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Authors

James B. Cummings and Chuck Withers

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(321) 638-1000

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Balanced Return Air, Duct Airtightness, and Combustion/Dilution Air Code Compliance in 40 Central Florida Homes

James B. Cummings

Chuck Withers

This report has been extracted from a larger report titled “Florida Building Code – Enhance Florida’s Building to Next-Generation Energy & Mechanical Codes and Enrich Compliance”, FSEC-CR-1678-06, November 29, 2006, which can be found at <http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1678-06.pdf>

Background and Project Description

Per the project scope of work, 40 houses were to be tested to investigate the degree to which specific elements of the Florida Building Code were being implemented, and the degree to which that implementation was achieving a successful outcome. Three specific codes issues were studied:

1. the balanced return air requirements of the Florida Mechanical Code
2. the degree to which duct systems are being built to be substantially airtight
3. the degree to which combustion/ dilution air is being provided for combustion equipment.

Test houses were obtained from four counties (# houses in parentheses); Brevard (16), Martin (6), Flagler (6), and Polk (3). The method of obtaining those houses is described in the following.

To obtain volunteer homes built since March 1, 2002 (when the return air requirements of the code went into effect), lists of homes constructed since that date were obtained from building departments in four counties. Letters were sent to 605 homes in four counties (Brevard 200, Martin 141, Flagler 109, Polk 151). Name and address information for each candidate home was obtained over the internet from building departments and on-line tax roles. A business reply post card accompanied the letter. When cards were received back from respondents, they were contacted to find out details about their house. Some screening was done; seeking houses generally between 1000 square feet and 3300 square feet, having one AC system, and with no registers higher than 12 feet. We also limited mailings so that we would not test more than five homes by one AC contractor or one builder. Coordination of field-testing scheduling was maintained using FileMaker Pro database on the FSEC intranet.

Two types of tests were performed.

- 20 of the 40 homes had the shorter test, which includes house airtightness, system airflows, pressure pan test, pressure mapping, and characterization of the location and dimensions of the return air systems.

- The other 20 homes had the extended test that includes all of the testing and inspection from the shorter test plus a duct system airtightness test and a tracer gas decay infiltration test.

Financial incentives were paid to the homeowners; \$40 to those with the shorter test and \$60 to those with the longer test.

Field test data was assembled into a spreadsheet file. A copy of this database is included on a separate CD which is included with this final report.

RESEARCH FINDINGS – House Characteristics

Following are some descriptive details about the 40 houses.

House size. The average house size was 2014 ft². A distribution of house size is shown in Figure 1.

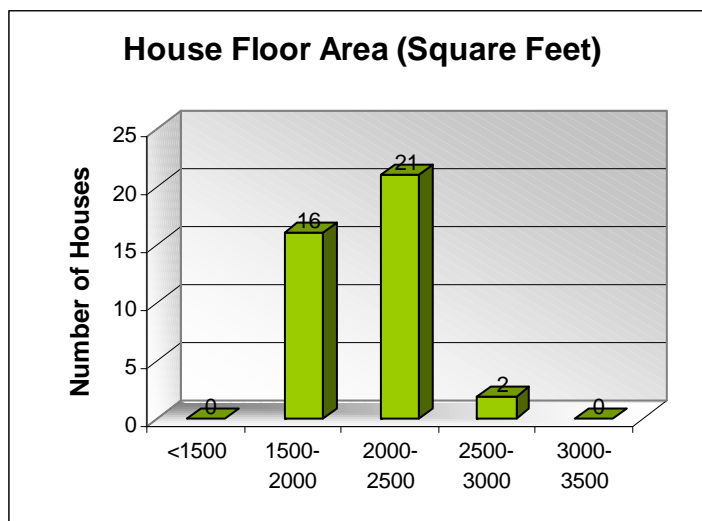


Figure 1. Distribution of house size.

Age of house.

- 6 houses were built (completed) in 2002.
- 15 houses were built (completed) in 2003.
- 19 houses were built (completed) in 2004.
- None of the houses were built (completed) in 2005 or 2006.

AHU location.

- 22 AHUs were in garage.
- 14 AHUs were indoors.
- 4 AHUs were in the attic.

Number of stories.

- 34 houses were one-story.
- 6 houses were two-story.

AC system size. The average AC system size was 3.54 tons, or 1.79 tons per 1000 ft².

Airtightness. Blower door tests were performed on all 40 homes. The average house airtightness was 5.2 ACH50. (ACH50 is the air changes per hour leakage when the house is depressurized or pressurized to 50 pascals with respect to outdoors.) The leakiest house had an ACH50 of 7.8, still moderately tight. The tightest house had an ACH50 of 1.6, or very airtight. A distribution of airtightness is shown in Figure 2.

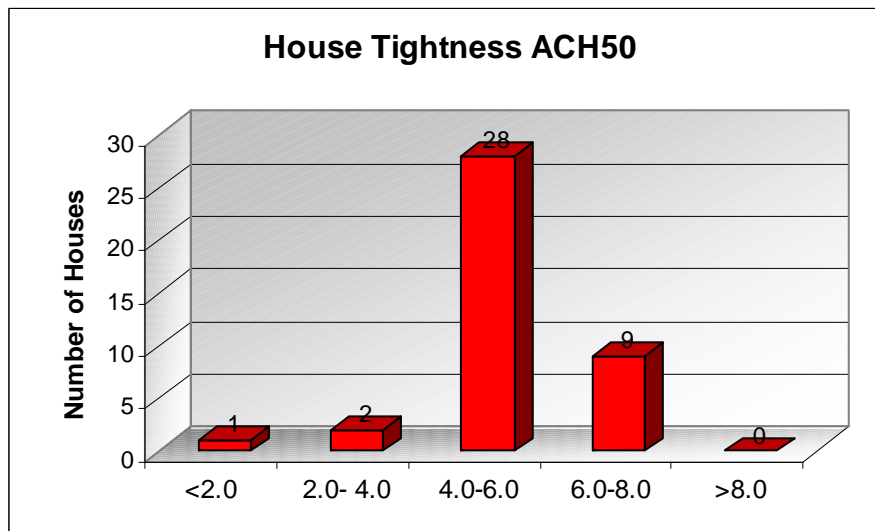


Figure 2. Distribution of house airtightness.

RESEARCH FINDINGS – Balanced Return Air

Code Requirements.

40 houses were tested in this project to determine the extent to which they were in compliance with Section 601.4 of the Mechanical Code (2004), “Balanced Return Air”, which reads as follows --

601.4 Balanced return air.

Restricted return air occurs in buildings when returns are located in central zones and closed interior doors impede air flow to the return grill or when ceiling spaces are used as return plenums and fire walls restrict air movement from one portion of the return plenum to another. Provisions shall be made in both residential and commercial buildings to avoid unbalanced air flows and pressure differentials caused by restricted return air . Pressure differentials across closed doors where returns are centrally located shall be limited to 0.01 inch WC (2.5 pascals) or less. Pressure differentials across fire walls in ceiling space plenums shall be limited to 0.01 inch WC (2.5 pascals) by providing air duct pathways or air transfer pathways from the high pressure zone to the low zone.

Exceptions:

- 1. Transfer ducts may achieve this by increasing the return transfer one and one-half times the cross-sectional area (square inches) of the supply duct entering the room or space it is serving and the door having at least an unrestricted 1-inch (25 mm) undercut to achieve proper return air balance.*
- 2. Transfer grilles shall use 50 square inches (.03 m²) (of grille area) to 100 cfm (.05 m³/s) (of supply air) for sizing through-the-wall transfer grilles and using an unrestricted 1-inch (25 mm) undercutting of doors to achieve proper return air balance.*
- 3. Habitable rooms only shall be required to meet these requirements for proper balanced return air excluding bathrooms, closets, storage rooms and laundry rooms, except that all supply air into the master suite shall be included.*

Compliance with the Balanced Return Air Requirements

In an earlier study of 70 Central Florida homes (testing done in 1989 but houses were five years or less old), it was found that the pressure differential across closed interior doors (with all interior doors closed at once) averaged 9.1 pascals¹. In the 40 homes of this study, the comparable pressure averaged 2.6 pascals. This indicates a 71% reduction in pressure differential across the closed doors.

There are a couple of factors that have changed in homes. Because of the Balanced Return Air requirements of the code, most homes built since March 1, 2002 have return

¹ James B. Cummings and Charles R. Withers, Jr.. "Unbalanced Return Air in Residences: Causes, Consequences, and Solutions". ASHRAE Transactions Vol 112, Part 1, January 2006.

ducts or return transfers to most rooms. This tends to relieve pressure. Additionally, houses have become considerably more airtight. The average ACH50 for the 1989 testing was 7.2 ACH50, whereas the 40 homes in this study have an average envelope airtightness of 5.2 ACH50. The tighter the envelope of a vessel, the greater the pressure differential that will result when exposed to unbalanced air flows.

According to Section 601.4 of the Florida Mechanical Code, return pathways (return air ducts or return air transfers) are required only for habitable rooms. Bathrooms, storage rooms, mechanical rooms, closets, and utility rooms do not require return air. The exception is that all supply air into the master suite (whether going to closets, bathrooms, etc.) shall be considered when providing return air to the master suite. In 38 of the 40 houses, the number of rooms that required return air pathways (whether ducted or transfers) was either 3, 4, or 5. One home required 6 return pathways, and it had two AC systems. One home required only 2 return pathways.

For rooms that require return air pathways, there are three ways that Section 601.4 can be satisfied.

1. The pressure differential across the closed door can be 2.5 pascals or less.
2. Provide a return transfer from the closed room to the central zone equal in size to 1.5 times the cross-sectional area of the supply duct or ducts that serve that room.
3. A through-the-wall transfer can be sized to 50 square inches (grill area) per 100 cfm of supply air (to that room) plus an unrestricted 1-inch door uncut.

For the entire sample of 40 homes, 147 rooms were required to meet Section 601.4 of the Mechanical code. In total, 87 of those 147 rooms (or 59%) were in compliance. 60 of the 147 rooms (or 41%) were not in compliance. Of the 40 homes, a total of 11 were in full compliance, meaning that all rooms requiring return air pathways met the 2.5 pascal requirement or one of the exceptions. In 6 of the 40 homes, none of the rooms were in compliance with the code. In 4 of the 40 homes, no return pathways were provided (as if the builder was unaware of the code requirement). Note that some of the rooms that met the 2.5 pascals requirement did not have designated return air pathways (either ducted returns or return transfers).

The Importance of Equipment Sizing – Comparison of Two Houses

Airflow rates are very important in achieving balanced return air. Consider a comparison of Houses 1 and 5 (Table 1). In both houses four rooms were subject to the balanced return air requirements.

In House 1, two rooms (Master Bedroom and Office) had ducted returns. Two other bedrooms had no return pathways but still met the code requirement because pressure drop across the closed doors was only 1.4 pascals in each case.

In House 5, all 4 rooms had transfer ducts. Pressure differentials across the closed doors ranged from 2.8 to 7.0 pascals, with an average of 4.6 pascals. None of the transfer ducts were large enough to meet the sizing requirements of Exception 1 which calls for a return

transfer with a cross-sectional area at least 1.5 times the cross-sectional area of the supply duct or ducts that serve that space. The cumulative cross-sectional area of the supply ducts (to all four rooms) was 110 in². The return transfers had a total cumulative return transfer duct size of 135 in², or 123% of the size required. In terms of the door undercut, two rooms had 1.0 inch undercut, one had a 7/8th inch undercut, and one had a 3/4th inch undercut. Overall, the return air requirements of the code were very nearly complied with, and yet the pressure differentials were much higher at this house compared to House 1.

What can account for the dramatic difference between Houses 1 and 5? Specifically, in House 1, two bedrooms had no return pathways and yet had pressure differentials of only 1.4 pascals. Furthermore, door undercuts were only 1/4th inch for each of these two rooms. In House 5, all four rooms had return transfers that were not greatly undersized and had door undercuts of nearly 1 inch. So again, what accounts for the difference? The answer lies with the AC system airflow rate (Table 1).

Table 1. Comparison of house, AC system, and airflow sizing characteristics of two residences.

	House 1	House 5
Floor area (ft ²)	2115	1960
AC tons	3.3	4.0
AC tons/1000 ft ²	1.56	2.04
AC cfm	872	1718
AC cfm/100 ft ²	41.2	87.7
AC cfm/ton	265	430
Average closed door dP (Pa)	0.75	4.58
Average door undercut (in)	0.233	0.906
House ACH50	4.9	4.2

- House 1 AC system is sized at 1.56 tons per 1000 ft² while House 5 has 2.04 tons per 1000 ft². The average size is 1.75 tons per 1000 ft² for the 40-house sample.
- House 1 cfm/ton is 265 per ton while House 5 cfm/ton is 430. So not only is the AC system capacity for House 5 (most likely) oversized, the cfm/ton is oversized as well. Note that while the outdoor AC unit for House 5 is 4 tons, the air handler unit is rated for 5 tons.
- AC system cfm/ton at House 1 is 38% lower than at House 5.
- AC system cfm/100 ft² at House 1 is 53% lower than at House 5.
- Lower airflow rates into closed rooms yield reduced pressure differential.
- While the airflow rate at House 1 is too low (typically much below 300 cfm/ton is considered risky), the airflow rate at House 5 is too high. An excessive airflow rate leads to a warmer cooling coil temperature and less indoor RH control. It also leads to higher pressure differentials across closed interior doors.

- This points to the importance of not over-sizing AC systems and not over-sizing air handlers.

Summary of House Pressure Differentials

When the air handlers were OFF and interior doors were open, house pressure averaged -0.35 pascals with reference to (wrt) outdoors. Pressures will be wrt outdoors unless stated otherwise. When the AHUs were turned ON, house pressure went to -0.18 pascals. While this value is negative, the impact created a slight pressurization compared to AHU OFF. When the AHUs were turned ON and all interior doors were closed, house pressure (in the central zone) went to -1.53 pascals, on average.

Pressure in the closed rooms averaged $+2.45$ pascals wrt the central zone. A distribution of closed room pressure differentials is shown in Figure 3.

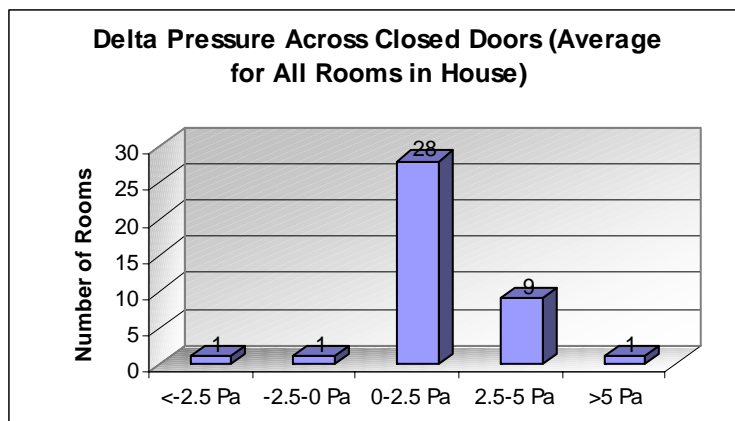


Figure 3. Distribution of average pressure differential across closed interior doors for 40 houses.

Provision of return pathways, whether ducted returns or return transfers, yields substantial reduction in closed-door pressure differentials (Table 2). For houses with 0 to 20% of rooms in compliance with the code, average pressure differential (dP) was 5.5 pascals. For those with 41% to 60% of rooms in compliance, average dP was 2.7 pascals. For those with 81% to 100% of rooms in compliance, average dP was 0.7 pascals. There is a systematic trend of decreasing pressure differential with greater compliance with the code. Clearly 100% successful implementation of the code almost completely eliminates the closed-door pressure differentials.

The degree of house central-zone depressurization is also directly controlled by the degree of compliance with the balanced return air requirements of the code (Table 2). The same can be said for house infiltration rate, however, with somewhat weaker correlation. The amount of increase in house infiltration rate resulting from closure of

interior doors shows a general decline as compliance with the code requirements increases (Table 2).

Table 2. Closed-door pressure differential versus the percent of rooms in compliance with the code.

For Each House, % of Rooms in Code Compliance	Average dP Across Closed Doors (Pa)	House (Central Zone) Pressure wrt Out	Increase in House Infiltration with Doors Closed (ach)
0% – 20%	5.50	-4.0	0.12
21% – 40%	4.67	-2.9	0.18
41% – 60%	2.68	-0.97	0.09
61% – 80%	1.65	-0.80	0.05
81% - 100%	0.71	-0.53	0.02
ALL	2.45	-1.38	0.06

37 of the 147 rooms requiring return pathways (from the 40 houses) were provided with ducted returns, meaning that ductwork ran from the closed room back to the return side of the air handler.

39 of the 147 rooms requiring return pathways (from the 40 houses) were provided with no return pathway other than door undercut.

71 of the 147 rooms requiring return pathways (from the 40 houses) were provided with return transfers (either ducted above the ceiling or a through-the-wall transfer). Of those 71 rooms, 28 experienced pressure differential greater than 2.5 pascals with the door closed (transfer open). When the return transfer was sealed (using masking material on one end of the transfer), the number of rooms that experienced pressure differential greater than 2.5 pascals increased to 61. Pressure drop across the closed doors of those 71 rooms averaged 2.42 pascals. When those return transfers were temporarily sealed, the pressure differential across the closed doors went to an average 6.53 pascals.

The closed door pressure differential is strongly related to the size of the return transfer. In Figure 4, one can see a rather strong relationship between pressure drop across closed doors and the transfer cross-sectional area per 100 cfm of supply air.

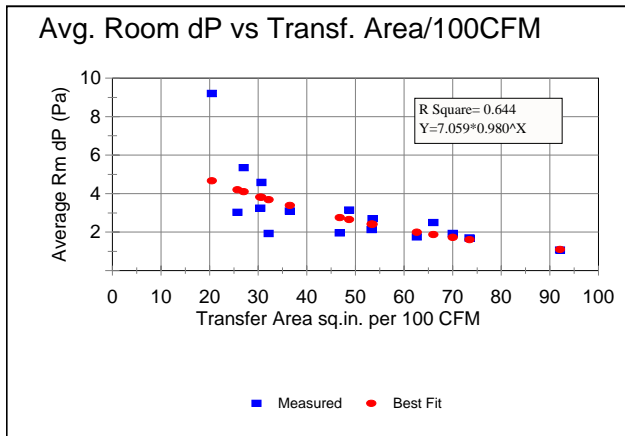


Figure 4. Pressure drop across closed interior doors versus the size of return transfer pathways.

Tracer Gas Assessment of Unbalanced Return Air

In 20 houses, tracer gas decay testing was used to characterize the house infiltration rate, which is the exchange rate of air between indoors and outdoors, expressed as air changes per hour (ach). An air change rate of 1 (ach = 1.0) means that during 1 hour, the amount of air that leaves the house and is replaced by air from outdoors (or from a house buffer zone) is equal to the house air volume.

A small quantity of tracer gas (nitrous oxide or sulfur hexafluoride) was injected into the return grill and allowed to mix in the house for about 20 minutes. A target concentration of 15 to 40 ppm (parts per million) was typical. Upon mixing, room tracer gas concentrations were measured at 10 to 15 minute time steps typically for a period of 60 to 90 minutes. The rate of decay of the tracer gas concentration was used to calculate the infiltration rate using the following formula.

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

where

N is the number of minutes of the test

ln is natural log

C_i is the initial concentration of tracer gas (ppm)

C_f is the final concentration of tracer gas (ppm).

The tracer gas decay test was performed twice; 1) once with the air handler running continuously with interior doors open and 2) once with the air handler running continuously with interior doors closed.

On average, the infiltration rate of the house with the air handler running was 0.326 ach (Table 3). On average, the infiltration rate of the house with the air handler running and interior doors closed was 0.385 ach, or 18% higher than with the doors open. The expectation is that door closure would increase the infiltration rate because door closure

increases pressure differentials across the building envelope. In 15 of the 20 houses the infiltration rate is higher with the doors closed. In 5 cases the infiltration rate is higher with the doors open. In 4 of those 5 cases, the differential is very nearly zero, so we can conclude that there is essentially no change in infiltration rate as a function of door closure in those rooms. The only exception is House 37. After examining the weather data (wind and temperature), we can gain no further insight into why the infiltration rate was 43% higher with the doors open, the reverse of the normal pattern.

If House 37 is excluded from the analysis, the infiltration rate of the house with the air handler running (doors open) declined to 0.310 ach. On average, the infiltration rate of the house with the air handler running and interior doors closed declined to 0.382 ach, or 23% higher than with the doors open.

By contrast, in a study done in 1989 in 50 homes, the average infiltration rate increased from 0.46 ach to 0.60 when interior doors were closed (AHU ON in both tests)². For these 50 homes, door closure increased the infiltration rate by 30%. Note that the infiltration rate with the air handler operating (doors open) was 48% higher in the houses tested in 1989 compared to the current study (0.46 ach versus 0.31 ach). (Note that the houses in the 1989 were 0 to 5 years old at the time of testing.) On average, these homes were built in 1987. We can conclude that houses built in the past few years have less duct leakage (at least leakage to outdoors) and that the infiltration caused by door closure has declined substantially, from an infiltration increment of 0.14 to 0.07 ach. The reduced infiltration increase caused by closed doors would seem to be the result of both reduced pressure differentials across closed doors (as a result of the Balanced Return Air requirements of the code that went into effect March 1, 2002) and tighter building envelopes (ACH50 was 7.2 in 1989 study and 5.1 in the current study).

Table 3. House infiltration rate with interior doors open and closed.

House #	Infiltration Rate (ach) [with AHU ON]		
	Doors open	Doors closed	Delta-ach
1	0.202	0.201	-0.002
2	0.578	0.598	0.020
3	0.453	0.503	0.050
4	0.254	0.310	0.056
6	0.157	0.173	0.016
7	0.350	0.289	-0.061
10	0.320	0.300	-0.019
18	0.170	0.230	0.059
20	0.198	0.389	0.190
22	0.356	0.539	0.183
24	0.241	0.362	0.121
27	0.408	0.408	0.000
28	0.332	0.324	-0.008
29	0.309	0.369	0.060

² Cummings, J.B., Moyer, N., and Tooley, J.J., "Radon Pressure Differential Project, Phase II: Infiltration," FSEC-CR-370-90, Florida Solar Energy Center, Cocoa, FL, November 1990.

30	0.217	0.369	0.152
31	0.406	0.571	0.164
33	0.409	0.509	0.100
34	0.289	0.562	0.273
37	0.639	0.446	-0.194
40	0.238	0.244	0.006
AVG	0.326	0.385	0.058

House airtightness also, in part, explains the infiltration rates with AHU operating and doors closed. R^2 is 0.39, indicating that about 39% of the variation in the house infiltration rate is explained by the house envelope airtightness alone (Figure 5). When the doors are open and the AHU is ON, about 25% of the variation in house infiltration is explained by the house envelope airtightness (Figure 6).

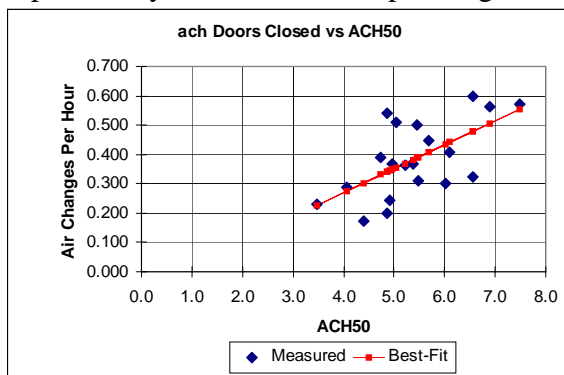


Figure 5. House infiltration rate (ach) with AHU ON and interior doors closed.
 $Y=0.082*X-0.06$ $R^2=0.385$

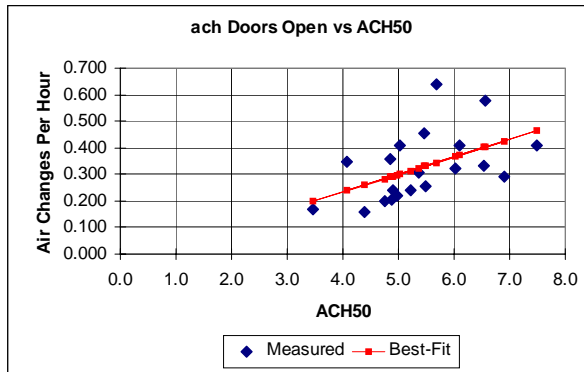


Figure 6. House infiltration rate (ach) with AHU ON and interior doors open.
 $Y=0.066*X-0.03$ $R^2=0.249$

RESEARCH FINDINGS – Duct Leakage

Duct system airtightness and air leakage was characterized in 20 of the 40 homes. This testing was designed to determine the degree to which duct systems in new Florida homes

are achieving airtight construction. The Florida Mechanical Code does not specify an acceptable air leakage amount. Rather it provides proscriptive measures.

Following in italics is language from the Florida Mechanical Code (2004) regarding the airtightness of duct systems. This is not all language regarding that topic, but represents the majority of all of the material addressing the airtightness of ductwork.

Florida Mechanical Code (2004) Language

All enclosures which form the primary air containment passageways for air distribution systems shall be considered ducts or plenum chambers and shall be constructed and sealed in accordance with the applicable criteria of this section.

603.1.1 Mechanical fastening.

All joints between sections of air ducts and plenums, between intermediate and terminal fittings and other components of air distribution systems, and between subsections of these components shall be mechanically fastened to secure the sections independently of the closure system(s).

603.1.2 Sealing.

Air distribution system components shall be sealed with approved closure systems.

603.1.7 Approved closure systems.

Closure system materials, including adhesives when used, shall have a flame spread rating not over 25 without evidence of continued progressive combustion and a smoke-developed rating not over 50 when tested in accordance with the ASTM E 84. The following closure systems and materials are approved for air distribution construction and sealing for the applications and pressure classes prescribed in Sections [603.2](#) through [603.10](#):

1. Metal Closures.

a. Welds applied continuously along metal seams or joints through which air could leak.

b. Snaplock seams, and grooved, standing, double-corner, and Pittsburgh-lock seams as defined by SMACNA, as well as all other rolled mechanical seams. All seams shall be rolled or crimped.

2. Gasketing, which achieves a 25/50 flame spread, smoke density development rating under ASTM E 84 or UL 723, provided that it is used only between mated surfaces which are mechanically fastened with sufficient force to compress the gasket and to fill all voids and cracks through which air leakage would otherwise occur.

3. Mastic Closures. Mastic shall be placed over the entire joint between mated surfaces. Mastics shall not be diluted. Approved mastics include the following:

- a. *Mastic or mastic plus embedded fabric systems applied to fibrous glass ductboard that are listed and labeled in accordance with the UL 181A, Part III.*
- b. *Mastic or mastic plus embedded fabric systems applied to nonmetal flexible duct that are listed and labeled in accordance with the UL 181B, Part II.*
- c. *Mastic ribbons, which achieve a 25/50 flame spread, smoke density development rating under ASTM E 84 or UL 723, provided that they may be used only in flange-joints and lap-joints, such that the mastic resides between two parallel surfaces of the air barrier and that those surfaces are mechanically fastened.*
- 4. *Tapes. Tapes shall be applied such that they extend not less than 1 inch (25 mm) onto each of the mated surfaces and shall totally cover the joint. When used on rectangular ducts, tapes shall be used only on joints between parallel rigid surfaces and on right angle joints. Approved tapes include the following:*
 - a. *Pressure-sensitive tapes.*
 - 1) *Pressure-sensitive tapes applied to fibrous glass ductboard that are listed and labeled in accordance with the UL 181A, Part I.*
 - 2) *Pressure-sensitive tapes applied to nonmetal flexible duct that are listed and labeled in accordance with the UL 181B, Part I.*
 - b. *Heat-activated tapes applied to fibrous glass ductboard that are listed and labeled in accordance with the UL 181A, Part II.*
- 5. *Aerosol Sealant. Such sealants shall be installed by manufacturer-certified installers following manufacturer instructions and shall achieve 25/50 flame spread/smoke density development ratings under ASTM E 84 or UL 723.*

603.5.6.2 Duct core to duct fitting, approved closure systems.

The reinforced lining shall be sealed to the duct fitting using one of the following sealing materials which conforms to the approved closure and mechanical attachment requirements of Section [603.1](#):

- 1. *Gasketing.*
- 2. *Mastic, mastic-plus-embedded fabric, or mastic ribbons.*
- 3. *Pressure-sensitive tape.*
- 4. *Aerosol sealants, provided that their use is consistent with UL 181.*

603.5.6.3 Duct outer jacket to duct collar fitting.

The outer jacket of a flexible duct section shall be secured at the juncture of the air distribution system component and intermediate or terminal fitting in such a way as to prevent excess condensation. The outer jacket of a flexible duct section shall not be

interposed between the flange of the duct fitting and the flexible duct, rigid fibrous glass duct board, or sheet metal to which it is mated.

603.7 Air-handling units.

All air-handling units shall be mechanically attached to other air distribution system components. Air-handling units located outside the conditioned space shall be sealed using approved closure systems conforming to the approved closure and mechanical application requirements of Section [603.3](#).

603.8 Cavities of the building structure.

Cavities in framed spaces, such as dropped soffits and walls, shall not be used to deliver air from or return air to the conditioning system unless they contain an air duct insert which is insulated in accordance with Table 13-410.1.ABC.2.2 or Table 13-610.1.ABC.2.1 of Chapter 13 of the Florida Building Code , Building and constructed and sealed in accordance with the requirements of Section [603.1](#) appropriate for the duct materials used.

Exception: *Return air plenums.*

Cavities designed for air transport such as mechanical closets, chases, air shafts, etc. shall be lined with an air barrier and sealed in accordance with Section [603.9](#) and shall be insulated in accordance with Table 13-410.1.ABC.2.2 or Table 13-610.1.ABC.2.1 of Chapter 13 of the Florida Building Code, Building.

Building cavities which will be used as return air plenums shall be lined with a continuous air barrier made of durable non-porous materials. All penetrations of the air barrier shall be sealed with a suitable long-life mastic material.

Exception : *Surfaces between the plenum and conditioned spaces from which the return/mixed air is drawn.*

Building cavities beneath a roof deck that will be used as return air plenums shall have an insulated roof with the insulation having an R-value of at least R-19.

603.9 Mechanical closets .

The interior surfaces of mechanical closets shall be sheathed with a continuous air barrier as specified in Section [603.9.1](#) and shall be sealed with approved closure systems as specified in Section [603.9.2](#) . All joints shall be sealed between air barrier segments and between the air barriers of walls and those of the ceiling, floor and door framing. All penetrations of the air barrier including, but not limited to, those by air ducts, plenums, pipes, service lines, refrigerant lines, electrical wiring, and condensate drain lines shall be sealed to the air barrier and approved closure systems.

Exception: *Air passageways into the closet from conditioned space that are specifically designed for return air flow.*

Through-wall, through-floor and through-ceiling air passageways into the closet shall be framed and sealed to form an airtight passageway using approved air duct materials and approved closure systems.

Duct penetrations through any part of the ceiling, walls or floor of a mechanical closet shall have sufficient space between surrounding ceiling, walls or floor and any duct or plenum penetration to allow for sealing of the penetration and inspection of the seal.

Clothes washers, clothes dryers, combustion water heaters and atmospheric combustion furnaces shall not be located in mechanical closets used as return air plenums.

603.9.1 Approved air barriers.

The following air barriers are approved for use in mechanical closets:

- 1. One-half-inch-thick (12.7 mm) or greater gypsum wallboard, taped and sealed.*
- 2. Other panelized materials having inward facing surfaces with an air porosity no greater than that of a duct product meeting Section 22 of UL 181 which are sealed on all interior surfaces to create a continuous air barrier.*

603.9.2 Approved closure systems.

The following closure systems are approved for use in mechanical closets:

- 1. Gypsum wallboard joint compound over taped joints between gypsum wallboard panels.*
- 2. Sealants complying with the product and application standards of Section [603.4.2.1](#) for fibrous glass ductboard;*
- 3. A suitable long-life caulk or mastic compliant with the locally adopted mechanical code for all applications.*

603.10 Enclosed support platforms.

Enclosed support platforms located between the return air inlet(s) from conditioned space and the inlet of the air handling unit or furnace, shall contain a duct section constructed entirely of rigid metal, rigid fibrous glass duct board, or flexible duct which is constructed and sealed according to the respective requirements of Section [603.1](#) and insulated according to the requirements of Section 13-410.1.ABC.2.2 and 13-610.1.ABC.2.1 of Chapter 13 of the Florida Building Code, Building .

The duct section shall be designed and constructed so that no portion of the building structure, including adjoining walls, floors and ceilings, shall be in contact with the return air stream or function as a component of this duct section.

The duct section shall not be penetrated by a refrigerant line chase, refrigerant line, wiring, pipe or any object other than a component of the air distribution system.

Through-wall, through-floor and through-ceiling penetrations into the duct section shall contain a branch duct which is fabricated of rigid fibrous glass duct board or rigid metal and which extends to and is sealed to both the duct section and the grille side wall surface. The branch duct shall be fabricated and attached to the duct insert in accordance with Section [603.3](#) or Section [603.4.2](#), respective to the duct type used.

Duct System Testing

Three types of tests were performed to provide measurement or approximate measurement of the leakage characteristics of the duct system.

- Duct system airtightness test
- Return leak fraction test
- Pressure pan test

Duct Airtightness Test

To perform this test, the air handler was turned OFF. Masking material was placed over the return and supply grills. Two calibrated fans (Duct Blasters) were connected to the return and supply sides of the system. Each testing fan was then turned ON, and the two sides of the system were depressurized to -25 pascals wrt the house. A digital manometer with resolution to $1/10^{\text{th}}$ pascal was used to determine that there was no pressure differential between the return and supply sides of the system. The air flow rate through the two Duct Blasters was then recorded. The test result is called Q_{25} , total (duct leakage of the duct system to both indoors and outdoors). The test also provides $Q_{25,r}$ and $Q_{25,s}$, leakage on the return and supply sides of the system.

The test was then repeated with the house also depressurized to -25 pascals. In this test circumstance, with both the ductwork and the house at -25 pascals wrt outdoors, the pressure difference between the house and the ductwork was then 0.0 pascals. The test result is called Q_{25} (duct leakage of the duct system to outdoors). Q_{25} is more relevant to the air infiltration and energy consequences of duct leakage than $Q_{25,\text{total}}$. The definitions of Q_{25} and $Q_{25,\text{total}}$, and the duct system test methods, are found in ASHRAE Standard 152³.

³ American Society of Heating, Refrigerating, and Air Conditioning Engineers, ASHRAE Standard 152-2004, "Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems", January 2004.

Note that Q_{25} is duct air leakage at the (test) pressure of 25 pascals. Actual duct air leakage will be different because actual duct operating pressure in the ductwork will be different than 25 pascals. Furthermore, duct system (or more accurately “air distribution system”) pressure varies throughout the system with the greatest pressures occurring near the blower. In a typical system, actual operating pressures might be –30 at return grille, –40 at return plenum, –140 at the air handler, +50 at supply plenum, +30 at supply main, +25 at supply junction boxes, +15 at supply branches, and only about +5 pascals at supply boots. Therefore, the amount of actual duct leakage that occurs depends upon where in the system the leaks actually occur and what the operating pressure differentials are at those locations. In some respects, Q_{25} is not a particularly good predictor of actual air distribution system air leakage. It is, however, a good method for measuring the equivalent hole size of all of the leak sites in the ductwork. In other words, Q_{25} is an indication of the (cumulative) size of the holes in the duct system. Actual duct leakage (Q) is a function of the hole size (Q_{25}) and the driving force across that hole (pressure differential).

ASHRAE Standard 152 provides a method for calculating actual leakage based on Q_{25} and duct operating pressure. The equation is

$$Q = Q_{25} \times (dP_a/25)^{0.60}$$

Where Q is the actual airflow rate of the duct leak and dP_a is the actual duct operating pressure.

This calculation of Q yields a more realistic duct system air leakage amount. However, it is, in practice, very difficult to characterize the duct system operating pressure (dP_a) since to do so requires measuring duct system pressures at multiple locations and requires knowledge of what proportion of the duct leak “holes” are located at which locations. This knowledge is rarely obtained for a specific duct system. Consider that if the duct leakage (Q_{25}) is located primarily in the air handler, which might be operating at –140 pascals, the leakage may be five times greater than if the leaks are primarily at the connection of branch duct to supply boot.

Summary of Q_{25} Testing Results

The Florida Mechanical Code has no specific duct system airtightness requirement for Florida residences. However, every new home must have an energy rating based on the Florida Energy Code. To pass, each home must achieve a rating score of 100 points or less. One measure that can be used to meet the rating target is a tight duct system. Specifically, a “substantially airtight duct system” must have a Q_{25} value less than or equal to 3% of house floor area (ft^2) and $Q_{25,\text{total}}$ less than or equal to 9% of house floor area. There are other factors that can reduce the energy score such as the location of the ductwork, the location of the air handler, and a tight air handler credit (cabinet leakage of 2% or less of system flow at 250 pascals), but we will not go into those here.

Looking at Table 4, one can see that Q_{25}/sf (sf = square foot) is less than or equal to 3% in only 3 of 20 houses. In each of those three cases, $Q_{25,\text{total}}/\text{sf}$ is less than or equal to 9%, which means that these three houses would qualify for the “substantially airtight duct system” credit. This also means that 17 of the 20 houses would not qualify for the “substantially airtight duct system” credit.

While 3% is considered the cut-off for a “substantially airtight duct system” (based on Q_{25}), the average of these 20 homes has leakage of 5.7% of house floor area (ft^2), or nearly twice the standard. In two cases, duct leakage (to out) was greater than 11.5% of house floor area.

Table 4. Duct system airtightness testing results expressed in cfm, including total leakage ($Q_{25,\text{total}}$) and leakage to out (Q_{25}). Note that “sf” is square feet of house floor area.

House #	$Q_{25,r,\text{total}}$	$Q_{25,s,\text{total}}$	$Q_{25,\text{total}}$	$Q_{25,\text{total}}/\text{sf}$	$Q_{25,r}$	$Q_{25,s}$	Q_{25}	Q_{25}/sf	Q_{25}/ton
1	145	257	402	19.0%	63	107	170	8.0%	51.7
2	164	132	296	17.2%	131	68	199	11.6%	61.2
3	28	230	258	10.8%	22	120	142	5.9%	28.5
4	38	130	168	12.3%	16	30	46	3.4%	23.2
6	64	141	205	10.1%	16	80	96	4.7%	29.5
7	38	200	238	11.7%	29	87	116	5.7%	34.8
10	NA	267	267	11.5%	NA	139	139	6.0%	34.8
18	108	15	123	6.4%	12	24	36	1.9%	12.7
20	111	104	215	10.2%	30	49	79	3.8%	20.6
22	668	146	814	42.6%	57	108	165	8.6%	45.0
24	30	142	172	7.4%	5	49	54	2.3%	15.4
27	10	116	126	5.2%	10	63	73	3.0%	14.2
28	41	84	125	9.6%	21	53	74	5.7%	40.4
29	52	161	213	10.6%	25	81	106	5.3%	30.3
30	24	153	177	9.9%	3	89	92	5.1%	32.1
31	217	246	463	16.6%	132	193	325	11.7%	69.0
33	80	215	295	11.0%	45	114	159	5.9%	31.8
34	NA	86	86	3.9%	NA	27	27	1.2%	14.0
37	67	229	296	13.0%	41	129	170	7.5%	35.5
40	54	141	195	12.8%	16	87	103	6.7%	43.8
AVG	107.7	159.7	267.4	12.6%	37.4	84.8	118.5	5.70%	34.5

Duct leakage had also been examined in an earlier study of 20 (primarily central) Florida homes that had been built during 2001 or 2002⁴. Q_{25} in that set of 20 homes was 97 cfm, compared to the 119 cfm for this current project’s 20 homes that were built between March 2002 and December 2004. However, when Q_{25} is normalized to floor area and tons of AC capacity, the more recently built houses have duct airtightness as tight or tighter than the 2001-2002 group (Table 5).

⁴ Cummings, James B., Chuck Withers, Janet McIlvaine, Jeff Sonne, and Matt Lombardi. “Field Testing and Computer Modeling to Characterize the Energy Impacts of Air Handler Leakage; Final Report”, FSEC-CR-1357-02, Florida Solar Energy Center, Cocoa, FL, August 2002.

Table 5. Duct system airtightness testing results expressed in cfm, cfm/ft², and cfm/ton from two studies; houses built in 2001 and 2002 and houses built in 2002-2005 (current study).

	Floor area served by tested AC system (ft ²)	Q ₂₅	Q ₂₅ /ft ²	Q ₂₅ /ton
20 2001-02 houses	1696	97	0.064	31.6
20 2002-05 houses (current study)	1979	119	0.057	31.5

From the same 2001-2002 study, actual duct system operating pressures were examined. Based on the measured air distribution pressures and careful examination of the distribution (location) of the leakage sites, estimates of actual duct leakage were made. On average, actual duct leakage (Q) was found to be 54% greater than the leakage at 25 pascals (Q₂₅). If we use the same relationship between Q₂₅ and, then Q, system leakage to/from outdoors (Q) is estimated to be 182 cfm or 15.2% of total system airflow for the 20 houses of the current study.

From this analysis, we can conclude that duct systems are still not being built with appropriate airtightness. The relatively high levels of duct leakage have consequences for house infiltration rates, house heating cooling energy use, and potential IAQ issues (transported contaminants from the garage or attic, and elevated indoor RH).

Tracer Gas Assessment of Duct Leakage

Tracer gas decay testing also sheds light on duct leakage. The natural infiltration rate (when all HVAC is turned OFF) was not measured by tracer gas. However, past research has demonstrated that the natural infiltration rate of a Florida home can be predicted based on the blower door test. Two separate studies, one of 70 homes and another of 100 homes found that dividing ACH50 by 40 yields good prediction of natural infiltration, on average⁵⁶. ACH50 and predicted natural infiltration are shown in columns 2 and 3 of Table 6. Column 4 is the measured infiltration rate with the AHU ON continuously with interior doors open. Duct leakage, therefore, is indicated to increase the house infiltration rate by 142%, from 0.135 to 0.326.

Table 6. House airtightness and infiltration rates, and duct leakage measurements in 20 homes. Note that ach with AHU OFF is calculated based on ACH50/40.

House #	ACH50	AHU OFF	AHU ON	Q _{25,r}	Q _{25,r}	Return Leak
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⁵ Cummings, J.B., Moyer, N., and Tooley, J.J., "Radon Pressure Differential Project, Phase II: Infiltration," FSEC-CR-370-90, Florida Solar Energy Center, Cocoa, FL, November 1990c.

⁶ Cummings, J.B., Tooley, J.J., and Moyer, N., "Investigation of Air Distribution System Leakage and Its Impact in Central Florida Homes," FSEC-CR-397-91, Florida Solar Energy Center, Cocoa, FL, January 1991.

		ach ^a	ach	cfm	% rated flow*	% of actual air flow
1	4.87	0.122	0.202	63	4.8%	NA
2	6.57	0.164	0.578	131	10.1%	13.2%
3	5.47	0.137	0.453	22	1.1%	7.9%
4	5.48	0.137	0.254	16	2.0%	1.0%
6	4.40	0.110	0.157	16	1.2%	1.2%
7	4.07	0.102	0.350	29	2.2%	2.6%
10	6.03	0.151	0.320	NA	NA	3.8%
18	3.46	0.087	0.170	12	1.0%	0.7%
20	4.74	0.119	0.198	30	2.0%	1.9%
22	4.85	0.121	0.356	57	3.9%	6.3%
24	5.21	0.130	0.241	5	0.4%	0.2%
27	6.10	0.152	0.408	10	0.5%	4.9%
28	6.55	0.164	0.332	21	2.9%	4.0%
29	5.36	0.134	0.309	25	1.8%	2.8%
30	4.97	0.124	0.217	3	0.3%	1.5%
31	7.48	0.187	0.406	132	7.0%	9.4%
33	5.03	0.126	0.409	45	2.3%	1.0%
34	6.89	0.172	0.289	NA	NA	0.5%
37	5.68	0.142	0.639	41	2.1%	4.3%
40	4.91	0.123	0.238	16	1.7%	1.7%
AVG	5.41	0.135	0.326	37.4	2.6%	3.6%

* rated flow is based on a nominal 400 cfm per ton.

^a predicted natural infiltration rate based on ACH50/40

Figure 7 shows significant correlation between the house infiltration rate (ach) and duct system airtightness, with the AHU running continuously. R^2 is 0.31, suggesting that 31% of the variation in house infiltration rate (with AHU ON) is explained by the size of the holes in the ductwork (note that Q_{25} can be thought of as a measure of the cumulative hole size of the duct leaks).

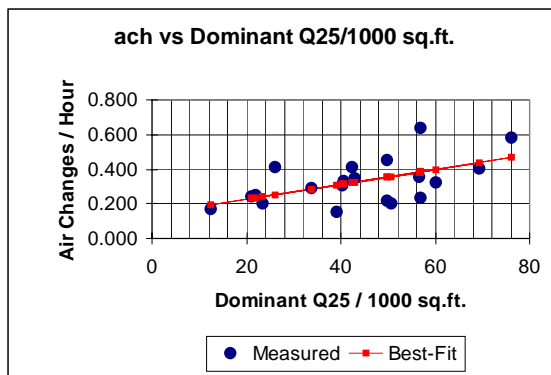


Figure 7. House infiltration rate (ach) with AHU ON versus dominant Q_{25} (normalized to floor area of 1000 ft²). $Y=0.004 \cdot X+0.14$ $R^2=0.312$

During the tracer gas decay test, a return leak fraction (RLF) test was also performed. In this test, the concentration of tracer gas was sampled at the return(s) and a supply register. The RLF is calculated as follows.

$$RLF = (A - B)/(A - C)$$

Where

A is the concentration of tracer gas (ppm) at entering the return grill

B is the concentration of tracer gas (ppm) discharging from a supply grill

C is the concentration of tracer gas (ppm) at the return leak location (attic, outdoors, etc.)

RLF is shown in the right-most column of Table 6. On average, 3.6% of the air entering the return side of the AHU is originating from outdoors or a non-conditioned buffer zone of the house. The amount of return leakage is probably underestimate somewhat because the tracer gas concentration at C was not measured at 16 of 19 houses, but rather assumed to be zero. To the extent that there was some tracer gas in the air entering the return leaks, these RLF values are underestimating the leakage.

By way of comparison, $Q_{25,r}$ is also shown in Table 6. It is shown as a percentage of rated system airflow. The average $Q_{25,r}$ is 2.6% of the rated system air flow. This is not fully comparable to the RLF for two reasons. 1) The rated airflow rate is higher than the actual system air flow rate. 2) The Q_{25} leakage is at 25 pascals, whereas the actual RLF is at whatever operating pressure happens to exist where the return leak openings (holes) are located. Figure 8 shows that there is a rather high correlation ($r^2 = 0.67$) between the RLF and the $Q_{25,r}$. Figure 9 also shows a substantial correlation between the house infiltration rate (AHU ON) and the return leak fraction ($r^2 = 0.45$).

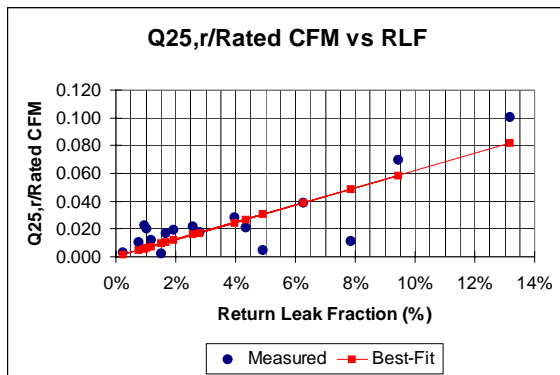


Figure 8. Correlation between $Q_{25,r}$ per rated cfm and RLF. $Y=0.622 \cdot X+0$ $R^2=0.670$

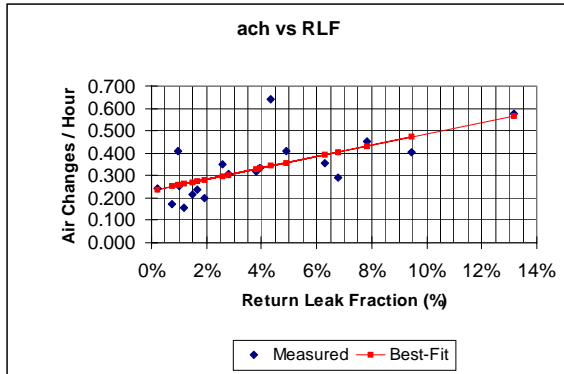


Figure 9. Correlation between house infiltration rate (AHU ON) and RLF.

$$Y=2.53*X+0.23 \quad R^2=0.451$$

Some duct operating pressures were measured. The average return plenum operating pressure in the 40 homes was -71 pascals, or 2.84 times the 25 pascal test pressure. However, the return portion of the AHU was operating at -140 pascals (between blower intake and cooling coil). Other portions of the return ducting would be at lower pressures.

In a study of 70 (0 to 5 year old) Florida homes from 1989, the return leak fraction was found to be 9.1% of system airflow. In a study of 160 (mixed-age) Florida homes from 1990, the return leak fraction was found to be 10.7% of system airflow. In both of these field studies, the testing took into account the tracer gas concentration at C (the leak location). Subsequently, the Florida Mechanical Code was modified in 1993 to disallow use of the AHU support platform as a return plenum, because so much leakage was occurring to the adjacent wall cavities and space. The new code required a duct from the return grill to the bottom of the AHU. This change in the code would appear to be the cause of the large reduction in RLF, from about 10% prior to 1990 to 3.6% in this current study.

Summary of Pressure Pan Testing Results

A pressure pan test was performed in 39 of the 40 homes. This is a test that can put a quantitative number to leakage and also provide indication of where the largest leaks may exist in the ductwork.

The test is carried out in the following manner. The AHU is turned OFF. The house is depressurized (or pressurized) to 50 pascals by a blower door. A cake-pan (or similar) is placed on a pole, and the pan (with gasket on lip of pan) is placed over each supply register and return grill, one at a time. A tube running from a pressure tap in the pan is attached to a digital manometer (0.1 pascal resolution). The pressure inside the pan (which is also the pressure inside the duct) is measured. Typical values for normal duct construction are 0.2 to 3.0 pascals, indicating slight to considerable duct leakage. The maximum possible reading is 50 pascals, where a duct is completely disconnected (e.g., you can look up through the supply grill and see the attic). The average pressure pan reading was 0.64 pascals, indicating slight to moderate duct leakage, on average.

Figures 10 and 11 show pressure pan readings for all 534 supply registers and all 78 return grills, respectively.

- *Supply.* In the 39 houses in which pressure pan testing was performed, there were 524 supply registers. 147 registers (28.1%) had readings of 0.0 to 0.2 pascal, meaning that there was essentially no significant leakage in the adjacent portion of the duct system. 279 registers (53.2%) had readings of 0.3 to 1.0 pascal, meaning that there was slight-to-moderate leakage in the adjacent portion of the duct system. 76 registers (14.5%) had readings of 1.1 to 2.0 pascals, meaning that there was significant leakage in the adjacent portion of the duct system. 17 registers (3.2%) had readings of 2.1 to 4.0 pascals, meaning that there was substantial leakage in the adjacent portion of the duct system. 5 registers (1.0%) had readings of 4.1 pascals and higher, meaning that there was large leakage in the adjacent portion of the duct system.

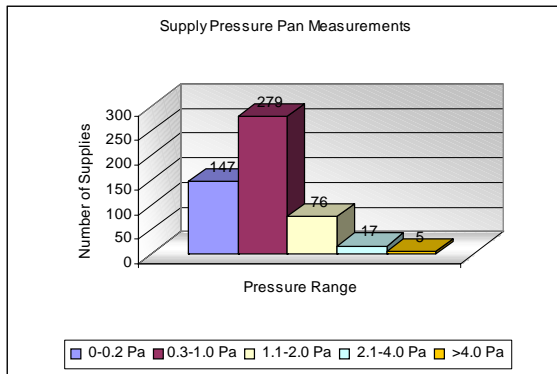


Figure 10. Distribution of supply pressure pan readings arranged for different ranges of pressure.

- *Return.* In the 39 houses in which pressure pan testing was performed, there were 78 return grills. 20 grills (26%) had readings of 0.0 to 0.2 pascal, meaning that there was essentially no leakage in the adjacent portion of the duct system. 35 grills (45%) had readings of 0.3 to 1.0 pascal, meaning that there was slight-to-moderate leakage in the adjacent portion of the duct system. 17 grills (22%) had readings of 1.1 to 2.0 pascals, meaning that there was significant leakage in the adjacent portion of the duct system. 4 grills (5%) had readings of 2.1 to 4.0 pascals, meaning that there was substantial leakage in the adjacent portion of the duct system. 2 grills (2.6%) had readings of 4.1 pascals and higher, meaning that there was large leakage in the adjacent portion of the duct system.

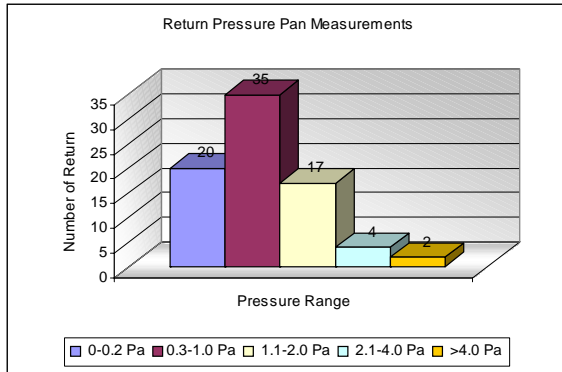


Figure 11. Distribution of return pressure pan readings arranged for different ranges of pressure.

The average supply pressure pan reading (PPs) was 0.63. By comparison, the average return pressure pan readings (PPr) was considerably higher, with PPr = 1.15.

Examining the data in Table 7 (with bins by PPr), one can observe that both $Q_{25,r/ton}$ and RLF correlate rather strongly with PPr. Higher PPr indicates higher both $Q_{25,r/ton}$ and RLF. (Note that PPr and PPs are the average pressure pan readings for the returns and supplies for each house, respectively.) Figure 12 shows a reasonably strong correlation ($r^2 = 0.40$) between $Q_{25,s}$ (normalized to house floor area) and PPs. Figure 13 shows a relatively weak correlation ($r^2 = 0.18$) between $Q_{25,r}$ (normalized to house floor area) and PPr.

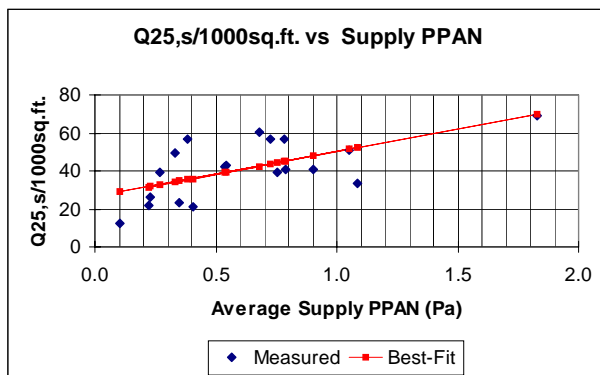


Figure 12. Plot of supply duct airtightness versus supply pressure pan readings.
 $Y = 23.73 \cdot X + 26.30$ $R^2 = 0.397$

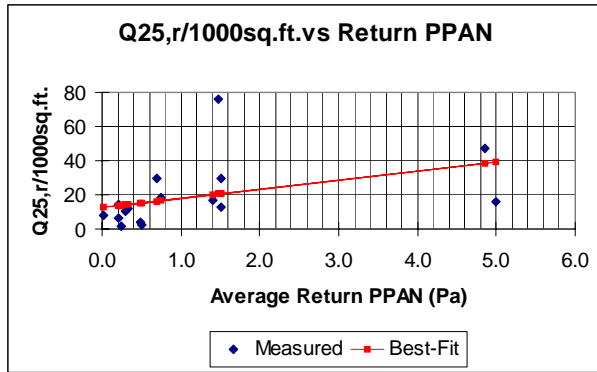


Figure 13. Plot of return duct airtightness versus return pressure pan readings.

$$Y=5.30 \cdot X+12.62 \quad R^2=0.178$$

Examining the data in Table 8 (with bins by PPs), one can observe that there is only a weak correlation between PPs and $Q_{25,s/ton}$. There is also little correlation between the house infiltration rate (with AHU ON, interior doors open) and either PPr or PPs. In general, however, we can say that houses with PPr < 0.51 pascals and PPs < 0.31 pascals have substantially lower infiltration (about 0.25 ach) compared to all others (about 0.36 ach). Note also that there is a significant correlation between PPr and PPs.

Table 7. Pressure pan, Q_{25}/ton , RLF, and infiltration rate with AHU ON (interior doors open) for PPr bins.

PPr bin (Pa)	# of houses	PPr,ave (Pa)	$Q_{25,r}/ton$	RLF	PPs,ave (Pa)	$Q_{25,s}/ton$	ach on
0 – 0.50	8	0.235	4.978	2.1%	0.371	22.006	0.245
0.51 – 1.0	3	0.647	8.510	3.6%	0.505	23.459	0.412
1.0 – 2.0	4	1.469	18.913	5.6%	0.811	24.843	0.375
2.1 +	2	4.925	19.745	6.7%	1.307	34.950	0.369
ALL	17	1.15	10.970	3.6%	0.608	24.453	0.320

Table 8. Pressure pan, Q_{25} , RLF, and infiltration rate with AHU ON (interior doors open) for PPs bins.

PPs bin (Pa)	# of houses	PPr,ave (Pa)	$Q_{25,r}/ton$	RLF	PPs,ave (Pa)	$Q_{25,s}/ton$	ach on
0 – 0.30	4	0.258	4.792	2.0%	0.205	15.111	0.247
0.31 – 0.60	6	0.618	6.093	1.9%	0.426	22.275	0.343
0.61 – 1.0	6	1.513	16.252	5.3%	0.771	29.033	0.356
1.1 +	3	3.175	23.618	5.0%	1.321	29.154	0.299
ALL	19	1.15	10.836	3.4%	0.630	23.987	0.320

RESEARCH FINDINGS – Combustion/dilution air

The Florida Mechanical Code (2004) requires combustion and dilution air when vented combustion vented devices are located in homes. Much of the language pertaining to

combustion/dilution air in residences is contained in the following sections shown in italics.

701.1 General.

Air for combustion, ventilation and dilution of flue gases for gas utilization equipment installed in buildings shall be provided by application of one of the methods prescribed in Sections 702 through 705. Where the requirements of Section 702 are not met, outdoor air shall be introduced in accordance with one of the methods prescribed in Sections 703 through 705. Direct-vent appliances, gas appliances of other than natural draft design and vented gas appliances other than Category I shall be provided with combustion, ventilation and dilution air in accordance with the equipment manufacturer's instructions.

Exception: *Type 1 clothes dryers that are provided with makeup air with an opening having an area of not less than 100 square inches (645 mm²) in the closet enclosure, or by other approved means.*

702.1 Indoor combustion air.

The required volume of indoor air shall be determined in accordance with Section 702.1.1 or 702.1.2, except that where the air infiltration rate is known to be less than 0.40 air changes per hour (ACH), Section 702.1.2 shall be used. The total required volume shall be the sum of the required volume calculated for all appliances located within the space. Rooms communicating directly with the space in which the appliances are installed through openings not furnished with doors, and through combustion air openings sized and located in accordance with Section 702.1.3, are considered to be part of the required volume.

702.1.1 Standard method.

The minimum required volume shall be 50 cubic feet per 1,000 Btu/h (4.8 m³/kW) of the appliance input rating.

702.1.2 Known air-infiltration-rate method.

Where the air infiltration rate of a structure is known, the minimum required volume shall be determined as follows:

For appliances other than fan-assisted, calculate volume using Equation 7-1.

$$\text{Required Volume}_{\text{other}} \geq \frac{21 \text{ ft}^3}{\text{ACH}} \left(\frac{I_{\text{other}}}{1,000 \text{ Btu/hr}} \right) \quad (\text{Equation 7-1})$$

For fan-assisted appliances, calculate volume using Equation 7-2.

$$\text{Required Volume}_{\text{fan}} \geq \frac{15 \text{ ft}^3}{\text{ACH}} \left(\frac{I_{\text{fan}}}{1,000 \text{ Btu/hr}} \right) \quad (\text{Equation 7-2})$$

where:

I_{other} = All appliances other than fan assisted (input in Btu/h).

I_{fan} = Fan-assisted appliance (input in Btu/h).

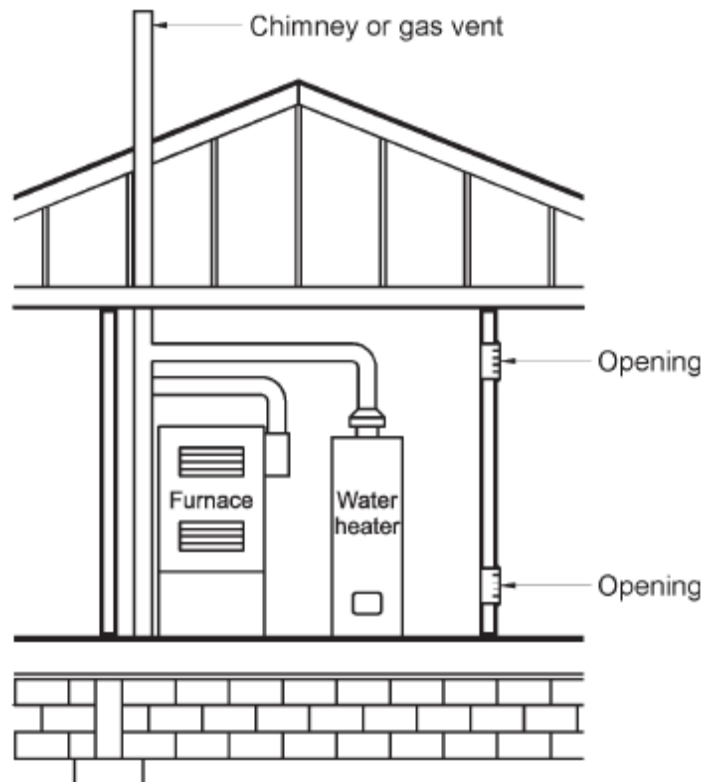
ACH = Air change per hour (percent of volume of space exchanged per hour, expressed as a decimal).

For purposes of this calculation, an infiltration rate greater than 0.60 ACH shall not be used in Equations 7-1 and 7-2.

702.1.3 Indoor opening size and location.

Openings used to connect indoor spaces shall be sized and located in accordance with Sections [702.1.3.1](#) and [702.1.3.2](#) (see Figure [702.1.3](#)).

FIGURE 702.1.3
ALL AIR FROM INSIDE THE BUILDING
(See Section [702.1.3](#))



702.1.3.1 Combining spaces on the same story.

Each opening shall have a minimum free area of 1 square inch per 1,000 Btu/h (2,200 mm² /kW) of the total input rating of all gas utilization equipment in the space, but not less than 100 square inches (0.06 m²). One opening shall commence within 12 inches (305 mm) of the top and one opening shall commence within 12 inches (305 mm) of the bottom of the enclosure. The minimum dimension of air openings shall be not less than 3 inches (76 mm).

702.1.3.2 Combining spaces in different stories.

The volumes of spaces in different stories shall be considered as communicating spaces where such spaces are connected by one or more openings in doors or floors having a total minimum free area of 2 square inches per 1,000 Btu/h (4402 mm² /kW) of total input rating of all gas utilization equipment.

703.1 Outdoor combustion air.

Outdoor combustion air shall be provided through opening(s) to the outdoors in accordance with Section [703.1.1](#) or [703.1.2](#). The minimum dimension of air openings shall be not less than 3 inches (76 mm).

703.1.1 Two-permanent-openings method.

Two permanent openings, one commencing within 12 inches (305 mm) of the top and one commencing within 12 inches (305 mm) of the bottom of the enclosure, shall be provided. The openings shall communicate directly, or by ducts, with the outdoors or spaces that freely communicate with the outdoors. Where directly communicating with the outdoors, or where communicating with the outdoors through vertical ducts, each opening shall have a minimum free area of 1 square inch per 4,000 Btu/h (550 mm² /kW) of total input rating of all equipment in the enclosure [see Figures [703.1.1\(1\)](#) and [703.1.1\(2\)](#)].

Where communicating with the outdoors through horizontal ducts, each opening shall have a minimum free area of not less than 1 square inch per 2,000 Btu/h (1,100 mm² /kW) of total input rating of all equipment in the enclosure [see Figure [703.1.1\(3\)](#)].

FIGURE 703.1.1(1)
ALL AIR FROM OUTDOORS—INLET AIR FROM VENTILATED CRAWL SPACE AND OUTLET AIR TO VENTILATED ATTIC
 (See Section [703.1.1](#))

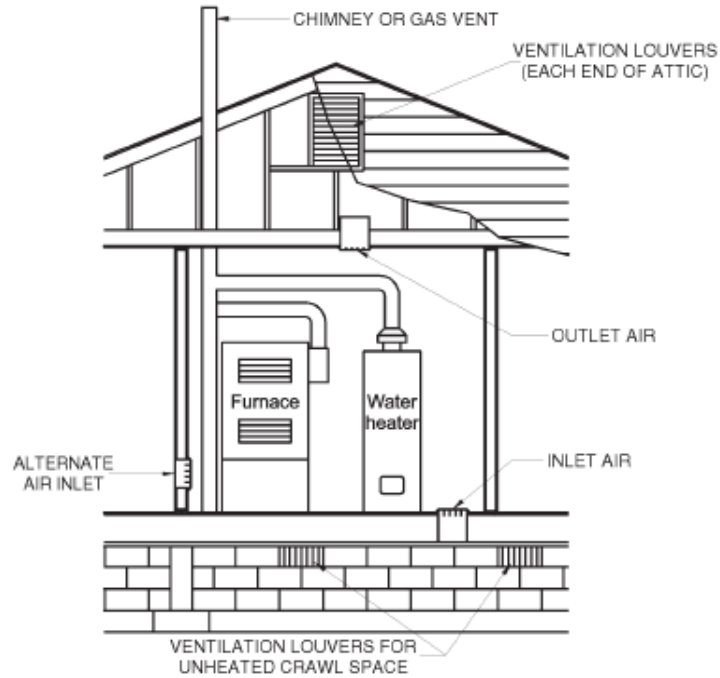


FIGURE 703.1.1(2)
ALL AIR FROM OUTDOORS THROUGH VENTILATED ATTIC
 (See Section [703.1.1](#))

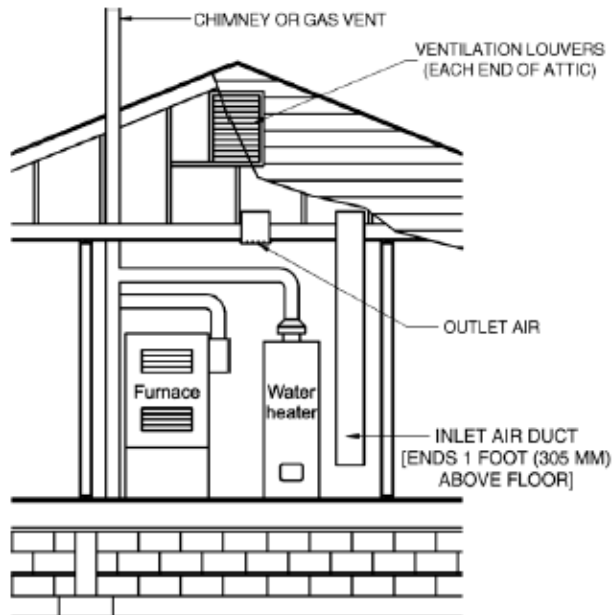


FIGURE 703.1.1(3)
ALL AIR FROM OUTDOORS
(See Section [703.1.1](#))

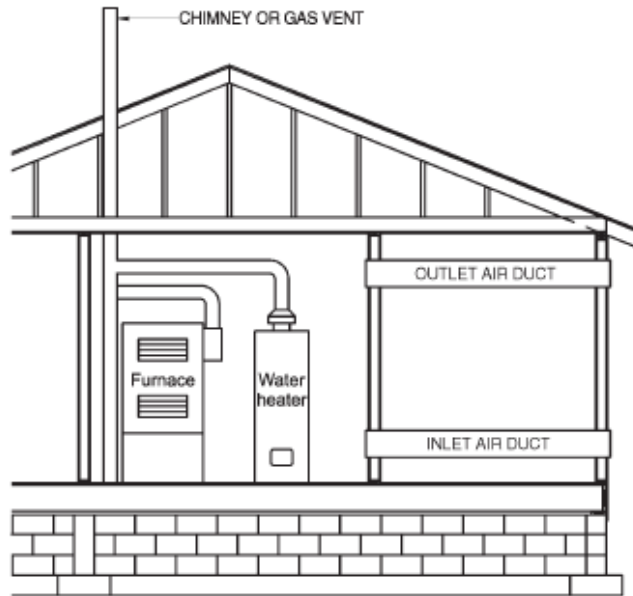
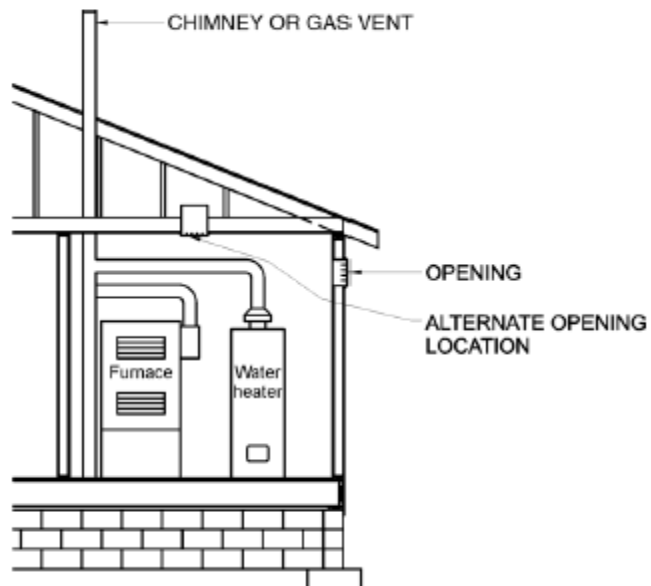


FIGURE 703.1.2
SINGLE COMBUSTION AIR OPENING
ALL AIR FROM OUTDOORS
(See Section [703.1.2](#))



703.1.2 One-permanent-opening method.

One permanent opening, commencing within 12 inches (305 mm) of the top of the enclosure, shall be provided. The equipment shall have clearances of at least 1 inch (25 mm) from the sides and back and 6 inches (152 mm) from the front of the appliance. The opening shall directly communicate with the outdoors or through a vertical or horizontal duct to the outdoors or spaces that freely communicate with the outdoors (see Figure [703.1.2](#)) and shall have a minimum free area of 1 square inch per 3,000 Btu/h (734 mm² /kW) of the total input rating of all equipment located in the enclosure, and not less than the sum of the areas of all vent connectors in the space.

704.1 Combination indoor and outdoor combustion air.

The use of a combination of indoor and outdoor combustion air shall be in accordance with Sections [704.1.1](#) through [704.1.3](#).

704.1.1 Indoor openings.

Where used, openings connecting the interior spaces shall comply with Section [702.1.3](#).

704.1.2 Outdoor opening location.

Outdoor opening(s) shall be located in accordance with Section [703.1](#).

704.1.3 Outdoor opening(s) size.

The outdoor opening(s) size shall be calculated in accordance with the following:

- 1. The ratio of interior spaces shall be the available volume of all communicating spaces divided by the required volume.*
- 2. The outdoor size reduction factor shall be 1.0 minus the ratio of interior spaces.*
- 3. The minimum size of outdoor opening(s) shall be the full size of outdoor opening(s) calculated in accordance with Section [703.1](#), multiplied by the reduction factor. The minimum dimension of air openings shall be not less than 3 inches (76 mm).*

Combustion/dilution Air Findings from 40 Homes

Vented combustion devices were found in 8 of the 40 homes. A total of 13 vented, combustion devices were found in these homes (Table 9).

Table 9. A total of 13 combustion appliances were found in 8 homes.

House #	Furnace (gas)	Water heater (gas)	Clothes Dryer	Fireplace (vented)
2	x	x		
7	x	x	x	
9		x		
15		x		
21		x	x	
25				x
33		x	x	
38				x
SUM	2	6	3	2

None of the 8 homes had combustion/dilution air openings in a combustion appliance zone. As an alternative to providing combustion/dilution air vents, the combustion/dilution air requirements can be met by the volume of the space in which the combustion appliance is located. The required volume of the combustion appliance zone (CAZ) is based upon the gas input capacity.

Table 10 lists the input capacity of atmospherically vented combustion devices (except fireplaces) and the combustion/dilution air requirements. Six houses had atmospherically vented combustion appliances (Table 10). None, however, had combustion/dilution vent openings. However, four of the houses could meet their combustion/dilution air requirements based on the volume of the CAZ zone.

The two houses that were not in compliance were Houses 2 and 7. Because they had both a furnace and a gas water heater, with total gas input of 120 kBtu/hr and 128 kBtu/hr, respectively, they would require a larger CAZ volume. House 2 had a volume requirement of 6000 ft³ but had a CAZ volume of only 3600 ft³. House 7 had a volume requirement of 6400 ft³ but had a CAZ volume of only 3747 ft³. Therefore, these houses would be required to have combustion/dilution vents, sized at 40 in² and 42.7 in² (or larger), respectively.

Table 10. Gas input, required volume, available volume, and vent grill size required for combustion/dilution air.

House #	Furnace (kBtu/hr)	Water heater (kBtu/hr)	Clothes dryer ² (kBtu/hr)	Required volume (ft ³)	Available volume (ft ³)	Vent opening required (in ²)	Is house in code compliance?
2	88	32		6000	3600	40	NO
7	88	40	35	6400	3747	42.7	NO
9		40		2000	3320	Not necessary ⁴	YES
15		40		2000	3360	Not necessary ⁴	YES
21		40 ¹	35	2000	3360 ³	Not necessary ⁴	YES
33		40 ¹	35	2000	3360 ³	Not necessary ⁴	YES

¹ Water heater capacity unknown.; 40,000 Btu/hr capacity assumed.

² Dryer gas input estimated (typical value). Dryer gas input is not considered for calculation of required volume, because in all cases the clothes dryer was not located in the same CAZ as the furnace and water heater.

³ Volume of garage is estimated.

⁴ Vent opening not necessary because combustion/dilution air requirement can be met by space volume.

It was a surprise to the research team that there were relatively few combustion appliances in this sample of 40 homes. Even more surprising was that none of the CAZs of the 7 homes with furnace, gas DHW, or gas clothes dryer had combustion/dilution air openings.

In previous field-testing, project staff had observed combustion/dilution vents in new homes. In some cases, the vents were grills in the ceiling of the laundry room with a short duct open directly into the attic space. In some cases, the combustion/dilution vent (to the attic) was provided even though the clothes dryer actually installed had electric heating (gas stub-out was provided).

One of the 40 houses in this study had an identical situation. While none of the combustion appliance zones in these 40 homes had combustion/dilution air vents, one laundry room (with no combustion devices) had a combustion/dilution vent (in House #2). This laundry room had both gas and electric dryer service, but in this instance the installed dryer was electric. The vent was in the ceiling of the small laundry room and consisted of a 4" x 8" register (supply register type) with a boot with 4" round collar at the top. A piece of batt insulation had been positioned on top of the collar, so that if you looked up through the register you would see the Kraft backing of the batt (apparently someone placed the batt over the vent because the dryer was not a combustion device).

If a typical 35,000 Btu/hr input gas clothes dryer (Table 5.4.2.1 in National Fuel Gas Code 2002 lists 35,000 Btu/hr as the typical dryer) had been installed instead of the electric unit, would the ceiling vent have been sufficient to meet code? For this ceiling vent location, the size requirement is 1 in² per 3000 Btu/hr input. Dividing 35 (kBtu/hr) by 3 yields 11.7 in² vent area. The 4" round collar at the top of the boot has a cross-sectional area of 12.6 in², or just greater than the vent size requirement. The answer is YES, it would be large enough for a gas clothes dryer.

Summary and Conclusions

In Florida houses constructed after March 1, 2002, there has been a substantial reduction in pressure differentials created by closure of interior doors and unbalanced return air. With all interior doors closed, the central zone pressure went to -1.4 pascals in these 40 homes. By comparison, 70 homes built in the period 1985 – 1989 had a central zone pressure of -2.9 pascals with all interior doors closed. The house infiltration rate with interior doors closed was 23% greater than with doors open (air handler operating in each case; excluding the unusual results from House 37). By contrast, those built in the period 1985-1989 showed a 30% higher infiltration rate with interior doors closed (air handler operating in each case).

Florida homes continue to show a trend of becoming more airtight. In 70 houses built in 1985-1989, house envelope airtightness was 7.1 ACH50. In a study of 20 houses built in 2001-2002, ACH50 had declined to 6.1. In the current sample of 40 homes, ACH50 had fallen to 5.2 ACH50.

Duct leakage has declined since the 1980's. The house infiltration rate for a sample of 70 houses built in the period 1985-1989 was 0.46 ach (AHU running continuously). By comparison, 20 houses in this study had an infiltration rate of 0.31 ach with AHU running continuously. Some of the infiltration may be related to the tighter house envelope. Nevertheless, the dramatic reduction from 0.46 to 0.31 ach strongly suggests that duct leakage has declined.

The decline, however, has been mostly on the return side of the system, with return leak declining from about 10% in houses built before 1990 to current 3.6% of system air flow. This decline in return leakage is likely the result of 1993 code change which required a return duct section to connect the return grill to the bottom of the air handler even inside of a support platforms.

More recently, duct leakage has shown some improvement. Q_n in 20 houses built in 2001-2002 was 0.064 cfm/ft^2 , while Q_n in 20 houses built in the current study (2002-2005) was 0.057 cfm/ft^2 . Therefore, duct leakage shows about 11% improvement on a per unit of floor area basis. Q_{25}/ton remains essentially unchanged, however, at 35.6 cfm/ton for the 2001-2002 sample and 35.5 cfm/ton for the 2002-2005 sample

Combustion/dilution air requirements were in compliance in 4 of 6 homes where the code requires action. In one laundry room, which contained only an electric clothes dryer (and no combustion appliances), a combustion/dilution vent was installed in the case that a gas dryer would be installed. If a gas dryer had been installed, the combustion/dilution vent provided would have met the code requirement.