Infiltration and Pressure Differences Induced by Forced Air Systems in Florida Residences

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J.B. Cummings J.J. Tooley, Jr.

ABSTRACT

Five homes were tested by tracer gas and blower door to assess infiltration caused by leaks in air distribution systems. These homes are not a random sample and therefore may not give an accurate representation of Florida housing. Techniques used to determine the amount of return leak and the amount of infiltration caused by duct leaks are described.

Average infiltration with the air handler running was 1.42 air changes per hour (ach), while with the air handler off, it averaged only 0.14 ach. The infiltration rate with the air handler running is equivalent to an average 290 cubic feet per minute (cfm) (0.1369 m³/sec). Return leaks were much larger than supply leaks in all five homes. The return leak fraction averaged 21.6%, or an average of 263 cfm (0.142 m³/sec). Blower door tests found average air changes per hour at 0.20 in H_2O (50 pascals [Pa]) (ach50) to be 11.79 and the duct system represented 19% of the total leak area in three houses.

Return plenums were repaired and the tests were repeated. Infiltration with the air handler on dropped from 1.42 ach to 0.31 ach. The return leak fraction dropped from 21.6% to 2.6%. Duct system ELA was determined for only three homes. While only 43% of the duct leak area or 8% of the house ELA was sealed, the reduction in infiltration when the air handler was running was nearly 80%.

After the repairs were made, tests were performed to assess the impact of closing interior doors on the infiltration rate of the home. When the interior doors were closed, and the air handler was running, infiltration jumped from an average 0.31 ach to 0.91 ach.

INTRODUCTION

Infiltration impacts energy use and indoor humidity conditions in residential buildings. Duct-system leaks produce more infiltration than wind and stack effects in many homes. This impact is even more severe in cooling climates if the leak air originated in a hot attic. We present results from computer simulations of infiltration of outdoor air. We then examine the impacts of attic-infiltration air upon air-conditoner cooling performance.

Review of previous research indicates that infiltration in homes is greatly affected by air-handler operation. We present results from tracer-gas tests and fan-pressurization tests on five homes before and after duct-system repair. We conclude that return plenum leaks can have major impacts on energy use, air-conditioner capacity, and indoor comfort, and that they are relatively easy and cost effective to repair.

COMPUTER SIMULATION OF INFILTRATION

Infiltration rates are very important to understanding energy use and indoor humidity conditions in residential buildings. In hot, humid climates, influx of outdoor air adds to the cooling load and raises indoor relative humidity. Computer simulation results using TARP (Thermal Analysis Research Program), modified to account for moisture adsorption and desorption into and out of building materials and furnishings, and using typical meteorological year (TMY) weather data, are presented in Figure 1 (a,b,c) for Orlando, FL. The simulated house is a typical Florida home: 1500 ft² (139.4 m²) slab-on-grade, single-story block wall construction with R3 (h·ft²·°F/Btu) (0.53 m²·°C/W) wall insulation, R19 (h·ft²·°F/Btu) (3.35 m²·°C/W) attic insulation, and 224 ft² (20.8 m²) of single-pane windows. A typical SEER = 8.0 air conditioner is used.

As the infiltration rate is increased from 0.10 to 0.90 ach, annual cooling electricity use rises from 3400 kWh to 4469 kWh, a 31% increase (Figure 1a). Increase in sensible heat gain is very small, since the average outdoor temperature is only 3°F (1.7°C) greater than indoors. Increase in latent load is large because the humidity ratio is about 75% higher outdoors than indoors (0.0175 vs. 0.0100 lb/lb). Eighty-five percent of the added load from infiltration is latent heat. Heating load is more sensitive to increased infiltration. It rises 127% when infiltration is increased from 0.10 to 0.90 ach, from 4.9 to 11.1 million Btu (5.2 to 11.71 GJ) per year (Figure 1b).

Duct system leaks can produce a much greater impact upon energy use and peak electrical demand during the cooling season than naturally occurring infiltration. The magnitude of the energy gain to the house can be assessed by looking at the difference in the average enthalpy of the air leaving and entering the house. In natural infiltration, indoor air leaving the house has about 31 Btu/lb (54.1

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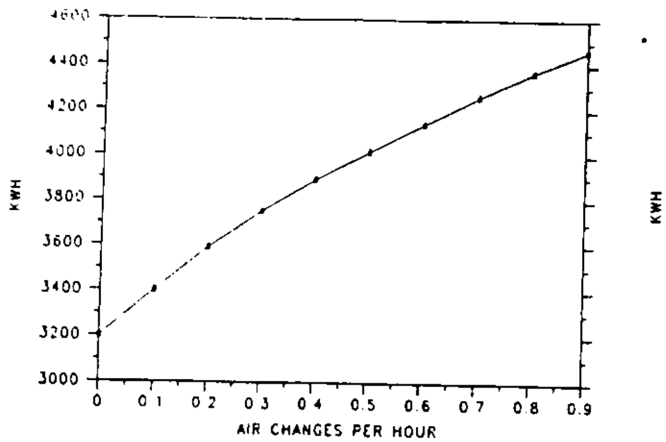

Figure 1a *Annual cooling energy use in Orlando as a function of infiltration (78°F setpoint; 1500 ft² house)*

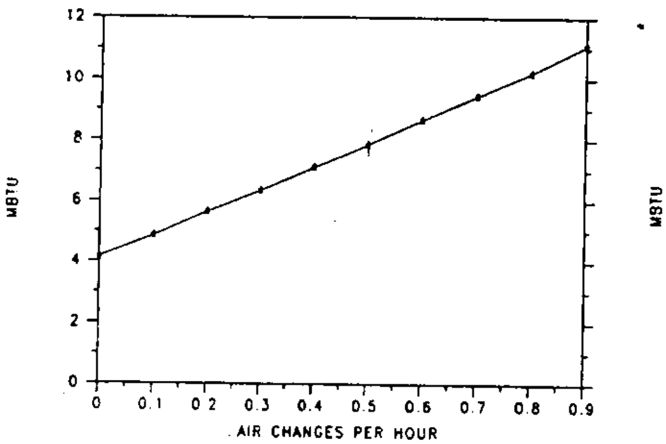

Figure 1b *Annual heating energy use in Orlando as a function of infiltration (72°F setpoint; 1500 ft² house)*

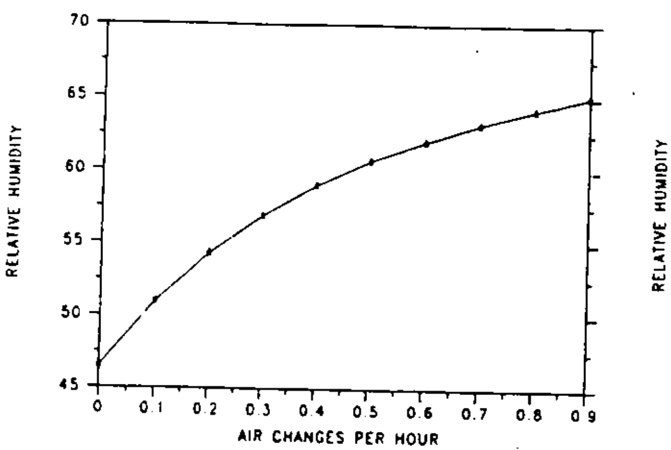

Figure 1c *Average July relative humidity in Orlando as a function of infiltration (78°F setpoint; 1500 ft² house)*

kJ/kg) enthalpy, and the entering outdoor air is at about 39.5 Btu/lb (73.9 kJ/kg). Enthalpy gain is 8.5 Btu/lb (19.8 kJ/kg). In the case of supply duct losses, highly conditioned air with an enthalpy of about 24 Btu/lb (37.8 kJ/kg) is lost to the ambient, and outdoor air with an enthalpy of 39.5 Btu/lb (73.9 kJ/kg) is pulled into the house to make up for the loss. Enthalpy gain is 15.5 Btu/lb (36.1 kJ/kg). If half of the air coming into the house is from the attic, where enthalpy may average 48 Btu/lb (93.6 kJ/kg), then the enthalpy gain may be 19.5 Btu/lb (45.4 kJ/kg).

What would be the impact of a 20% return leak upon cooling season energy use? If all the return leak is from the outdoors, the enthalpy gain may be the same as for natural infiltration—8.5 Btu/lb (19.8 kJ/kg). The 20% return leak times 8.5 Btu/lb (19.8 kJ/kg) enthalpy rise equals 1.7 Btu/lb (4.0 kJ/kg). However, from TARP simulations we find that because most of the added enthalpy is latent heat, producing an increase in indoor relative humidity (RH), only about 70% of the potential enthalpy becomes added load. Thus (0.70 × 1.7 =) 1.19 Btu/lb (2.77 kJ/kg) is added enthalpy. If the air conditioner provides cooling of 6.5 Btu/lb (15.1 kJ/kg) of (dry) air, then net air-conditioner efficiency is reduced by (1.19/6.5 =) 18%, and energy use increases by 22%.

If the return leak is from the attic, where enthalpy may average 48 Btu/lb (93.6 kJ/kg), the enthalpy gain may be 16 Btu/lb (37.2 kJ/kg). A 20% return leak would add an average 3.2 Btu/lb (7.4 kJ/kg) to the air entering the evaporator coil. Since average cooling by the coil is 6.5 Btu/lb (15.1 kJ/kg), the return leak from the attic may cut the net efficiency of the air conditioner by about 50% (3.2/6.5) and nearly double the cooling energy consumption.

The impact upon peak cooling electrical demand is even greater than the impact upon total cooling energy use. This is important to electric utilities because it may increase the electric utility's need to build new generating capacity. During hot afternoon hours, enthalpy in the attic can reach 61.5 Btu/lb (125.0 kJ/kg), or 30.5 Btu/lb (70.9 kJ/kg) higher than in the house. Calculation of the enthalpy of the air entering the air handler yields (0.20 × 61.5 Btu/lb + 0.80 × 31.0 Btu/lb =) 37.1 Btu/lb (68.3 kJ/kg). This 6.1 Btu/lb (14.2 kJ/kg) enthalpy rise represents 95% of the air conditioner's capacity.

PREVIOUS RESEARCH

Earlier research indicates that forced-air systems cause elevated infiltration rates in residences. Fourteen tracer gas tests were performed on a 1½-story townhouse in Cocoa, FL, with the air handler blower on and off under a number of wind conditions. Infiltration averaged about 0.57 ach with the air handler on and 0.22 ach with the air handler off (Cromer and Cummings 1986). Gammage et al. (1984) found from tracer gas testing in 31 Tennessee homes that infiltration averaged 0.78 ach when the air handler was running and 0.44 ach when the air handler was off. Tracer gas testing done on nine Florida single-family homes found infiltration of 0.62 ach with the air handler on and 0.22 ach with the air handler off (Cummings 1988).

Lower heating system efficiency in homes with forced-air systems was observed in a study done by the Northwest Power Planning Council (Parker 1987). It was found that forced-air electric heating systems used 28% more heat (normalized for house size) than baseboard and wall heating units. Evidence indicates that elevated infiltration is the primary cause of this added heating load. Long-term perfluorocarbon tracer gas tests found 0.41 ach in homes with duct systems, and only 0.24 ach for nonducted homes. This 74% higher infiltration occurs in spite of the

TABLE 1
Infiltration Rates and Return Leak Fraction with Air Handler on and off, Before and After Return Plenum Repair

House	Floor Area (ft²)	Air Handler CFM	AIR HANDLER ON Before Repair ACH[3]	CFM	RLF[4]	CFM	After Repair ACH	CFM	RLF	CFM	AIR HANDLER OFF[5] ACH	Wind Speed (MPH)	Air Temp. In F	out F
F	1431	805[2]	1.15	219	22.3%	180	.47	90	5.6%	45	.25	4-6	77	78
B	1376	1374	.91	173	10.8%	148	.32	68	1.3%	18	.08	7-10	76	59
D	1590	1301	.84	178	10.0%	130	.30	64	3.0%	39	.10	6-9	75	74
M	1686	1377	3.36	755	55.0%	757	.21	47	0.0%	0	.10	5-7	70	49
N	1050	1002	.82	125	9.8%	98	.24	37	2.0%	20	.18	2-4	75	65
Ave.	1427	1172	1.42	290	21.6%	263	.31	61	2.4%	24	.14	6		

House	Floor Area (m²)	Air Handler (m³/s)	AIR HANDLER ON Before Repair ACH[3]	m³/spc	RLF[4]	m³/s	After Repair ACH	m³/s	RLF	m³/s	AIR HANDLER OFF[5] ACH	Wind Speed (m/s)	Air Temp. In °C	out °C
F	133.0	0.382[2]	1.15	0.103	22.3%	.085	.47	.042	5.6%	.021	.25	1.8-2.7	25.0	25.6
B	127.9	0.649	.91	0.082	10.8%	.070	.32	.032	1.3%	.008	.08	3.1-4.5	24.4	15.0
D	147.8	0.614	.84	0.084	10.0%	.061	.30	.032	3.0%	.018	.10	2.7-4.0	23.9	23.3
M	156.7	0.650	3.36	0.356	55.0%	.375	.21	.022	0.0%	.000	.10	2.2-3.1	21.1	9.4
N	97.6	0.473	.82	0.059	9.8%	.046	.24	.017	2.0%	.009	.18	0.9-1.8	23.9	18.3
Ave.	132.6	0.553	1.42	0.137	21.6%	.124	.31	.029	2.4%	.011	.14	2.7		

1. All homes are single-story slab-on-grade construction.
2. 805 CFM (0.382 m³/s) resulted from a very dirty filter. After testing was complete, we measured 1172 cfm (0.553 m³/s) with the filter removed.
3. Air changes per hour
4. Return leak fraction. This is the proportion of the total air handler flow that is leaking into the return from outside the envelope
5. Infiltration tests with the air handler off were only 30 minutes in duration, therefore, their accuracy is not as great as if a more lengthy test was performed.

fact that blower door testing predicted only 13% more infiltration in the ducted homes (Parker 1987). Given an average home size of 1600 ft² (148.7 m²) and 6000 heating degree days (3333 in °C), the difference in infiltration accounts for about 1.1 kWh/ft² (0.10 kWh/m²) of the total 1.5 kWh/ft² (0.14 kWh/m²) electricity use difference. Since air-handler-induced infiltration occurs more during hours when it is coldest outdoors, it is expected that this infiltration would cause more heating load than the calculated 1.1 kWh/ft² (0.10 kWh/m²).

CURRENT TEST RESULTS

Five homes recently were tested for air-distribution leakage, and then repaired. The objectives were to:

1. Measure impact of duct leaks on infiltration.
2. Measure return and supply duct air leakage.
3. Measure leak area of house and duct system.
4. Observe the impact of duct system repair upon infiltration, duct-air leakage, and house and duct leak area.
5. Measure house pressures associated with duct leakage and closing of interior doors.

These five homes were not randomly selected, but were known or suspected of having air-distribution system leaks.

These five houses are all single-story slab-on-grade construction. Four are block construction; one is frame. The average floor area is 1427 ft² (132.6 m²) (Table 1). All homes have central forced-air heating and cooling systems. Four of the air handlers are located in closets within the conditioned space, and one is located in the garage. All of the supply ductwork is located in the attic. There is no return ducting; a return plenum is located underneath the air handler. Air handler flow rates average 1172 cfm (0.553 m³/sec). Three of the homes are about 20 years old, one is 5 to 10 years old, and the frame house, which has the air handler in the garage, is only 6 months old.

Air distribution system leakage was measured in three ways:

1. House infiltration was measured once with the air handler on and again with the air handler off, using tracer gas.
2. Return leak fraction was determined using tracer gas.
3. Blower door measurement of the effective leak area of the air distribution system.

A description of the infiltration test, the return leak test, and the blower door test procedures is presented in Appendix A.

From test 1 two infiltration rates were obtained—when the duct blower was on, and when it was off (Table 1). For these five homes the average infiltration rate when the air handler was on was 1.42 ach, and when it was off averaged 0.14 ach. From test 2 we obtained the fraction of the return air originating from outside the envelope (Table 1). The average return leak fraction was 21.6%. From test 3 the ELA of the duct system was determined (Table 2). For the three homes tested it averaged 24.7 in² (0.0159 m²), or 19% of the total house ELA.

Leaks in the return plenum were repaired in all five homes and the testing was repeated. The average infiltration rate when the air handler was on decreased 78% from 1.42 to 0.31 ach. The return leak fraction decreased by

TABLE 2
Blower Door Test Results, Showing Air Change Rate at 0.20 in H_2O (50 Pa) and the ELA of the House and the Air Distribution System, Before and After Repair

House	Floor Area		Constr. Type	Before Repair					After Repair				
				ACH50	ELA		ELA Ducts[2]		ACH50	ELA		ELA Ducts	
	ft^2	m^2			in^2	m^2	in^2	m^2		in^2	m^2	in^2	m^2
F	1431	(133.3)	block	14.34	179.3	(.116)	21.1	(.014)	12.50	170.6	(.110)	12.4	(.008)
B	1376	(127.9)	block	8.70	80.6	(.052)	23.4	(.015)	6.86	68.0	(.044)	10.8	(.007)
D	1590	(147.8)	block	10.50	125.7	(.081)	29.5	(.019)	9.92	119.3	(.077)	19.4	(.013)
M[1]	1686	(156.7)	block	16.66	279.3	(.180)	NA	NA	9.37	100.4	(.065)	NA	NA
N	1050	(97.6)	frame	8.76	86.1	(.056)	NA	NA	NA	NA	NA	NA	NA
5 Houses				11.79	150.2	(.097)	NA	NA	NA	NA	NA	NA	NA
4 Houses (F,B,D,M)				12.55	166.2	(.107)	NA	NA	9.66	114.6	(.074)	NA	NA
3 Houses (F,B,D)				11.18	128.5	(.083)	24.7	(.016)	9.76	119.3	(.077)	14.2	(.009)

1. In house M, in addition to sealing the return plenum, some other attic leaks were also sealed. It is estimated that 70% to 80% of the total 179 in^2 (.116 m^2) that was sealed was in the return plenum.
2. ELA in the duct system was found by doing a blower door test once with supply and return grilles covered and then again with them uncovered.

TABLE 3
Impact of Closing Interior Doors on Infiltration When Air Handler is On

House	Floor Area		Air Handler[1]		ACH OFF	ACH ON	ACH[3] Doors Closed	Pressure Difference in H_2O (Pa)			
								House Outdoors		Rooms Main House[4]	
	(ft^2)	m^2	CFM	m 3/5							
F	1431	(133.0)	805[5]	(.382)	.25	.47	.58	NA	NA	.012	(3.1)[5]
B	1376	(127.9)	1374	(.649)	.08	.32	.82	−.004	(−1)	.032	(8.1)
D	1590	(147.8	1301	(.614)	.10	.30	.98	−.004	(−1)	.036	(9.1)
M	1686	(156.7)	1377	(.650)	.10	.21	1.27	NA	NA	.033	(8.2)
N	1050	(97.6)	1002	(.473)	.18	.24	.88	−.008	(−2)	.010	(2.6)
	1427	(132.6)	1172	(.553)	.14	.31	.91			.025	(6.2)

1. Air handler air flow was measured at supply grilles by air flow hood.
2. Low flow rate is a consequence of a dirty filter. When the filter was removed, air flow increased to 1172 cfm (.553 m 3/5).
3. Interior doors closed with air handler running.
4. "Rooms" means rooms behind closed doors. This is the average of the rooms.
5. 0.012 in H_2O (3.1 Pa) average pressure across the interior doors with dirty filter in place. After filter was removed, delta pressure doubled to 0.026 in H_2O (6.4 Pa).

89% from 21.6 to 2.4%.

Blower door tests were available after repair on only four houses (Table 2). Ach50 for these four houses declined 31% as a result of return plenum repair. In house M, we estimate that about one-quarter of the sealed leak was other attic openings besides the return plenum. Correcting for this, return plenum repairs account for a 24% reduction in total house ELA.

Duct system ELA was measured on three houses after repair. ELA of the ducts fell from 24.7 in^2 (0.0159 m^2) to 14.2 in^2 (0.0091 m^2), a 43% decrease. Duct ELA declined from 19.2% of the house ELA to 11.9%. On these three homes, infiltration (measured by tracer gas test) with the air handler on decreased from an average 1.02 ach before repair to an average 0.36 after repair. Therefore, sealing 8.2% of the total leak area of the house, in the return duct system only, resulted in a 65% reduction in infiltration with the air handler on.

Following is a discussion of results from each house. Test results for the houses are summarized in Tables 1, 2, and 3.

House F

This 20-year-old block construction house has a relatively large leak area, 179.3 in^2 (0.116 m^2) ELA, which yields 14.34 ach50. Of the five houses tested for naturally induced infiltration, this had the highest rate of 0.25 ach.

Only 12% of the leak area is associated with the duct system, but infiltration is dominated by air distribution leaks. When the air handler is running, infiltration rises to 1.15 ach, or an equivalent 219 cfm (0.1034 m^3/sec). The return leak fraction was 22.3%, or 179 cfm (0.0845 m^3/sec).

When the return plenum leaks were sealed, the total leak area of the house decreased by only 4.9%. Sealing this relatively small leak area caused infiltration in the house with the air handler on to drop 59% from 1.15 to 0.47 ach, and the return leak fraction fell 75% from 22.3% to 5.6%. The homeowner immediately noted that the house could be easily cooled on hot afternoons and that it cycled normally instead of running continuously. The remaining return leak is probably caused by leaks in the air handler, which is a gas furnace. Because the furnace requires combustion air, the ceiling of the air handler closet was not sealed.

The impact of a 22% return leak of attic air (assume 120°F [48.9°C] temperature and 80°F [26.7°C] dew point temperature) upon air-conditioner capacity can be seen in the psychrometric chart shown in Figure 2. The top line, labeled "A," shows room and attic conditions at points R and A, respectively, mixing to produce point C, which is the air conditions entering the evaporator coil. Point S is the condition of the cool air coming from the supply. The net temperature drop from R (room) to S (supply) is only about

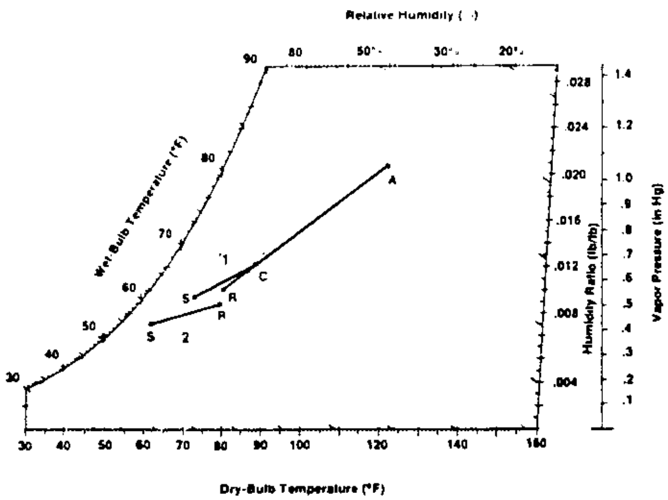

Figure 2 *Impact of 22% return leak from 120°F attic upon the effective cooling capacity of an air conditioner*

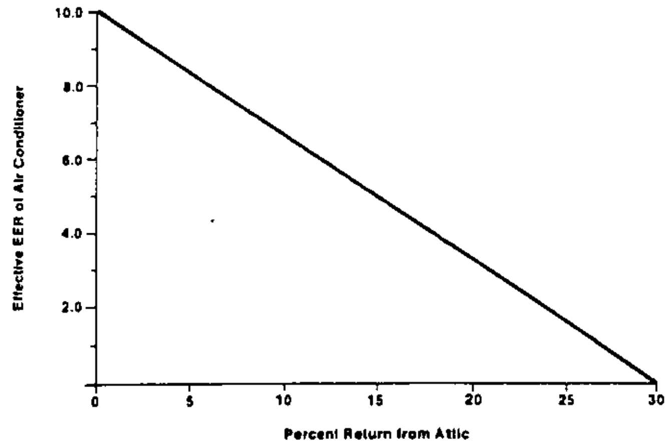

Figure 3 *Performance degradation of air conditioner when attic air is drawn into air handler, assuming room is 78° and attic air is 120°F*

5°F (2.8°C). The lower line, labeled "B," shows the air conditioner cooling the air by 18°F (10°C) after the return leak is eliminated. Thus the net sensible cooling capacity of the air conditioner is reduced by 72% by the return leak. Figure 3 shows the impact of return leaks from the attic upon the effective EER of the air conditioner for various leak amounts during the peak cooling period of the day. A 15% return leak cuts EER in half and, with a 30% return leak, the capacity of the air conditioner is negated.

An additional infiltration test was performed with interior doors closed with the air handler on. Infiltration increased slightly to 0.58 ach from 0.47 ach (Table 3). This increase is small compared to other houses. The reason for this is that the total airflow to the bedrooms and baths, which have doors that can be closed, is relatively small. The crack size at the bottom of the doors is about ½ in. Pressure drop across the five doors averaged a relatively low 0.0124 in H_2O (3.1 Pa). However, when the filter in the air handler was removed (it was very dirty) and the total system airflow increased from 805 to 1172 cfm (0.520 to 0.7565 m^3/sec), the average pressure drop across the doors increased to 0.0256 in H_2O (6.4 Pa).

House B

This five-year-old, 1376 ft^2 (127.9 m^2) block construction house is the tightest in the group, with only 80.6 in^2 (0.0520 m^2) ELA and 8.7 ach50. This house also had the lowest naturally induced infiltration, 0.08 ach, even with the strongest winds of all the tests.

A rather large 29% of the ELA of the whole house is in the air distribution system. Infiltration is dominated by return leaks. When the air handler is running, infiltration rises to 0.91 ach, or an equivalent 173 cfm (0.0817 m^3/sec). The return leak fraction is 10.8%, or 148 cfm (0.0699 m^3/sec). With the air handler running, the house operated at +0.004 in H_2O (+1 Pa) pressure, which is consistent with return leaks.

When the return leaks were repaired, the total leak area of the house decreased by 16%. Sealing 12.6 in^2 (0.0082 m^2) of return leak lowered infiltration in the house when the air handler was on from 0.96 to 0.32 ach, and reduced the return leak fraction from 10.8% to 1.3%. House pressure with the air handler running also decreased to neutral.

The air handler cabinet caused a portion of the return leak. In order to achieve 1.3% return leak, penetrations and cracks in the air handler were taped. Attic air could get into the air handler closet because the ceiling was not fully sealed. When the cracks were not sealed, the closet (immediately above the return plenum) operated under −0.004 in H_2O (−1 Pa) pressure. When the cracks were sealed, pressure dropped to 0.0 in H_2O (0 Pa).

When interior doors were closed with the air handler running, the infiltration rate in the home increased to 0.82 ach (Table 3). Pressure drops across the four doors averaged 0.032 in H2O (8.1 Pa). Cracks at the bottom of the doors are about ½ in (0.013 m).

The master bedroom has a grille above the door to allow return airflow (it was closed during the testing reported above). When it was closed, the room pressure was 0.038 in H_2O (9.5 Pa). When it was opened, pressure in the room dropped to 0.015 in H_2O (3.8 Pa). This return path then helps reduce unwanted pressures in the house, but a larger opening would be even more desirable.

House D

This 20-year-old, 1590 ft^2 (147.8 m^2) block construction house has an ELA of 125.7 in^2 (0.0811 m^2), which yields 10.50 ach50. Its naturally induced infiltration was measured at 0.10 ach.

A large 23.5% of the leak area of the house is in the duct/air handler system. Infiltration is dominated by air distribution leaks. When the air handler is running, infiltration rises to 0.78 ach, or an equivalent 178 cfm (0.0840 m^3/sec). The return leak fraction is 10.0%, or 130 cfm (0.0614 m^3/sec).

This house previously had a gas furnace in the hall closet. Several years ago a high-efficiency heat pump (SEER = 11) was installed in the closet, but the return plenum was not reconstructed. The whole closet was the return plenum. In order to seal this closet from the attic we had to put foam into numerous cracks and penetrations in the ceiling. Working in the attic, we used a smoke stick to

Return leak pathways into return plenum from the attic

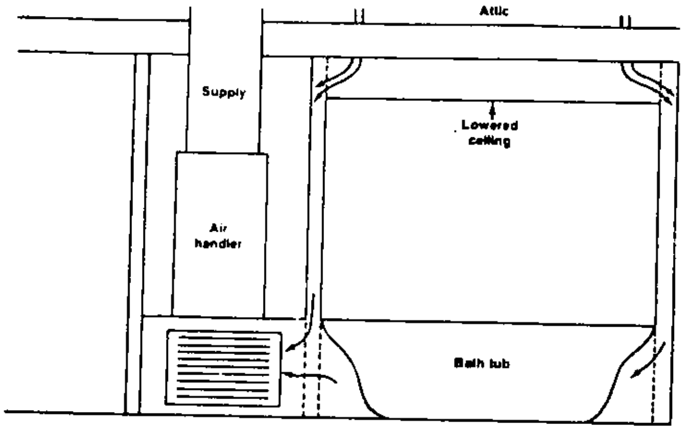

***Figure 4** Return leak pathways into return plenum from the attic*

identify where return air was being drawn into the closet. After sealing, the house ELA dropped about 5%. This resulted in infiltration being reduced from 0.84 to 0.30 ach with the air handler running, and the return leak fraction dropped from 10.0% to 3.0%.

When the interior doors were closed, the infiltration rate increased from 0.30 ach to 0.98 ach (Table 3). This increase is typical of what we have observed in a number of Florida homes. The crack size at the bottom of the doors is about ½ in (0.013 m). Pressure drop across the four closed doors averaged 0.036 in H2O (9.1 Pa), which is the highest of the five houses tested. The impact of this elevated infiltration was observed by the author at this house at a social event on a summer evening. The air conditioner did not shut off the whole period from 7 to 10 p.m., though it was not an unusually hot day and there were only about 10 people in the house. The apparent cause for the excessive run time was that three bedroom doors were closed, increasing infiltration and bringing in heat and humidity from outdoors and the attic.

When a pulse of humidity is introduced into the space, a good deal of the latent heat is converted to sensible heat as the moisture adsorbs into the materials in the house. Research done at the Florida Solar Energy Center has found that the furnishings of a house can store about 10 times as much moisture for a given RH change as the air in the house (Cummings and Kamel 1987). Therefore, when a large pulse of latent heat comes into the house, such as when the doors are closed, much of this latent heat converts to sensible heat.

System imbalance caused by closed doors is typical in Florida homes. In a sample of 81 other homes with single returns that we tested in the Orlando area, the average pressure drop across the master bedroom door was 0.032 in H_2O (8.0 Pa). In a sample of 16 homes that have multiple returns, pressure drop across the master bedroom door was only 0.006 in H_2O (1.6 Pa). Providing multiple returns can help maintain even pressure throughout the house and reduce infiltration. Whether multiple returns, typically running through the attic, cause more problems from conduction heat gains and from return leaks than they solve is an issue still open to question.

House M

This 20-year-old, 1686 ft² (156.7 m²) block construction house began as the loosest house of the five with 279.3 in² (0.1803 m²) ELA and 16.66 ach50. The naturally occurring infiltration rate was measured at 0.10 ach under calm wind conditions.

A blower door test with the registers covered was not performed, so the ELA of the air distribution system is not known. The return plenum leak was very large. One whole wall (about 5 ft² [0.46 m²]) of the return plenum had no sheet rock (Figure 4). This opening passed into the bath/shower enclosure, which also had no sheet rock below the top edge of the bathtub. Above the bath/shower was a lowered ceiling, thereby resulting in large pathways up the walls into the attic. With the air handler running, the infiltration rate rose to 3.36 ach, which is 755 cfm (0.356 m³/sec). The return leak fraction of 54.9% is in close agreement; it is equivalent to 757 cfm (0.357 m³/sec).

When the return plenum on this house was sealed, some additional sealing between the attic and the house was done. We estimate that 75% of the sealing was in the return plenum. The house ELA dropped from 279.3 to 100.4 in² (0.1803 to 0.0648 m²) (64% reduction), and ach50 dropped from 16.66 to 9.37 (44% reduction). The infiltration rate of the house dropped from 3.37 ach to 0.21 ach with the air handler on, a 94% reduction. The return leak fraction dropped from 54.9% to 0.0%. The final infiltration rate and return leak fraction are the lowest of the five houses. The homeowners were very pleased and wrote a complimentary letter to the electric utility. During the 16 years they had lived in the house they had called in air-conditioning contractors an estimated 12 times to repair the system and had been told that the equipment was working fine.

When the interior doors were closed with the air handler on, infiltration jumped from 0.21 to 1.27 ach. This is the largest increase in any of the homes. Pressure drop across the doors averaged 0.033 in H_2O (8.2 Pa).

House N

This is a six-month-old frame construction house with a fairly tight envelope. The house ELA was measured at 86.1 in² (0.0556 m²) and ach50 was 8.76 ach. This house had natural infiltration of 0.18 ach and 0.17 ach measured before and after repair.

A blower door test with the registers covered was not done, so the ELA of the air distribution system is not known. Infiltration tests on this house were done three times before the repairs were finally completed. In the first test, the infiltration rate was 0.94 ach with the air handler running, which is equivalent to 144 cfm (0.0680 m³/sec). The return leak fraction was measured at 11.3%, or 113 cfm (0.0533 m³/sec). Because this was a new house and was under warranty, the homeowner contacted the air-conditioning contractor to repair the leaks in the system. Based on our instructions he sealed the return plenum box joints where the air handler joins the plenum, and openings in the attic at the tops of walls. When a second test was performed it was found that the infiltration rate had dropped only slightly to 0.87 ach (133 cfm or 0.0628 m³/sec), and the return leak fraction was reduced to only 10.1% (101 cfm or 0.0477 m³/sec). We were surprised at how little of the leak was sealed.

We proceeded to perform a number of additional repairs. All cracks and openings in the air handler cabinet were sealed with tape. The infiltration rate then dropped to 0.49 ach (75 cfm or 0.0354 m³/sec) and the return leak fraction fell to 6.6% (66 cfm or 0.0312 m³/sec). Therefore, 3.5% (35 cfm or 0.0165 m³/sec) of the return air was leaking through penetrations in the air handler. The final stage of repair was to "paint" the inside surface of the return plenum, which was 1 in ductboard with the fiberglass facing in, with a mastic sealing compound over fiberglass mesh. This made the return plenum airtight. The final test found infiltration had dropped to 0.24 ach (37 cfm or 0.0175 m³/sec), and the return leak fraction was down to 2.0% (20 cfm or 0.0094 m³/sec).

We learned from this house that sealing return leaks is sometimes a difficult task. We also concluded that the surest fix on a system like this is to completely seal the return plenum itself, instead of trying to seal pathways in walls through which the leaking air travels. In other cases, such as house D, sealing the attic floor above the air handler is the best approach.

Another lesson from this house is that a system constructed according to "standard practice" and which was done neatly and carefully can have major leakage problems. Therefore, we feel that construction practices in Florida need to be examined and new "standard practices" need to be adopted.

When the interior doors were closed and the air handler was running, infiltration increased from 0.24 to 0.88 ach. This increase was about average for the five houses tested. The pressure drop across the four closed interior doors averaged only 0.10 in H_2O (2.6 Pa). This is not a true picture, because air distribution is poorly balanced. While 279 cfm (0.1317 m³/sec) was going to the master suite, only 171 cfm (0.0807 m³/sec) went to the other three rooms combined. With the master bedroom suite having a 0.024 in H_2O (6.0 Pa) drop, the airflow weighted pressure drop is 0.0172 in H_2O (4.3 Pa). During this test the main body of the house was −0.0084 in H_2O (−2.1 Pa) with respect to the outdoors.

DISCUSSION

Test results from these five homes are not intended to present a broad representation of Florida housing. The sample is small and not a random selection. The purpose is to illustrate the kind of air distribution problems that exist, to show how they can be detected and quantified, and to demonstrate that they can be repaired effectively.

This group, with an average return leak fraction greater than 21%, probably has more duct leak problems than typical Florida housing. Based on a total of about 25 homes we have tested it appears that average leakage may be in the range of about 10%. The smallest return leak we have found is 5%.

Results from these five homes demonstrate the usefulness of tracer gas testing in identifying air distribution leak problems in homes. Finding infiltration once with the air handler running and once with it off provides a good measure of the air distribution leak problem. If infiltration is much higher with the air handler running, then there is a major leak problem. The volume of the leak can be determined by the air change rate times the volume of the house. Natural infiltration generally disappears when large duct losses occur because air-handler-induced pressures in the house overwhelm those produced by wind and temperature difference.

What is actually known from the infiltration test with the air handler on is the leak rate of the larger of the supply and the return leak, not the sum of the two. It is possible to determine whether the return or the supply is the dominant one by checking the house pressure. If it is negative relative to outside, then the supply leak is larger. If it is positive, then the return leak is larger. Pressure differences of 0.004 or 0.008 in H_2O (1 or 2 Pa) are commonly observed in homes with major leaks. A smoke pencil can be used to observe this pressure by observing whether air is being pulled into or out of the house.

The return leak test, described in Appendix A, also indicates which is the dominant leak. If the return leak is dominant, then the return leak fraction multiplied by the air handler flow rate will be close to the infiltration cfm. In this case, we know the size of the return leak but we do not know the size of the supply leak. The supply leak will be known only after the return leak is repaired. On the other hand, if infiltration with the air handler on is high, but the return leak fraction is low, then the supply leak is larger and both are known.

In these five homes, return leakage was dominant. After repair of the return plenum, infiltration with the air handler on generally fell to near the natural infiltration rate. This indicates that the supply leaks were small.

Duct air leakage determined by the return leak test generally was less than that determined by the infiltration test with the air handler on. Except for house M, the return leak cfm was only about 80% of the infiltration cfm. This is probably accounted for by the fact that the floor area of the house was calculated from exterior measurements. If the volume of the exterior block walls (9%), the volume of the interior frame walls (4%), and the volume of cabinets, some closets, and house furnishings are subtracted, the remaining corrected volume may be between 80% and 85% of the original.

Blower door tests were used to determine the effective leak area of the house and the duct system. ELA of the duct system averaged 19% of the total house ELA for three houses. Even though the duct ELA is less than one-fifth of the total, infiltration caused by the duct leaks is about seven times that of naturally occurring infiltration. The duct return leak fraction and house infiltration rate were reduced about 80% or more by sealing only 43% of the duct leakage area, which is only 8% of the total house ELA. Therefore, we can conclude that ELA in the duct system is much more important to infiltration than ELA in the rest of the house envelope. This makes sense, of course, because pressure differences across ducts leaks are much greater than those produced by wind and temperature effects.

TEST EQUIPMENT AND ACCURACY

The sulfur hexafluoride specific vapor analyzer performed well during the testing. It has a rated accuracy of ±5% of scale. We have checked it against calibrated gas concentrations and made calibration adjustments. The

TABLE 4
Duplicate Infiltration Tests with Air Handler On and Return Leak Tests Show Good Repeatability

House	Infiltration (ach) test number		Return Leak Fraction test number	
	1	2	1	2
B	.88.	95	11.2%.	10.4%
D	.78.	.91	9.6%.	10.6%
N	.74.	.87	9.8%.	10.1%

largest obstacle to accuracy is the zero drift that occurs when it is not fully warmed up. Therefore, the instrument should be warmed up for about half an hour before initial zeroing. We also suggest zeroing after each test period. Airflow measurements were made by an airflow hood with a rated accuracy of ±3% of reading plus 5 ft per minute (0.0254 m/sec). Pressure differential measurements were made with a pressure transducer with a listed accuracy of ±2% of reading plus one digit.

Accuracy of the infiltration test and return leak test seem to be quite high, based on observed repeatability. Tests on houses B, D, and N were repeated on two different days before the repairs were made. These duplicate test results are in good agreement (Table 4). Infiltration generally agreed within 15%, and return leak fraction varied by less than 10%.

Infiltration tests with the air handler off were only an average of 30 minutes long. The purpose of these tests was mainly to compare air-handler-induced infiltration with what occurs naturally. This period is long enough to determine the general range into which the house infiltration falls, but it is not long enough to obtain the best accuracy. Preferably, a period of one hour or more will be used in future tests.

Energy savings from duct repair can be quite large. As was discussed in the introduction, a 20% return leak from outdoors can increase air-conditioning costs by 22%. When the 20% return leak is from the attic, cooling costs may be increased by as much as 100%. This assumes that the air conditioner is sufficiently oversized to meet the higher peak cooling loads created by the return leak.

Impacts upon peak electrical demand are larger than upon energy use, because the conditions outdoors and in the attic are much more severe. If a 20% return leak comes from outdoors with conditions of 95°F (35°C) and a 75°F (23.9°C) dew point temperature, then net air conditioner capacity will be reduced by about 30%. If the 20% return leak comes from the attic with conditions of 130°F (54.4°C) and 85°F (29.4°C) dew point temperature, then net air conditioner capacity may be reduced 95%.

The cost of repairing these systems is quite low, based on estimates from a Florida company which specializes in these repairs. The cost for a house and duct system blower door diagnostic test is $50. The cost for the repair itself is typically less than $100—$60 for a simple fix and as much as $150 for a more complex situation. Given these costs, the payback time will typically be just a few years or less.

CONCLUSIONS

Air leakage has been found to be quite large in air distribution systems in Florida homes. A sample of five non-randomly selected homes illustrates the magnitude of the problem that exists in some homes. Return plenum leakage is often an invisible problem to the homeowner, air-conditioning contractor, and utility energy auditor. The house occupant often has no one to diagnose the problem. The high utility bills and uncomfortable living conditions may go on for years without solution.

Infiltration in these five homes dropped from an average 1.42 ach to 0.31 ach when the repairs were made, a 78% reduction. Return leaks dropped from an average of 21.6% to 2.4%, an 89% reduction. Much of the remaining leak was in the air handlers.

Duct leakage represented 19% of the ELA of three houses tested. Repairing the return plenums sealed 43% of the initial duct system ELA and 8% of the initial house ELA. Sealing this small portion of the house leak area resulted in major reductions in infiltration. The infiltration rate in these three homes dropped 63% and the return leak fraction was reduced 77%. Therefore, we can conclude that the leak area in the duct system creates much more infiltration than the leak area in the remainder of the house.

Return leaks are typically larger than supply leaks. Contractors and energy auditors generally understand the importance of sealing supply leaks, because conditioned air is being lost. However, the problems of return leaks are not widely recognized and the means to detect them is often missing. It is common for significant return leaks to exist in installations that are "standard practice."

One of the major problems with "standard practice" is that the return plenum is constructed with fiberglass ductboard, and is not carefully sealed. The fiberglass (which is facing in) is porous to airflow and allows air to be drawn in from any penetrations in the plenum. To correct this, we usually paint the interior surface of the plenum with mastic over fiberglass mesh to make it completely airtight.

Another problem is that the air handlers usually leak. Cabinet cracks, wire and pipe penetrations, and filter covers are all sources of return leaks. Return leaks in the air handler in the range of 3% to 5% have been observed. In some parts of Florida, more than 50% of air handlers are located in the attic. In conjunction with this, the joint where the air handler meets the plenum is often not thoroughly sealed.

Air distribution leaks can increase cooling energy use substantially. Twenty percent return leaks of outdoor air can increase cooling season energy use by about 20%. If the same leak is attic air, the increase may be as much as 100%.

Air distribution leaks can greatly reduce the effective cooling capacity of the air conditioner, thereby increasing peak demand and the potential for occupant discomfort. Return leaks of 15% attic air can reduce air-conditioner capacity by 50% or more during the peak cooling hours of the day when maximum capacity is needed. In two of five test homes, where return leaks from the attic were in excess of 20%, adequate cooling could not be achieved during summer afternoons and the house became uncomfortably warm.

However, with the proper tools, these return leaks can be easily detected. A blower door test to identify duct leakage can be done in half an hour. A tracer gas test to identify excessively high infiltration with the air handler on can be done in an hour or so. The cost of diagnosing and repairing these systems is usually between \$100 and \$200, and the payback is often less than one year. Electric utilities may find this an exceptionally good opportunity to reduce their peak demand at a very low cost. More research is needed to evaluate how widespread the problem is, to determine ways of preventing and correcting return leaks, and to assess the energy and peak demand penalties created by these leaks.

Closed interior doors impact the operation of single-return forced-air systems. High pressure in rooms behind the doors causes exfiltration, and low pressure in the main body of the house produces infiltration. Infiltration in these five homes increased from an average 0.31 ach with the doors open to 0.91 ach with the doors closed. This increases cooling load by drawing in outdoor and especially attic air. Further investigation is needed to fully assess the energy, comfort, indoor air quality, and peak demand impacts of this problem.

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APPENDIX A

Tracer gas testing is used to determine the infiltration rate of the home when the air handler is running and when it is off, and to determine the proportion of return air leaking from outside the conditioned envelope. A second infiltration test is described with the air handler on and the interior doors closed. Following is a description of the equipment, test procedures, and calculations used in these tests.

The primary piece of equipment is a specific vapor analyzer designed to detect sulfur hexafluoride (SF_6) concentration. It offers two ranges—0 to 5 parts per million (ppm) and 0 to 50 ppm. It is an 18-lb portable instrument that has a 1.06 cfm (0.5 L/sec) air pump for sampling room air. It operates on the principle of infrared detection. Using a high-temperature emitter and a detector, it determines the concentration of SF_6 by the amount of infrared absorption at the 10.7 micron wavelength. Because its operating principle is thermal detection, changes in its internal temperature

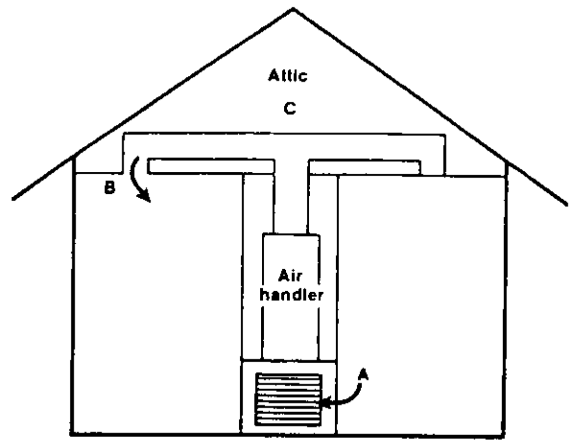

Figure A-1 *Procedure for determining proportion of return air coming from the attic. Measure SF_6 concentration (a) near return air grille, (b) at supply grille, and (c) in attic*

cause drift in its zero. Therefore, it is important to let the instrument warm up to a stable operating temperature, and to maintain fairly constant room conditions during the experiment. In order to reduce the sensitivity of the instrument to changes in room temperature, the outside case of the instrument has been insulated. In order to maintain maximum accuracy, it is recommended to zero the instrument throughout the testing.

Before testing can begin, the house must be prepared by ensuring that all windows are closed, all supply and return vents are open, that interior doors are open, and that exhaust fans, dryers, and vented grilles are not operating within the house.

After the detector has been warmed up and zeroed, SF_6 is injected into the return plenum of the forced-air system with the air handler running, until the concentration in the house reaches 30 to 50 ppm. Mixing in the house continues for about 15 minutes to ensure homogeneity throughout the house. With the air handler still on, SF_6 concentrations are recorded (along with time) in the room at the return grille, at a supply duct, and in the attic right at the location where attic air is being sucked into the return (if that is occurring). (Flexible ½-in tubes are run to the several locations—return, supply, attic, and outdoors—where samples are to be taken.) Figure A-1 shows the points A, B, and C where sampling should be done. These values are recorded about every five minutes for about half an hour.

Calculation of infiltration is done with the following formula:

$$\text{ach} = 60/N \ln(C_i/C_f) \qquad (1)$$

where

N = number of minutes of the test
C_i = initial tracer gas concentration
C_f = final tracer gas concentration

This calculated infiltration is not the true infiltration rate if the air being drawn into the house has tracer gas concentration. House M can be used as an example. The calculated infiltration was:

$$\text{ach} = 60/24 \ln(26.4/18.6) = 0.88$$

However, the air being drawn into the house from the attic by the return leak had 74% as much SF_6 in it as the house air. Therefore, the concentration of tracer gas was not declining nearly as much as if the incoming air had no tracer gas in it. (If the wind

TABLE A-1
SF_6 Concentration with Air Handler On and Interior Doors Closed

Time	Return	Bedroom	Attic
11:05	16.8	16.8	
11:12	13.8		
11:13		14.4	4.8
11:20	12.0	12.9	4.4
11:27	10.7	11.7	
11:28	10.6	4.4	

had been strong that day so that the attic was more rapidly ventilated, the attic tracer gas concentration would have been lower and the concentration in the house would have declined much more rapidly, indicating a higher infiltration rate.) Therefore, calculations are used to correct for the tracer gas being returned to the house using the following formula:

$$achcorr = ach \cdot (A/(A - C)) \quad (2)$$

where A is the concentration in the room and C is the concentration in the attic. This equation assumes that outdoor air enters the house through the attic only. The need for this correction could have been eliminated if multiple tracer gas testing had been done. Calculation of corrected infiltration for house M is:

$$achcorr = 0.88 \cdot (24.13/(24.13 - 17.83)) = 3.36$$

How can tracer gas get into the attic in large quantities? We found that return leaks cause the house to be pumped up like a balloon. Because the leak area of the house envelope was largely in the ceiling, which we believe is typical of Florida homes, house air was being pushed into the attic.

The return leak fraction is calculated from the first test as well. Knowing the tracer gas concentration in the room at the return grille, in the supply airstream, and in the attic (if the return leak is from the attic), the return leak fraction can be calculated from the following formula:

$$RLF = ((A - B)/(A - C)) \quad (3)$$

From house M, the calculation is:

$$RLF = ((24.13 - 20.67)/(24.13 - 17.83)) = .549$$

When the previous test is completed, all interior doors are immediately closed. The test is continued for a period of 20 minutes or more, sampling at the return, at a supply, in the attic, and now also in one of the rooms with a closed door. The concentration of tracer gas declines more rapidly in the main body of the house than in the closed rooms. Therefore, when the calculation of infiltration is done, a (floor area) weighted average of concentration in the closed rooms and the main house must be used.

A sample test from house M after the return leaks were sealed is presented in Table A-1. Infiltration is calculated at 1.08 ach.

However, this assumes that none of the infiltrating air has SF_6 concentration. If we make an assumption that half of the infiltration is from the attic (more than half of the area of the house envelope, excluding the slab, is ceiling), then the corrected infiltration is:

$$1.08 \text{ ach} \cdot (14.0/(14.0 - (4.6/2))) = 1.29 \text{ ach}$$

There is, of course, a certain range of uncertainty about the true infiltration rate since the proportion coming from the attic is unknown.

When the test with the doors closed is completed, the air handler is left on for 10 minutes or so to thoroughly mix the tracer gas throughout the house. Then the air handler is turned off and readings are taken near the return grille about every 10 minutes for a period of 40 minutes or more. In order to maintain good mixing in the house so that sampling at one location will provide a good approximation of the whole house tracer gas concentration, the air handler is turned on for the last two minutes of each 10-minute period. Having the air handler on, of course, increases infiltration above what occurs from wind, temperature, and diffusion effects alone. However, since the infiltration rate with the air handler on is known, this can be factored out of the calculated infiltration rate to leave only natural infiltration. The problems created by using the air handler could be avoided by using several desk fans to improve mixing. Because the length of the test is short, it is recognized that the results are more subject to error than if a longer test were done.

BLOWER DOOR TEST PROTOCOL

Blower door tests were done on each house before and after the duct system repair. The following steps were followed:

1. Close all windows, exterior doors, and fireplace flues.
2. Open all interior doors.
3. Switch off all fuel combustion equipment, exhaust fans, vented dryers, and air-conditioning and heating systems.
4. Install blower door across exterior partition.
5. Zero pressure gauges.

Depressurization test:

6. Increase blower speed and obtain five to eight readings of fan pressure as the house pressure is varied from 0.04 to 0.24 in H_2O (10 to 60 Pa) of pressure difference.

Duct system leak test:

7. Seal all supply and return grilles using paper and tape.
8. Repeat the depressurization test described in step 6.

Calculation of effective leak area:

9. Using the national laboratory's model, an effective leak area (ELA) is determined. The results of step 6 give the ELA for the whole house. The results of step 8 give the ELA for the whole house less the air distribution system. The difference between the two is the ELA of the air distribution system. Locate leaks in the air distribution system by means of a smoke stick.
10. Pressurize the house to 0.04 to 0.048 in H_2O (10 to 12 Pa) using the blower door.
11. Using a smoke pencil, check all supply and return registers to observe how fast the smoke goes into them. Vents with rapid smoke movement indicate a duct (or air handler) leak nearby.

After repairing the duct system leaks, repeat these tests in order to observe the decrease in total house ELA and duct system ELA.