6	17.2	1.0
27-SKA	25	B	P	C	1245	0.15	0.87	11.2	11.5	4.4
28-SUR	18	B	P	A	1705	0.11	1.01	10.4	9.8	11.1
29-TRO	63	F	P	C	3000	0.19	0.73	13.9	11.8	15.1
30-UND	30	B	P	A	1188	0.01	0.94	30.6	12.0	4.0
31-WEA	45	F	P	P	1417	0.35	1.96	11.5	31.9	8.1
32-WIL	30	B	P	A	1640	0.30	1.15	7.8	12.9	4.1
33-WIT	12	B	P	A	2570	0.35	0.69	12.5	12.0	14.9
34-YAR	21	B	B	G	2250	0.57	0.62	4.4	9.1	22.4
35-GIB	15	M	P	M	1248	0.27	0.84	4.8	9.1	10.6
36-HER	16	M	P	P	1488	0.31	0.71	4.8	12.8	9.0
37-KIB	11	M	P	P	1200	0.28	0.83	16.5	12.2	23.3
38-KIC	12	M	P	P	1440	0.00	1.47	23.8	8.5	17.6

39-LIG	14	M	B	P	1152	0.41	0.73	0.0	14.3	3.5
40-McF	12	M	P	P	1296	0.25	0.51	7.4	7.1	2.9
41-PAN	11	M	P	P	1344	0.21	0.62	5.1	9.2	6.5
42-PRI	17	M	P	P	1344	1.20	1.50	5.4	11.5	14.7
43-PRU	14	M	P	P	876	0.25	1.00	5.4	8.01	5.47
44-STE	15	M	P	P	1728	0.45	0.36	2.5	NA	5.2
45-TAG	17	M	P	P	1030	0.01	0.80	6.0	17.8	6.5
46-TOD	6	M	P	P	1460	0.12	0.35	3.9	5.6	5.0
47-FEI	NA	B	B	G	NA	0.16	0.36	8.7	NA	11.5
48-GIB	NA	B	P	P	NA	0.17	0.89	6.7	20.3	14.6
49-REN	54	F	P	P	840	1.01	2.48	9.2	31.8	5.9
AVG 49	22				1670	0.35	0.92	8.9	12.8	10.8
AVG 99	20				1616	0.32	1.03	13.0	12.6	12.7

Infiltration rates in 61 homes.

House	**Age**	**Const**	**Co.**	**AHloc**	**area ft²**	**ach off**	**ach on**	**RLF**
1-ALK	1	B	B	G	1400	0.05	0.51	4.9
2-ALL	16	F	P	P	1680	0.00	2.30	21.9
3-BAK	20	B	P	P	1431	0.26	0.92	5.0
4-BAN	70	F	P	C	2000	0.35	0.88	6.2
5-BOW	22	B	P	G	1750	0.33	0.88	7.9
6-CAL	15	F	P	A	2000	0.15	0.33	2.7
7-CAR	17	B	P	A	2262	0.36	0.90	25.5
8-CAS	30	B	B	C	1570	0.37	0.77	9.3
9-CLE	14	B	P	A	1729	0.14	0.69	8.1
10-COL	20	B	P	P	1100	0.35	2.08	37.1
11-CUM	26	B	B	P	1760	0.18	0.84	8.8
12-DAV	15	B	P	A	1575	0.31	0.81	3.8
13-FRA	15	F	P	A	3200	0.22	0.38	0.0
14-FRA	15	B	P	A	2000	0.23	0.67	6.7
15-FRE	6	F	B	G	1750	0.06	0.88	9.6
16-JON	24	B	P	A	1080	0.20	0.40	0.0
17-HOL	13	B	P	A	2080	0.13	0.61	14.4
18-HOU	15	B	P	A	1762	0.14	0.41	5.0
19-ING	11	B	P	G	1800	0.06	0.29	3.0
20-JUC	30	F	P	C	2000	0.61	0.90	0.0
21-KAT	30	B	P	A	1600	NA	NA	0.9
22-KIT	30	B	P	C	1505	0.14	1.16	0.0
23-LAM	35	B	P	A	1228	0.03	0.26	0.0
24-LON	5	B	P	P	1564	0.27	0.74	13.2
25-MAT	35	B	P	P	2000	0.25	0.44	5.3
26-MER	8	B	B	A	1700	0.48	1.04	15.1
27-MIT	17	B	P	A	1900	0.17	0.91	8.1
28-NOR	7	B	P	C	1136	0.08	0.51	5.9
29-OHA	1	B	B	G	1680	0.48	0.55	5.7
30-OPA	10	B	P	A	2200	0.16	1.16	0.0
31-PAL	30	B	P	C	1202	0.25	0.35	0.2
32-PAR	15	B	P	C	2200	0.14	0.44	2.9
33-PEA	16	B	P	C	2029	0.21	0.36	0.0
34-PID	25	B	P	C	2200	0.46	0.62	8.6
35-PLU	10	B	P	G	1384	0.02	0.41	6.5
36-REI	30	B	P	P	4000	0.25	1.11	19.3
37-RIC	9	B	B	G	2500	0.13	0.73	10.4

38-ROL	17	B	B	C	1750	0.35	0.64	0.0
39-ROS	8	F	B	A	1027	0.33	0.48	3.5
40-RUC	23	B	P	A	2800	0.29	0.29	6.3
41-SCA	14	B	P	A	1645	0.05	0.60	5.1
42-SEL	24	B	P	P	1704	0.04	0.20	1.5
43-SMI	1	B	P	A	1500	0.25	0.76	0.0
44-STE	17	B	P	P	1396	0.00	1.05	33.2
45-STE	15	B	P	G	1855	0.00	0.64	7.6
46-TOD	30	B	B	C	1460	0.15	0.47	1.5
47-JON	25	B	P	P	1276	0.18	0.81	15.6
48-WAL	24	B	P	A	1400	0.64	1.43	0.0
49-WAS	33	B	P	G	NA	0.15	0.64	6.4
50-WEN	14	B	P	A	1900	0.14	1.15	3.6
51-WIT	20	B	P	C	1194	0.38	0.68	4.5
52-WOO	12	B	P	A	1540	0.27	0.86	4.3
53-ZVA	12	B	P	A	2055	0.02	0.42	9.4
54-BEC	8	M	P	M	1536	0.18	0.42	4.9
55-BUR	5	M	P	M	853	0.29	0.43	0.0
56-CLA	27	B	P	P	1447	0.52	0.66	8.5
57-DUF	16	M	P	P	1200	0.21	0.32	1.3
58-DYK	13	M	P	P	1152	0.22	0.33	1.4
59-MAC	11	M	P	P	1056	0.14	1.18	12.7
60-MAH	16	M	P	P	1344	0.42	0.81	4.4
61-VOG	12	M	P	P	1440	0.20	0.47	0.0
AVG (61)	18				1708	0.22	0.72	6.9
AVG (160)	19				1653	0.28	0.91	10.7