DUCT LEAKAGE IMPACTS ON AIRTIGHTNESS, INFILTRATION, AND PEAK ELECTRICAL DEMAND IN FLORIDA HOMES

JAMES B. CUMMINGS
Senior Research Analyst
Florida Solar Energy Center
Cape Canaveral, FL 32920

JOHN J. TOOLEY, JR.
President
Natural Florida Retrofit, Inc.
Montverde, FL 34756

NEIL MOYER
Engineer
Natural Florida Retrofit, Inc.
Montverde, FL 34756

ABSTRACT

Testing for duct leakage was done in 155 homes. Tracer gas tests found that infiltration rates were three times greater when the air handler was operating than when it was off. Infiltration averaged 0.85 air changes per hour (ach) with the air handler (AH) operating continuously and 0.29 ach with the AH off. Return leaks were found to average 10.3% of AH total flow. House airtightness, in 90 of these homes, determined by blower door testing, averaged 12.58 air changes per hour at 50 Pascals (ACH50). When the duct registers were sealed, ACH50 decreased to 11.04, indicating that 12.2% of the house leaks were in the duct system.

Duct leaks have a dramatic impact upon peak electrical demand. Based on theoretical analysis, a fifteen percent return leak from the attic can increase cooling electrical demand by 100%. 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.

INTRODUCTION

Duct leakage has been observed in many homes by the authors of this paper and others. The authors have observed significant duct leakage in the majority of the 370 homes they have tested with blower doors (1). They have also reported on duct leakage in about 25 homes, indicating that significant duct leakage has been found (2, 3, 4). The authors have also reported on duct-leak testing in sample of 91 homes, which is a partial report on the project summarized in this paper (5). Other authors across the nation have detected duct leakage, as well. Infiltration rates in 31 Tennessee homes were found to be 77% higher when the air handler was operating (6). Tracer gas measured infiltration rates in 187 new Pacific Northwest homes were found to be 70% higher in those with forced-air systems for a four month winter period compared to those which used baseboard and radiant heating systems, even though blower-door testing indicated they should only be 12% leakier (7). Blower door tests done on 20 homes in the Pacific Northwest found about 10% of the house leak area in the duct system (8).

PROJECT DESCRIPTION

A study was begun in the spring of 1989 to investigate duct leakage in central Florida homes. Testing was done using tracer gas and blower doors. It will be completed in 1990.

Tracer gas testing has been done in a sample of 155 homes in order to detect duct leakage. The housing sample was randomly selected and the only screening criteria was that the house have a forced air 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 garage, 2) AH in an interior closet or utility room, 3) AH in the attic, 4) AH outdoors, and 5) manufactured homes.

Duct leakage was measured 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 the possibility of duct leaks was indicated. If the infiltration rate was much higher (say three to five times higher) because of AH operation, then duct leakage is strongly indicated. Another measure of duct leakage is the return leak fraction (RLF). It is the proportion of air returning to the AH which originates from outside the conditioned space. RLF was determined by measurement of tracer gas dilution from the return (in the room at the return register(s)) to supply registers. Tracer gas concentration was also measured in the attic at the return leak site. It provides a rather precise method for quantifying leaks on the return side of the air distribution system.

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 each of the return registers (typically Florida homes have one or two return registers). Mixing was maintained by the continuous operation of the AH.

In the tests with the air handler turned off (this test immediately precedes the AH on test), 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 minute during each 10-minute period. A change in this test protocol was made after 110 homes were tested because duct leakage during the minute of AH operation caused error in the result. On the last 45 homes, sampling was done at four distributed locations throughout the house, and the AH was not turned on during this test at all. These testing procedures are described in more detail in Cummings (9).

Because of funding limitations, blower door tests were

Proceedings of the Seventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, October 9-10, 1990

done on only 90 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 pressure levels, generally across the range from 10 to 60 Pascal (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.

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.

Tracer Gas Testing

Infiltration tests revealed that duct leaks are large and widespread in central Florida homes. The average infiltration rate of the 155 homes tested was three times higher with the AH operating than when it was off. Figure 1 shows these results. Infiltration averaged 0.85 ach when the AH was on, while only 0.29 ach with it off. More than 50% of the homes have natural infiltration less than 0.25 ach while only 3% have less than 0.25 ach when the air handler is operating.

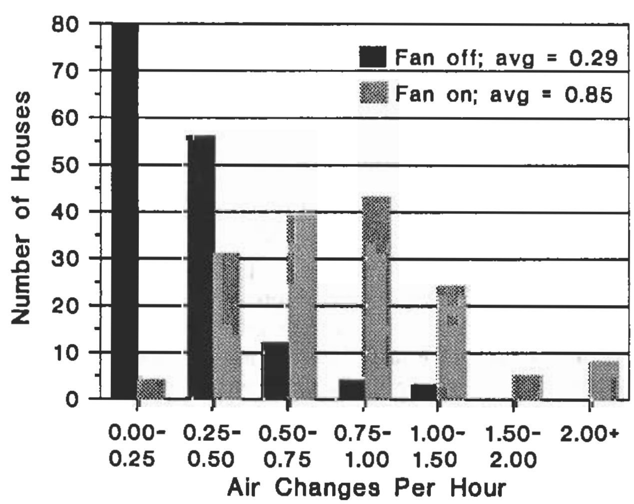

Figure 1. Tracer gas infiltration rates in 155 homes with the air handler off and on.

(These tests were all performed during the hours of 9 A.M. to 6 P.M. and usually in the summer months of April through October. Because daytime winds in Florida are typically stronger than nighttime winds, the measured natural infiltration rates are probably greater than actual annual average rates.)

To some, 0.29 ach natural infiltration may seem lower than expected. The following observations are offered as an explanation for low infiltration. Natural infiltration is driven by pressure differentials caused by wind and thermal stack. Florida winds are less than other parts of the country. Stack effect is small because: 1) temperature differences are less than 15 degrees most hours of the year, 2) homes are typically short (one story), and 3) concrete slabs (>90% of homes) and block walls (>80% of homes) do not offer many inlets for stack infiltration.

The return leak fraction (RLF) was measured in each home with the AH operating (Figure 2). Sixty-six percent were found to have return leaks equal to or greater than 5% of the AH total air flow. Thirty-eight percent have greater than 10% RLF. The average for 155 homes was 10.3% RLF.

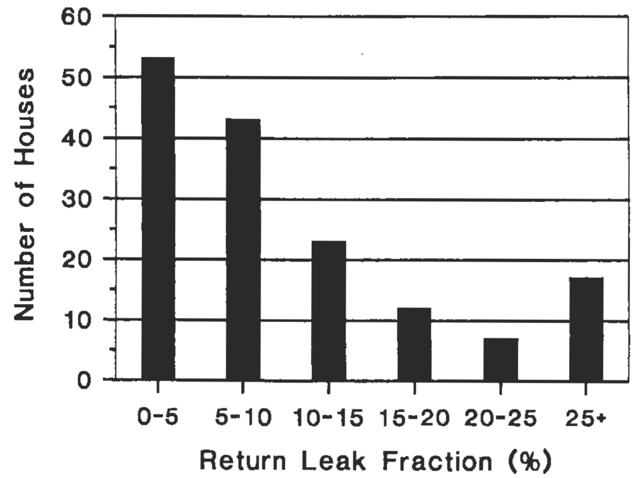

Figure 2. Return leak fraction in 155 homes measured by tracer gas dilultion.

Blower Door Testing

Blower door tests were performed on 90 homes. ACH50, the ventilation rate of the house when depressurized to 50 Pa, averaged 12.58 (Figure 3). When the supply and return registers were sealed by means of paper and tape, ACH50 dropped to 11.04 indicating that holes in the duct system account for 12.2% of the total house air leakage at 50 Pa pressure (Figure 4). Since the duct system is less than 1% of the volume of the house, it is remarkable that it contains such a large proportion of the leak area of the house. This indicates significant problems in air distribution system construction which must be addressed. The significance of leaks in the duct system becomes more important when it is considered that most of the duct system is under an order of magnitude greater pressure differential than the remainder of the house. It is interesting to note that the 12.2% of the house leaks located in the duct system account for 66% of the infiltration when the AH blower is on.

The 90 homes which had blower door tests appear to have slightly greater duct leakage than the larger sample of 155 homes. Infiltration with the AH on is 1.00 in these 90 homes compared to 0.85 for the 155 homes. RLF is 12.3% compared to 10.3%. Infiltration with the AH off is 0.28 compared to 0.29.

Blower door tests indicate that house airtightness is a function of age (Figure 5). 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.

Proceedings of the Seventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, October 9-10, 1990

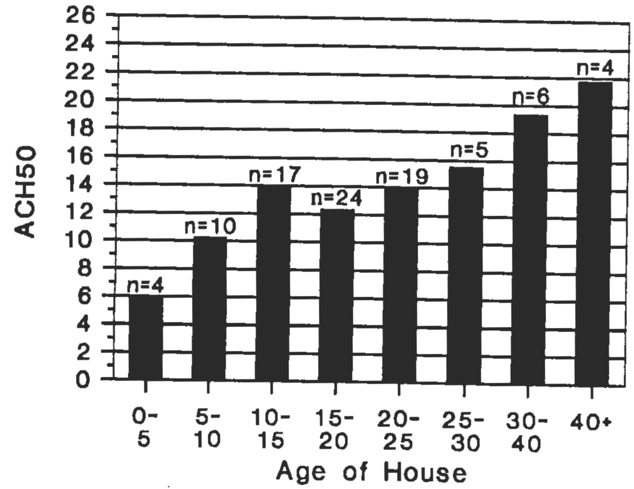

Figure 3. Airtightness of 90 Florida homes determined by blower door. (avg. = 12.58 ACH50)

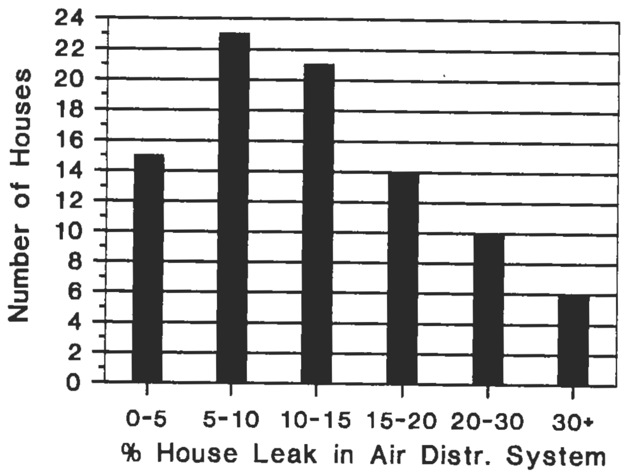

Figure 4. Percentage of house air leakage at 50 Pa which is in the air distribution system. (avg. = 12.2%)

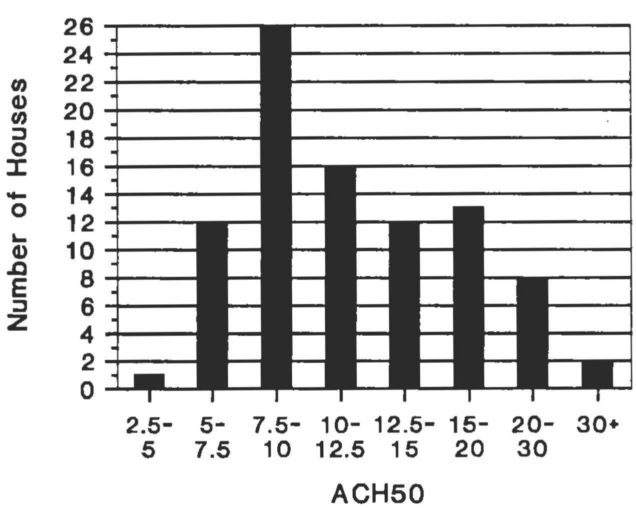

Figure 5. Airtightness of 89 homes with respect to age (n is the sample size).

Smoke Test Inspection

Visual inspection of the 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 the 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, typically with the smoke stick, for leaks.

Return leak air flow is estimated to be about twice as large as supply leakage in the tested homes. Because we estimate that 50% or more of the return leaks are from the attic, the impact upon air-conditioner performance is dramatic.

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 percent 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 they are framed or joined to the walls in the garage, closet, or utility room in which they are located. These walls have framing gaps and often are used as chaseways for plumbing and wiring. These chaseways also act as pathways for air from the attic, garage, or outdoors to be drawn into the return air stream. Dropped ceilings or soffits are also frequently framed into 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 delivery.

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 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, which carry freon and condensate lines from outdoors to the air handler, usually terminate in the return plenum and sometimes are not sealed. Consequently they are pathways for infiltration because they are under substantial depressurization.

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

Proceedings of the Seventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, October 9-10, 1990

1. Supply Plenums: Supply plenums often leak large amounts of air at the connection of the plenum to the air handler 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.

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. Leaks are small to moderate in a majority of homes, and large in a small portion.

3. Flex Duct Connections: Flex duct connections typically leak. The leaks are mostly small to moderate. These leaks typically 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 rips in the plastic linings which develop because of rough treatment. Duct board ducts sometimes leak because the closure system (usually tape) fails, resulting in small, medium, and infrequently very large (>30% of total air flow) leaks.

Duct Leak Impacts Upon Peak Electrical Demand

The impact of duct leakage upon peak electrical demand is large. Figure 6 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 5PM, when the attic is likely to be 120°F and have a dewpoint temperature of about 85°F, a 15% return leak can reduce the effective capacity and EER of the system by 50%. 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 caused by duct leaks 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.

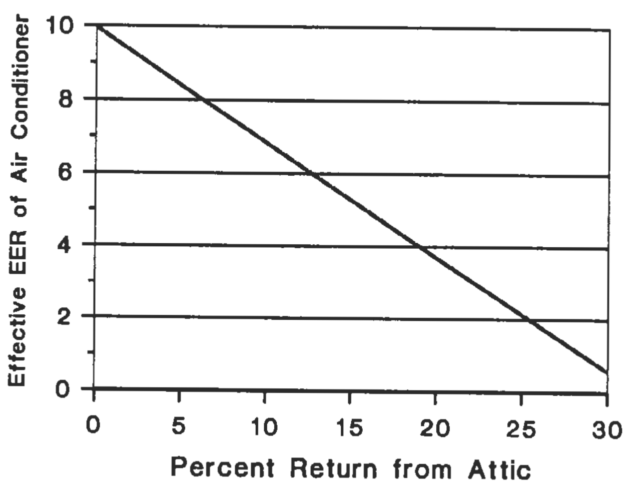

Figure 6. Performance degradation of air conditioner when attic air is drawn into air handler, assuming room is 78° and attic air is 120°F.

An illustration of duct leak impacts on demand is shown in Figure 7. Infiltration and air conditioner performance are shown before and after repair of a 30% return leak. Infiltration decreased 75% from 1.15 ach to 0.30 with the air handler operating. Temperature drop from return (measured in the room at the register) to supply increased from 7°F to 16°F, 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 103°F attic air into the return air stream. It is interesting to note that the room temperature was 87°F before repair, even though the air conditioner was running continuously, because the capacity of the air conditioner was insufficient to maintain the setpoint. Afterwards, the homeowner reported that the house could be easily cooled to 78°F with the air conditioner cycling normally.

Duct leak impacts upon winter peak electrical demand are much greater than summer peak electric demand. The reason for this is that heat pumps have electric resistance backup which can supply heat when the heat pump capacity is inadequate.

A theoretical analysis is presented in Table 1 of duct leak impacts upon peak electrical demand in a typical Florida house on a winter morning. 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 0.29 ach measured in our sample houses because we assume that wind and stack affects are greater.
- An indoor temperature of 72°F and an outdoor temperature of 30°F.
- 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.
- The floor area of the typical house is 1500 ft^2. Construction is concrete slab, R19 attic, R4 block walls, and 120 ft^2 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 30°F.

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 1 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. The infiltration load caused by the supply leaks is greater than for return leaks because the air lost from the house is hotter. A 30% supply leak causes more than 200% increase in electrical demand.

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 20°F instead of 30°F.

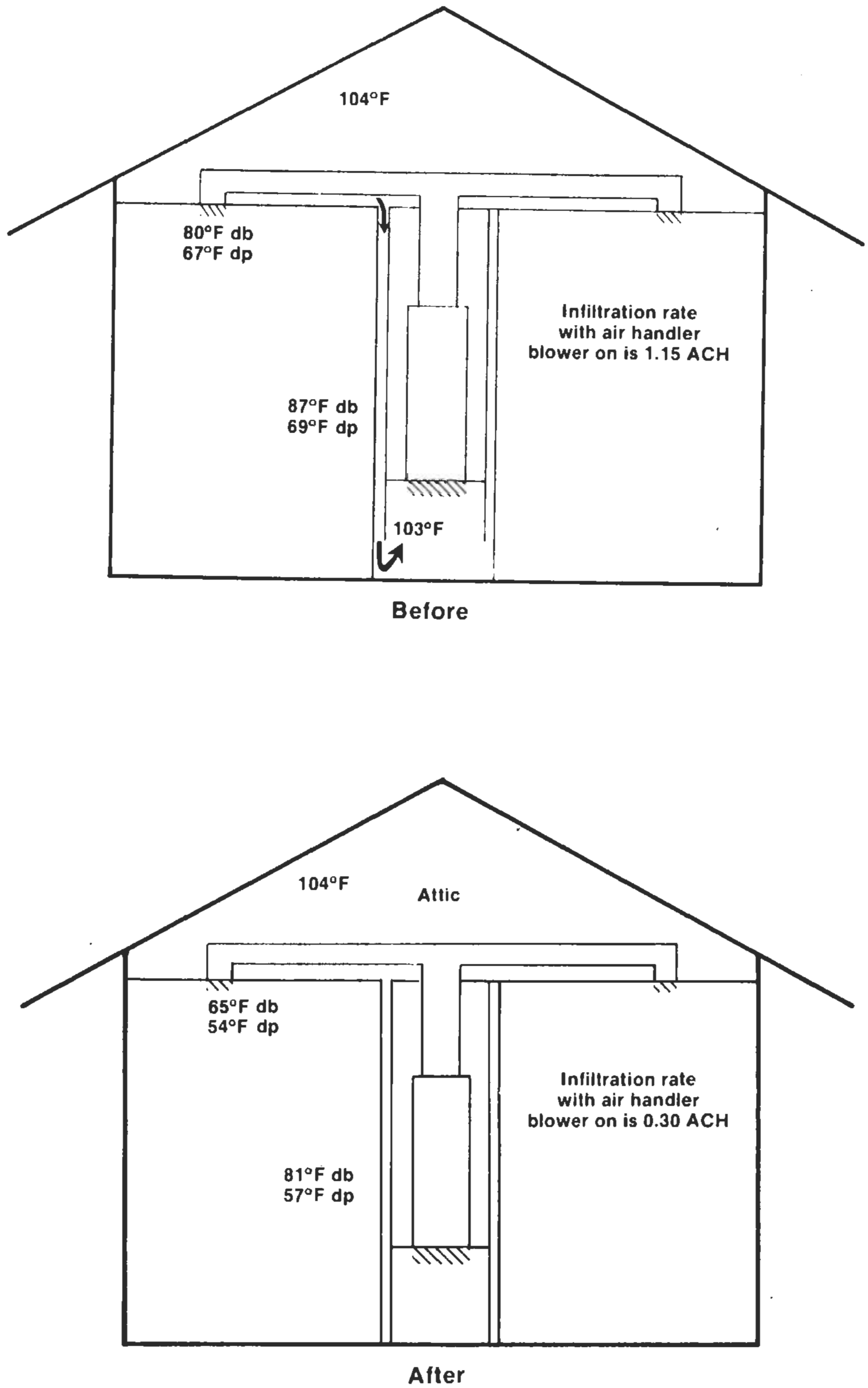

Figure 7. Infiltration rate with air handler on and air conditioner performance before and after repair of a 30% return leak.

Table 1

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

Consequently, the peak demand would be about 25% greater than indicated in this analysis if 20°F 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. Because most homes are not air conditioned during typical winter weather of 65°F to 80°F and high humidity, household furnishings and building materials have adsorbed 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 adds 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 are not considered.

Table 2. 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 155 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 1.
- The cost of duct repair is based on the fee schedule of $40/man-hour.
- The cost of new electrical generation capacity is $700/kW.
- 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 draw in air to make up for that "pumped" out of the house by the supply leak. As an example, if you have a 1500 ft^2 house with a large supply leak of 200 CFM, and no return leak, the infiltration rate will be 1.0 ach. If a return of 100 CFM develops, the house infiltration rate will remain 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 2. is an estimate based on only half of the return leak repairs producing demand reduction.

The results of this analysis show that repair of duct leaks can dramatically reduce Florida's winter electrical peak demand (most of Florida's utilities are winter peaking). At a typical cost of $200, duct repairs produce a 1.6 kW peak

Table 2

Potential Reduction in Statewide Winter Peak Electrical Demand Resulting From Repairing Duct Leaks in Electrically Heated Homes in Florida

duct leak %	housing[1] units (x1000)	repair cost (x10⁶)	demand reduction kW/house	demand reduction mW	capacity value (x10⁶)
Return Leaks					
2	1100	$55.0	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[2]	4949	$3464.3

[1]The proportion of duct leaks in Florida's 3,000,000 electrically heated homes is extropolated from test results on 100 homes.

[2]This assumes that only 1/2 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.

demand reduction per house, which has a new construction cost value of about $1100. Total peak demand reduction in the entire state of Florida is estimated at 5000 mW, or about 13% of the state's nameplate generation capacity. The cost of duct repair is estimated at $600 million and the avoided cost of new capacity is about $3.5 billion. Thus, duct repairs are a very cost-effective means of "building" new generating capacity.

CONCLUSIONS

Forced air distribution systems in Florida are leaky. Blower door tests found that on the average about 12% of the house ACH50 infiltration is in the duct system. These leaks cause the average infiltration rate of the sample of 155 houses to increase by 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.

Duct leak impacts upon peak electrical demand are dramatic, because the air handler is operating at its maximum (and thus, AH induced infiltration is at a maximum) and the air brought into the house is at its greatest temperature difference from inside during the utility's peak demand period. Based on theoretical calculations, a 15% return leak from the attic can decrease the effective capacity and efficiency of an air conditioner by 50%. Winter peak demand impacts are even greater, because when heat pumps run out of capacity, electric resistance backup kicks in to meet the added load caused. 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.

Some recommendations follow from these findings. Utilities should consider beginning duct repair programs. Training programs should be established to train appropriate trades people in duct leak diagnostics, duct leak repair, and correct installation of duct systems. Building/energy codes need to establish guidelines which will ensure that new homes will have airtight duct systems, using materials which last the life of the building.

Acknowledgements

We would like to thank the following persons for their help in preparing this research and paper: Daryl O'Connor with the Florida Governor's Energy Office for funding this research project, Ron Montwid and Rico Dunsmore of Lakeland Electric and Water for doing a large portion of the field testing and their support and administration of this project, Charles Sperry of Lakeland Electric and Water for having the vision to pursue this project, B.K. Chakraborty for extensive data processing and analysis, and Mable Flumm and Jeanette Holder for excellent word processing help.

REFERENCES

1. Tooley, John J., Jr., and Neil Moyer, "Mechanical Air Distribution and Interacting Relationships," Proceedings of Symposium on Improving Building Systems in Hot and Humid Climates, Dallas, Texas, October 3-4, 1989, pp. A-24-31.

2. Cummings, J.B, "Central Air Conditioner Impact Upon Infiltration Rates in Florida Homes," Proceedings of the 13th Passive Solar Conference, American Solar Energy Society, Boston, Massachusetts, June 20-23, 1988, pp. 133-138.

3. Cummings, J.B., and John J. Tooley, Jr., "Infiltration Rates and Pressure Differences in Florida Homes Caused by Closed Interior Doors When the Central Air Handler Is On," Proceedings of the 14th Passive Solar Conference, American Solar Energy Society, Denver, Colorado, June 19-22, 1989, pp. 392-396.

4. Cummings, J.B., and John J. Tooley, Jr., "Infiltration and Pressure Differences Induced by Forced Air Systems in Florida Residences," ASHRAE Transactions, Vol. 95, part 2, VA-89-5-4, June, 1989, pp. 551-560.

5. Cummings, J.B., J.J. Tooley, Jr., N. Moyer, and R. Dunsmore, "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, Pacific Grove, California, August 26-September 1, 1990, pp. 9.65-9.76.

6. Gammage, R.B. et al., "Parameters Affecting Air Infiltration and Airtightness in Thirty-one East Tennessee Homes," Measured Air Leakage of Buildings, ASTM STP904, Philadelphia, Pennsylvania, April 2-3, 1984, pp. 61-69.

7. Parker, D. S., "Thermal Performance Monitoring Results From the Residential Standards Demonstration Program," Energy and Buildings, #13, 1989, Elsevier-Sequoia, pp. 231-248.

8. Robinson, D.H., and L. A. Lambert, "Field Investigation of Residential Infiltration and Heating Duct Leakage," ASHRAE Transactions, Vol. 95, PART 2, VA-89-5-3, June, 1989, pp. 542-550.

9. Cummings, J.B., "Tracer Gas as a Practical Field Diagnostic Tool for Assessing Duct System Leaks," Proceedings of Symposium on Improving Building Systems in Hot and Humid Climates, Dallas, Texas, October 3-4, 1989, pp. A-16-20.