Contract Report

Interior Duct System Design, Construction, and Performance

Final Report

October 10, 2001

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Field Study of Interior Duct System Design, Construction and Performance

Duct Chases and Air Handler Closets

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DISCLAIMER

ABSTRACT

Field Study of Interior Duct System Design, Construction, and Performance
Duct Chases and Air Handler Closets

By removing air distribution and conditioning equipment from unconditioned spaces, homeowners stand to benefit substantially with respect to both energy savings and indoor air quality. Duct leakage introduces:

- Greater heating and cooling loads from air at extreme temperatures and humidity levels
- Outside air and air from unconditioned spaces that may contain air borne contaminants, combustion gases, pollen, mold spores, and/or particles of building materials.
- Higher whole-house infiltration/exfiltration rates

Exemplary studies[1] conducted since 1990 have demonstrated the prevalence of duct leakage throughout the United States and measured energy savings of approximately 20% during both heating and cooling seasons from leakage reduction. These all dealt with duct leakage to and/or from unconditioned spaces. In the building science community, leakage within the conditioned space is generally presumed to eliminate the negative consequences of duct leakage with the exception of possibly creating pressure imbalances in the house which relates to higher infiltration and/or exfiltration.

The practical challenges of isolating ducts and air handlers from unconditioned spaces require builders to construct an air-tight environment for the ducts. Florida Solar Energy Center researchers worked with four builders in Texas, North Carolina, and Florida who build a furred-down chase located either in a central hallway or at the edges of rooms as an architectural detail. Some comparison homes with duct systems in attics and crawl spaces were included in the test group of more than 20 homes.

Test data reveals that all of the duct/AHU systems built inside the conditioned space had lower duct leakage to unconditioned spaces than their conventional counterparts; however, none of the homes was completely free of duct leakage to unconditioned spaces.

Common problems included wiring and plumbing penetrations of the chase, failure to treat the chase as an air tight space, and misguided fresh air inlet design. Improvements were implemented by the Texas builder and retested in July. Results showed a 36% reduction in duct leakage, significant enough to warrant the builder adopting the new sealing procedure.

1. Research conducted by Cummings, Moyer, and Tooley (1990, 1993, 1996) and Dunsmore (1991); Davis (1991) and Manclark (1996); Ted Haskell (1996); Penn (1993); Proctor and Pernick (1992); Strunk, Kinney, Stiles, and Wilson (1997); and Vigil (1993).

Table of Contents

I. EXECUTIVE SUMMARY

Researchers from the Florida Solar Energy Center's (FSEC) Buildings Research Division worked with four builders in Texas, North Carolina, and Florida who independently developed interior duct chase/AHU closet designs to assess performance and provide others with the benefit of these builders' experience. The fundamental objective of the study was to determine if the builders had successfully isolated the ducts/AHU from unconditioned spaces.

"Interior Duct System" Defined

For this study, "duct system" includes all components of the air distribution and conditioning equipment excluding the condenser. To be considered "in conditioned space", the ducts and air handler must be completely within the house's thermal and air barriers. The zone housing the air distribution and conditioning equipment usually consists of a duct chase and an air handler closet. Throughout this study, the terms "in conditioned space" and "interior" refer to the ***intent*** to meet this definition.

Partner Builders

Four Partner Builders agreed to participate in this study who build houses with ducts and air handlers inside the conditioned space (Figure 1). Each added the detail to their homes to enhance energy efficiency, indoor air quality, and comfort. Together they have built more than 150 homes with interior ducts/AHUs.

Figure 1 *Hallway furred down duct chase continues out into living space creating an alcove. Broward County Habitat for Humanity.*

Each Partner Builder developed details independently and arrived at the construction solution based on information learned through energy efficiency and indoor air quality seminars, lectures, and independent research. Eager to have their solutions evaluated, each Partner invited a select group of homeowners to participate in the study to determine how well the interior duct chase/AHU closet designs work.

FSEC used an air tightness testing protocol developed in conjunction with researchers recognized as experts in the duct leakage field: John Andrews of Brookhaven National Laboratory, Jim Cummings and Neil Moyer both of FSEC. A testing roster of over 20 homes took researchers to Durham, NC; Waxahachie, TX (near Dallas); Gainesville, FL; and Fort Lauderdale, FL. The homes ranged in size including: small, affordable homes built by Habitat for Humanity, town homes, high end custom homes. Test results are reported in detail in Appendix A and discussed in Section IV: Results and Discussion.

Results from the study were presented at the American Council for Energy Efficient Economy Summer Study 2000 and at Affordable Comfort 2001. A newsletter style brochure and a more detailed FSEC professional paper (FSEC-PF-365-01) summarize the design and construction methods evidenced in the field research. Both are written for design and construction professionals and can be found as Adobe Acrobat files on the FSEC site www.fsec.ucf.edu, keyword "interior ducts."

II. INTRODUCTION – DUCT LEAKAGE AND HEAT TRANSFER

Motivation Behind Building Interior Duct Systems

By removing ducts/AHUs from unconditioned spaces (Figure 2), homeowners stand to benefit substantially with respect to both energy savings and indoor air quality.

This construction strategy is commonly referred to as "interior ducts" or "ducts in the conditioned space" and provides the following advantages:

- Reduces both conductive losses and duct leakage losses, which ranks among the top three opportunities for improving the energy efficiency in America's housing stock, for both new and existing homes.
- Improves indoor air quality by reducing infiltration of pollen, dust, building material particles, and VOC from building materials.
- Improves building durability by reducing pressure driven moisture migration through walls, floors, ceilings, and roofs which leads to rot, mold growth, and condensation.
- Improves mechanical system life by reducing heating and cooling loads as well as dirt accumulation.

These benefits are more apparent from a basic understanding of duct leakage and duct heat transfer.

Figure 3 *Ducts and air handlers in unconditioned spaces where supply leakage can create conditions ideal for condensation, mold growth, and building decay.*

Consequences of Duct Leakage in Unconditioned Spaces

By design, the fan in the air handler pulls air out of the house through a central return or return ducts, sends it across the conditioning element, and pushes it back into the house through supply ducts.

Ideally, the same amount of air is removed from the house as is supplied back to the house creating a state of pressure balance. When ducts in unconditioned spaces leak, the pressure balance is disrupted resulting in a negative or positive pressure in the house with respect to (WRT) outside. Though impercievable, even very small pressure imbalances (±1 pascals) can contribute significantly to energy waste, thermal discomfort, mold growth, indoor air pollution, and moisture damage.

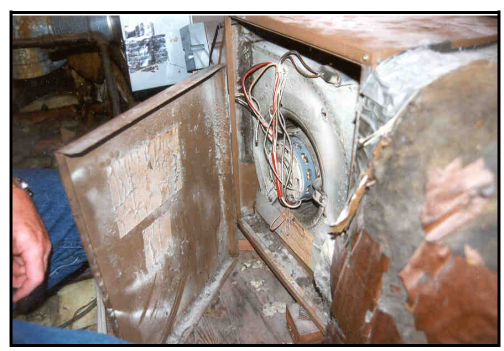


Figure 4 *Through leaks in the metal cabinets, air handlers in attics are exposed to dust, pollen, extreme air temperature and relative humidity, and building material particulates.*

Supply Leaks

When supply ducts leak, more air is removed from the house than is supplied, resulting in a net loss of air causing a negative pressure in the house (WRTout). To make up for the air deficit, air flow into the conditioned space through wall, ceiling, and floor joints; around windows and doors; under bottom plates; down flue chases; and through any other penetrations in the house's air barrier. Meanwhile, air intended for the house leaks out into the unconditioned space, such as the attic or crawl space.

During the heating season, supply leaks result in a drafty house with cold spots. The extra cold air being drawn into the house means that the heater has to work harder. Meanwhile, warm air is leaking out into a cold, unconditioned space. When the warm air meets the cold building surfaces, condensation can occur, wetting building surfaces not designed for moisture resistance.

During the cooling season, supply leaks result in a muggy house with high humidity levels. The negative pressure pulls in outside air, bringing heat and moisture which the cooling system must temper to maintain comfort. Meanwhile, cold air is leaking out into a warm unconditioned space cooling surfaces such as insulation and roof trusses. This creates an atmosphere conducive to both mold growth and condensation.

Return Leaks
Unless special care has been taken to seal the seams in the AHU, it will probably leak, pulling some air from surrounding unconditioned spaces (e.g. attic, garage, unconditioned utility room, crawl space) through joints in the AHU (Figure 3). This air, usually with extreme temperature and humidity characteristics, imposes a greater load on the conditioning system, increasing energy use and reducing machine life.

Additionally, unconditioned air from garages, attics, crawl spaces, wall cavities, and outside may contain air borne contaminants such as combustion gases from gas appliances or cars, tiny particles of fibrous building materials, mold spores, pollen, radon, soil gases, and dust. If the air enters the air handler somewhere between the filter and the fan, it bypasses the filter and deposits particles on the conditioning element (further reducing efficiency and system life) or in the supply air stream to be distributed throughout the house.

This can occur even if the air handler is in the conditioned space unless if interior wall cavities surrounding the air handler are thoroughly sealed.

Ducts in the Conditioned Space
A decade of field studies have documented the effectiveness of duct sealing through measured improvements after duct leakage repair. However, many energy experts recommend installing ducts/AHUs *inside the conditioned space* (Figure 4) to eliminate most of the energy losses as well as mitigating the durability and health risks associated with duct/AHU leakage. This also dramatically reduces conductive heat transfer by taking the ducts and air handler out of extreme temperatures and placing them within the house's thermal and air barrier.

From a building science perspective, this is the logical next step in improving conditioned air delivery. From a homebuilding perspective, it calls for new construction solutions that meet fire code and building code constraints. It also presents the logistical challenges of managing sub-contractors and materials handling requiring advanced planning and close supervision. This study undertakes the task of evaluating the design, construction, and effectiveness of solutions developed by several innovative Builder Partners. A summary of tasks appears in the Task Report on the next page.

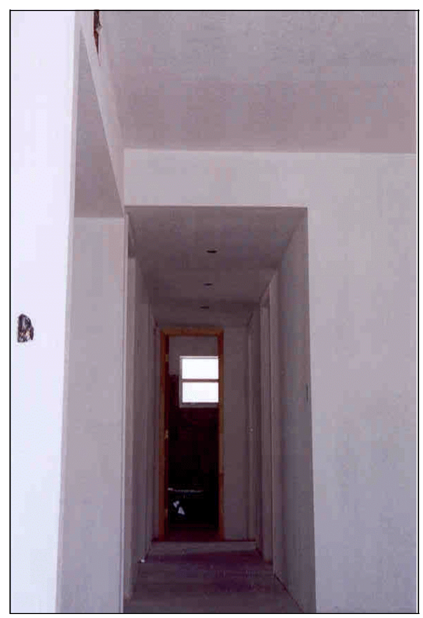


Figure 5 *Interior ducts (in hallway fur-down) are protected from extreme temperatures by attic insulation. Broward County Habitat for Humanity (South Florida).*

Task Report

Tasks Final Statement of Work (10/14/99)		Mile Stones Form 4600.3A		Success Criteria Technical Proposal Appendix A Section B	Planned Completion	Actual Completion
1	Testing Schedule and Design Documentation	1	Document Design and Construction Strategies	Document current details and associated design criteria	12/31/99	6/30/01
		2	Validate Test Procedure		12/31/99	11/30/99
		3	Finalize Partner Builder List		12/31/99	12/31/99
		4	Set Testing Schedule		1/30/00	1/30/00
2	Field Testing	6	Test Houses	Test 20-40 of the partner builders' homes to determine effectiveness and identify deficiencies	3/30/00	3/21/00
3	Full Development of Refined Details	7	Develop Fixes	Refine details to eliminate deficiencies and provide details and construction guidance to Builder Partners.	5/30/00	3/21/00
4	Field Validation	9	Test Fixes	Validate by testing one home built with the new details.	7/31/00	8/1/00
5	Impact on Home Energy Rating System Scores	5	Ratings I - From plans		1/30/00	5/4/00
		8	Ratings II - From site visits		6/30/00	6/30/01
		10	Rating Impact Study	Produce impact evaluation of findings on HERS Scores	8/30/00	6/30/01
6	Technology Transfer	11	Presentations	Present findings at two conferences	9/00 - end of agreement	8/21/01 5/2/01
			Papers	Newsletter style publication FSEC Professional Paper Draft Pending DOE approval	9/00 - end of agreement	5/30/01 4/30/01
7	Final Report Draft				6/30/01	7/26/01
	DOE Review				7/30/01	
	Final Report				8/30/01	

III. EXPERIMENTAL

Task 1 – Test Procedure Validation, Test Scheduling, and Design Documentation

Task 1 encompasses all pretesting activities. Milestone 1 proved more difficult than expected and carried over through the end of the project. Milestone 2, 3, & 4 were completed by January 30, as planned.

Mile Stones (Form 4600.3A)		Planned Completion	Actual Completion
2	Validate Test Procedure	12/31/99	11/30/99
3	Finalize Partner Builder List	12/31/99	12/31/99
4	Set Testing Schedule	1/30/00	1/30/00
1	Document Design and Construction Strategies	12/31/99	4/30/01

Milestone 2 - Validate Test Procedure

Two validation tests were conducted. The first at a Melbourne, Florida single family detached home not built by a Partner Builder and the second at a Gainesville, Florida single family attached home (Figure 5) built by Howard Wallace of Millpond Development Inc. associated with Builder Partner Ken Fonorow of Florida Home Energy Resources Organization (FlaHERO).

In the Melbourne home, the interior duct system was a retrofit installation located in a furred down chase finished with drywall under a tongue and groove wood ceiling. The air handler closet was lined with drywall but not well sealed. Researchers conducted a standard whole house infiltration test as well as running the full interior duct testing procedure which calls for a series of tests summarized here, detailed in Appendix B.

Figure 6 *Measuring pressure differentials with digital manometers (circled) during validation exercises in North Florida.*

Testing Equipment

- 1 Minneapolis Blower Door (MBD)
- 2 MBD Duct Blasters™
- 1 Additional Blower Door frame (Modified to fit narrow and short AHU closet doors) with Duct Blaster™ curtain
- 1 MBD automated pressure testing (APT) device and/or up to 7 MBD digital manometers (pressure gauges).

Zonal Pressure with AHU Operating and with House=50pa WRTout

- House WRToutside
- Attic with respect to the house (WRThouse)
- Chase (when present and accessible) WRThouse
- Supply duct system WRThouse
- Return duct system WRThouse

Standard Diagnostic Tests

- Whole house air tightness (CFM50 & ACH50)
- Duct/AHU air tightness, total and to outside, at operating and test pressures.

Duct Chase/AHU Closet Leakage Tests (when possible)
Last, when possible, researchers performed a set of special tests designed to evaluate the air tightness of the duct chase/AHU closet.

- ChaseCFM25total: chase/AHU closet pressure = 25 pascals WRTout
- ChaseCFM25out: chase/AHU closet pressure = house pressure= 25 pascals WRTout
- ChaseCFMOPtotal: Operating pressure in the chase/AHU closet
- ChaseCFMOPout: Operating pressure in the chase/AHU closet and the house
- Chase&DuctsCFM25total,chase (fan flow in duct tester at AHU closet door)
  Chase&DuctsCFM25total,ducts (fan flow in duct tester at return grill)
  chase/AHU closet pressure = ducts/AHU pressure = 25 pascals WRTout
- Chase&DuctsCFM25out,chase (fan flow in duct tester at AHU closet door)
  Chase&DuctsCFM25out,ducts (fan flow in duct tester at return grill)
  chase/AHU closet pressure = ducts/AHU pressure = house pressure = 25 pascals WRTout

Chase/AHU closet leakage was measured in three different configurations. Two standard leakage tests were conducted, one at 25 pascals (total and out) and one at operating pressure (total and out). In these tests, the chase/AHU closet was pressurized as if it were a duct system. For the "leakage to out" tests, the house was brought into pressure equalization with the chase/AHU closet. Then, in some cases, a third configuration using two duct testers was arranged to eliminate air flow between the chase/AHU closet and the ducts/AHU. Fan flow was measured at both duct testers and compared to results from the standard CFM25 and CFM25chase measurements. The Partner Builder's houses (except for the South Florida homes) were all configured with a central return under a platform-mounted AHU in an interior closet. The closet door way was above the platform (Figure 6).

Figure 7 *Interior air handler closet with return under a platform dividing the closet. Lakeland Habitat for Humanity, Central Florida.*

Validation Exercises
A number of problems with the testing procedure were encountered at the Melbourne house. The original protocol called for depressurization. This proved unsuccessful because leakage in the duct pulled air out of the duct chase causing the pressure in the chase to change proportionally with the flow into the duct system. Consequently, the protocol was changed to pressurization (reported in Quarterly Reports I & II).

At the Gainesville home, the interior duct system was also located in a furred down chase finished with drywall. The house air barrier forming the top and sides of the chase was drywall. Researchers again conducted a standard whole house infiltration test as well as ran the full interior duct testing procedure revised for pressurization. Results from the successful validation exercise are summarized in Table 1.

Later, the test procedure outlined in the proposal was amended to include elements of ASHRAE Draft Standard 152P by reference. See IV Results and Discussion, *Test 4*.

Table 1
Milestone 2 – Validate Test Procedure

Test #	Description	Result	Implication
1	Chase Operating Pressure	Chase Operating Pressure = 0 with AHU on and off WRThouse	The chase is fully connected to the house.
2	Chase Pressure with House at +50 pascals	Chase Pressure = 0.5pa	Chase is isolated from unconditioned spaces
3a	Chase leakage to outside (chaseCFM25$_{out}$)	Chase only leakage ChaseCFM25out = 49	Air that escapes the duct/AHU into the chase/AHU closet, has little chance of making it to unconditioned spaces.
3b	Total leakage of the ducts and the chase together	Chase and ducts leakage Chase&DuctsCFM25out =23*	Together, the duct/AHU and the chase/AHU closet allow very little air exchange with the attic.
4a	Duct leakage to outside	ductCFM25$_{out}$ = *20	Most of the duct leakage is ending up in the chase, not the attic.
* Indicates a very small flow, on the cusp of the instrument's ability to measure.			

Mile Stone 3 - Finalize Partner Builder List (Table2)
Both of the Partner Builders cited in the proposal participated in the study. They were joined by Broward County Habitat for Humanity in South Florida and Ken Fonorow, President of Florida Home Energy Resources Organization (FlaHERO), who works with builders in the Gainesville area (Alachua County) in North Florida. Seattle Habitat for Humanity expressed interest in participating, but changed their heating system to hydronic heating in 2000.

Table 2
Milestone 3 Finalized Partner List

Partner	Contact	Location	
Bentwood Custom Homes, Inc.	Jim Sargent, Owner & Builder 972-617-3788	Dallas area	3 Sargent Place Waxahachie, TX 17516
Durham County HFH	Bob Calhoun, Executive Director 919-682-0516	Raleigh/Durham	215 North Church Durham, NC 27701
Broward County HFH	Mary Lou Bowman, Architect Russ Cubbin, Const. Manager 954-396-3030	South Florida	3564 N. Ocean Blvd. Ft. Lauderdale, FL 33308
FlaHERO	Ken Fonorow, President 352-336-2060	North Florida	15220 NW 5th Ave. Newberry, FL 32669

Milestone 4 - Set Testing Schedule (Table 3)
The Partner Builders invited a select group of homeowners to participate in the field study set for March 2000. Researchers scheduled the participants from Durham County Habitat who each received a $100 cash incentive. Bentwood Homes, FlaHERO, and Broward County Habitat scheduled their own homeowners.

Table 3
Milestone 4 - Set Testing Schedule

Builder Partner	Location	Homes Tested	Testing Scheduled and Conducted
Bentwood Custom Homes, Inc.	Dallas area	10	March 18-21
Durham County Habitat for Humanity	Raleigh/Durham	10	March 13-17
Broward County Habitat for Humanity	South Florida	4	May/June
Energy Rated Homes of Florida	North Florida	1/1	Dec 99/June 00

Milestone 1 - Document Design and Construction Strategies
Documentation Prior to Testing
Researchers conducted phone interviews with representatives from each of the Partner Builders to determine how they were building interior duct chases/AHU closets (Table 4).

Some of the information gathered prior to testing was unfortunately misleading. This was due primarily to the complex nature of the construction details being discussed. Photographs of various details could have made a significant difference in the overall success of the project.

Specifically the interface between the AHU closet and the duct chase was not discussed thoroughly enough. During the pre-testing phone interviews, all Partner Builders indicated that air could flow from the AHU closet into the chase. However, in almost all test homes, the opening in the AHU closet through which the main supply trunk ran into the chase was more tightly toleranced than expected. This blocked air flow from the AHU closet into the duct chase. In practice, this is inconsequential since air flow through the chase is not essential, but the testing protocol developed for this study (validated in Gainesville) depends on being able to pressurize the chase which often proved impossible during testing (see *Task 2, Test Houses*).

Table 4
Milestone 1 - Pre-Testing Documentation of Design/Construction Strategies

	Durham County Habitat for Humanity	FlaHero	Broward County Habitat for Humanity	Bentwood Custom Homes
Supervisor for Chase Construction	Construction Manager	Site Supervisor	Construction Manager & Architect	Construction Manager
Attic construction:	Truss	Truss	Truss	Rafters and Joists
Chase construction	Fur down	Fur down	Fur down	Fur down and Fur up
Chase air barrier	Drywall	Drywall	Drywall (OSB in 2000)	Drywall and Rigid Foam Insulation
Air barrier seal	Drywall Mud	Mesh & Mastic and Sill Seal	Drywall Mud or None	Drywall Mud
Air barrier installer	Volunteers	Energy Specialist and Drywall Crew	Volunteers	Framers
Thermal barrier	Attic Insulation	Attic Insulation	Attic Insulation	Attic Insulation
AHU location	Interior Closet	Interior Closet	Interior Closet	Interior Closet
AHU closet air barrier	Drywall from top plate to sub-floor sealed with drywall mud except at the floor.	Lined with dry-wall top to bottom and sealed every- where with mastic.	Lined with drywall sealed with drywall mud except at the floor.	Lined with drywall from the AHU platform to top plate.
AHU closet open to duct chase?	Yes (later proved false)	Yes	Yes (later proved false)	Yes (later proved false)
Ceiling height in house? Under Chase?	8' 0" 7' 0"	9' 0" 8' 0"	8' 0" 7' 0"	9' 0" - 12' 0" 8' 0" - 10' 0"

Documentation During and After Testing
Once on site at each of the testing locations, researchers further documented the construction details used by each Partner Builder paying special attention to the solutions each had developed for dealing with the obstacles identified in the proposal:

- Meeting the code mandated 7' 0" minimum ceiling height requirement
- Integrating the chase into the house's floor plan and design
- Coordinating sub-contractors in a non-traditional construction process.

Each obstacle is summarized here and followed by three drawings of the Duct chase/AHU closet details and a more thorough description of the construction approaches used by Durham County and Broward County Habitat for Humanity (combined), Bentwood Custom Homes, and FlaHERO. Black and white versions of the drawings suitable for copying are included in Appendix C.

Ceiling Height Requirement: For homes with 8'0" finished ceilings, the Habitat affiliates dealt with the code mandated 7' 0" minimum ceiling height requirement by sizing the ducts to fit in the shallow chase and by specifying the smallest, structurally viable framing for the bottom of the chase to maximize the chase's interior space. Researchers observed use of light gauge metal framing, 2 X 2s, and 2 X 4s. They also carefully located the bottom of the chase to allow adequate space for trim on interior doors.

Design Integration: Without exception, the Builder Partners aligned elements of the house (closets, cabinets, halls, etc.) specifically to ease construction of the chase and avoid running the chase through walls or trusses. Installing and sealing the air barrier and duct system around framing significantly increases complexity and cost of the job. In general, the chase is kept as simple as possible while ensuring that each space can be served.

Trade Coordination: Each Partner Builder consulted key sub-contractors about the chase layout and design during the design phase. These included framing, drywall, insulation, and mechanical contractors. Each also had a designated construction supervisor in charge of ensuring that the chase was built to specification as noted in Table 4.

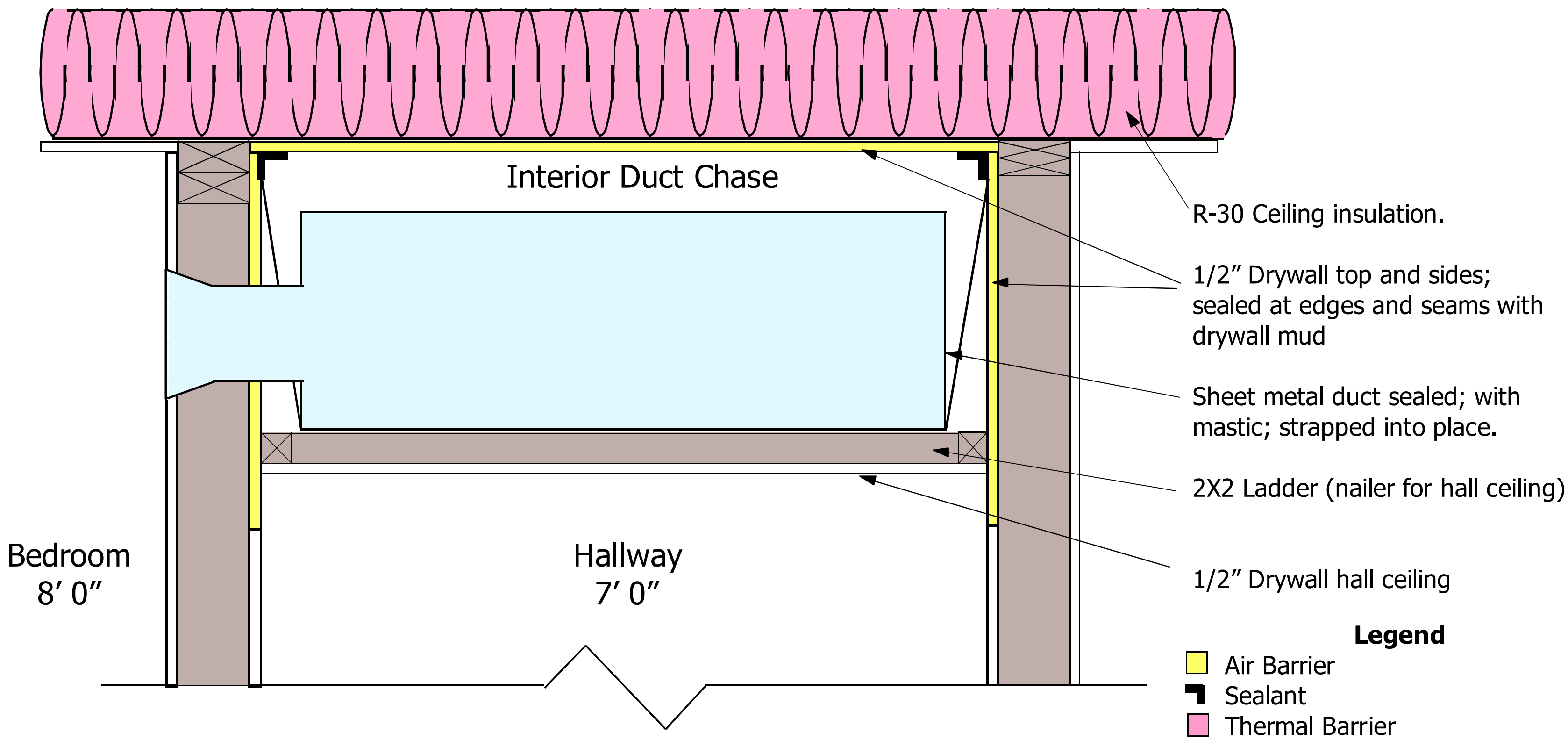
Durham County (Figures 7-10) and Broward County Habitat for Humanity
Background: Habitat for Humanity affiliates (local chapters) have full control over construction methodology within the context of design principals shared by all affiliates. This produces surprising similarity between Habitat homes throughout the country, though the details and construction techniques vary. Most are ranch style homes of about 1100 square feet with a hallway flanked by three or four bedrooms and a bathroom that opens onto a living area including kitchen, family room, and dining area. This similarity appears again in the strategy for building interior duct systems.

Duct Chase and AHU Closet Design: Independently, the two Habitat affiliates developed a similar approach for designing and building their interior duct chase and AHU closets. The AHU is located in a closet either near the center of the house or at one end of the hall. The furred down duct chase springs from there down the hallway and over cabinets and closets. This creates a lower hall ceiling which, to satisfy code, must not be lower than 7'0". Broward Habitat adds about a foot to the width of the hall and uses the upper portion of the bathroom to expand the duct chase if needed. Both affiliates have worked with their mechanical contractors to ensure that ducts are sized to fit inside the shallow chase. In the living room, the chase creates an alcove that many homeowners dedicate as an entertainment center.

Duct Chase and AHU Closet Construction: During framing, one important change is made. Where ever the duct system needs to pass through an interior wall (i.e., from the AHU closet into the hall) a rough opening large enough for the duct is created.

Using the floor plan as a guide, volunteers hang drywall on the trusses to form the top of the duct chase and on the ceiling and walls in the AHU closet. The wall separating the closet from the chase as well as the rough openings in interior walls are covered with drywall. (This factored heavily in blocking air flow during testing.)

Once the top of chase is in place, the chase layout is checked. If any mistakes are found, they can be corrected before the chase sides are installed. Then drywall is hung on the adjacent interior walls forming the chase sides. Neither affiliate seals between the drywall and the interior wall top plate (only the Gainesville home exhibited this), the most likely point of unplanned air exchange. Volunteers seal the drywall edges and seams with drywall mud. This constitutes the air barrier that isolates the ducts/AHU from unconditioned spaces. Supply register locations are marked before the mechanical rough-in.



<u>Assembly Notes for Interior Duct Chase and Interior Air Handler Closet, Details D1-D3:</u>

1. After laying out the path of the duct chase, cover the top and sides of the chase and the air handler closet with drywall.
2. Extend side drywall down to top of door rough opening. Seal drywall at all seams and edges with drywall mud, any code-approved sealant may be substituted. Seal the joint in the handler closet where the drywall meets the sub-floor with drywall mud,
3. Mark location of finished ceiling and ceiling framing. Mark openings for returns and supplies, build air handler platform, cut out rough openings in chase and air handler closet for duct work.
4. Install duct work with strapping. Bottom of duct work must be above height of finished ceiling framing in all hallsand rooms. Set air handler.
5. ALL WIRING OR PLUMBING PENETRATIONS IN THE CHASE AND AIR HANDLER CLOSET MUST BE SEALED.
6. Construct 2X2 “ladder” to support finished ceiling and provide nailing surface to allow drywall installation to cover entire chase and airhandler closet.

D 1

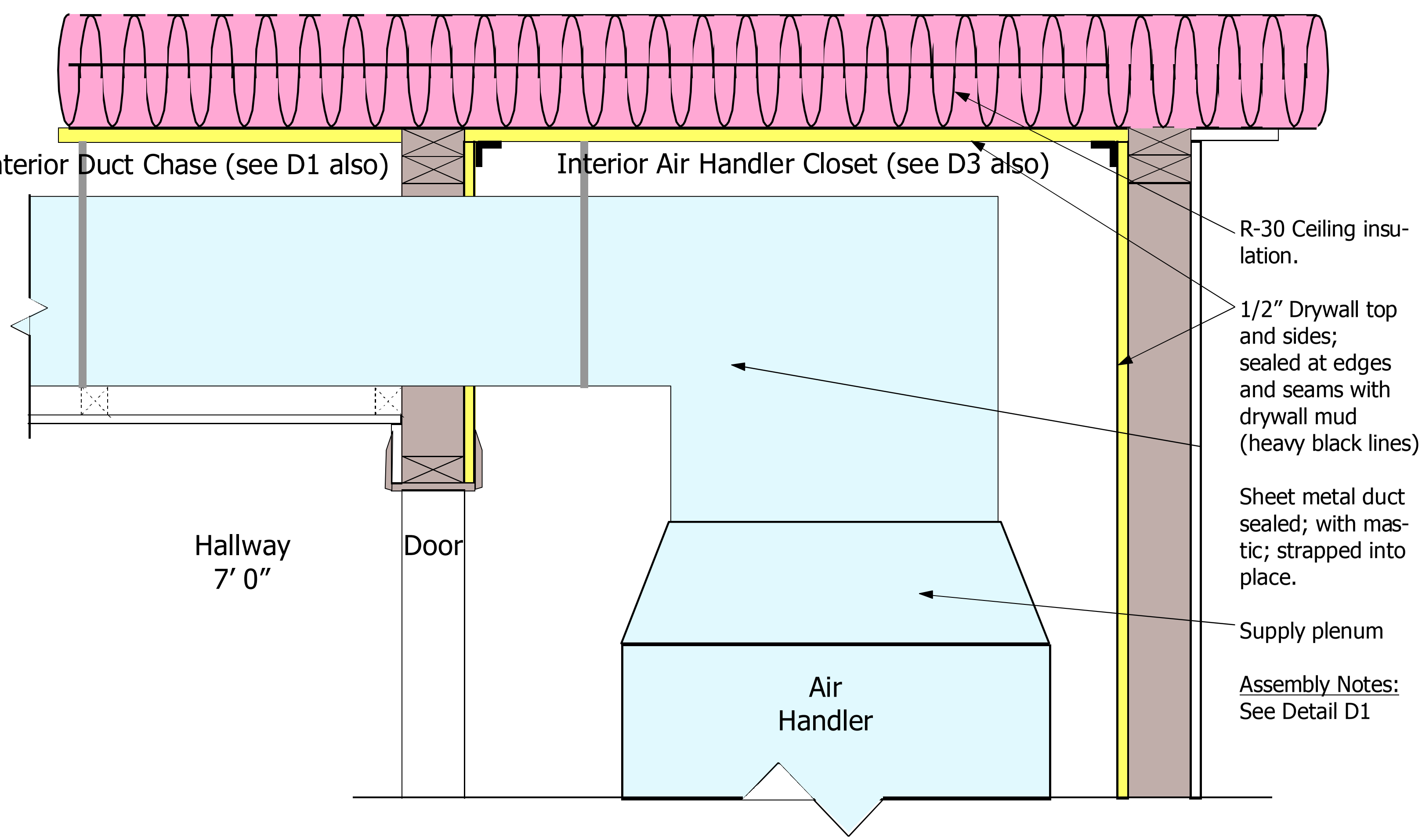
Figure 7 Interior Duct Chase - Section

Scale 1/8” = 1”

D 2

Figure 8 Interior Air Handler Closet - Section - Side View of Upper Closet

Scale 1/8” = 1”



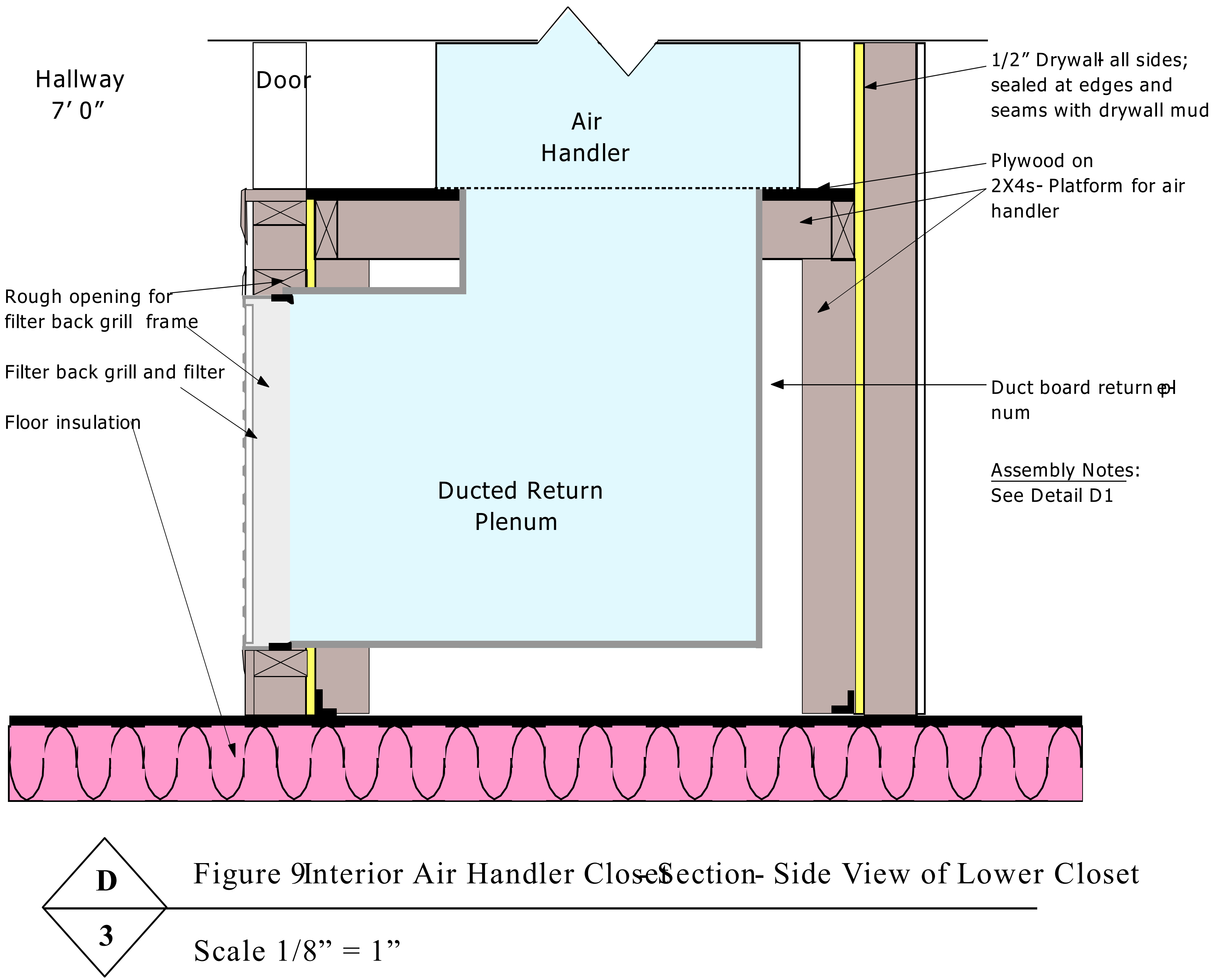


Figure 9 Interior Air Handler Closet - Section- Side View of Lower Closet

Scale 1/8" = 1"

Construction Differences between the Two Habitat Affiliates: Broward Habitat's AHU closet also contains the (electric) hot water heater. The closet is open to the house on two sides (return grill on wall shared with main body of house; louvered or no door wall shared with utility room).. Durham Habitat builds a platform for the AHU after the closet has been sealed. The upper portion contains the AHU and supply plenum. The lower portion contains a short, ducted central return.

To form the chase bottom (hall ceiling), Broward Habitat volunteers install light weight metal framing being careful to maintain the required 7' 0" ceiling height. Openings are made in the chase sides for supply registers and wherever the duct system passes through an interior wall. The mechanical contractor installs supply register boots on the interior wall studs. Then builds the duct system in sections on the floor and slides them into place from the end of the chase.

Durham Habitat waits until the ducts are strapped to the top of the chase before the framing for the bottom of the chase is installed.

Bentwood Custom Homes (Figure 11)
Background: Because the Bentwood homes are custom designs, the chase configuration varied substantially from house to house. Higher ceilings give the builder more flexibility in both chase and duct design. All but one of the Bentwood homes exceeded 1200 ft^2. The floor plans were configured with a master suite on one end, an open living area in the middle, and bedrooms with a bath on the other end.

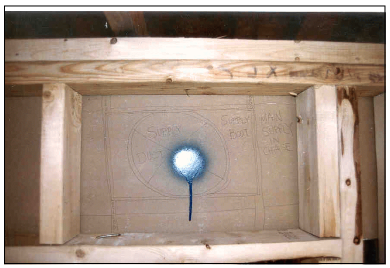
Duct Chase and AHU Closet Design, Construction, and Trade Coordination: Most often in the Bentwood homes, the duct chases also served as architectural elements at the edges of rooms or dividing an open living area. There is no fundamental difference in the construction approach. First, the top and one side are installed, rather than two sides. Then the ducts are installed and the framing for the other side and the bottom.

Generally, the duct chase ran from the master bedroom area in a hallway fur down, across the main living area in an architectural fur down, to the other bedrooms in a hallway fur down, with a centrally located AHU closet. The change in ceiling height provides architectural value by visually dividing the open living area, filling space above kitchen cabinets, and/or providing backing for tray ceilings (over the dining area, for instance). Like the Habitat affiliates, Bentwood's president and construction manager worked closely with sub-contractors on the layout and design of the interior chase.

FlaHERO and Associated Builders
Background: Ken Fonorow provides builders with comprehensive energy efficiency consulting. Hundreds of Energy Star homes, many with interior ducts and AHUs, have been produced in Alachua County (Florida) through the partnerships of FlaHERO and production builders who are motivated by the marketing value of the energy efficiency and indoor air quality benefits. This detail has been implemented in affordable housing (with Alachua County HFH and Lakeland HFH), custom housing, and town houses. Both hallway fur downs and architectural fur downs are used.

Figure 10 *Durham County Habitat for Humanity*

Top of chase from attic. Leakage path down interior wall (after supply run outs are installed).



Supply register location. Note absence of seal at top plate to chase side.

Back of chase side seen from bedroom. Registers are marked with blue spray paint

North Carolina construction. From living area looking down the hall toward bedrooms. Hallway fur down with drywall air barrier sealed at the seams and edges with drywall mud.

Sealed corner joint.

End of chase.

AHU closet. Note continuous air barrier over doorway in foreground. Installers cut a tightly toleranced opening here for the main supply trunk which blocked access to the chase

Duct Chase and AHU Closet Design, Construction, and Trade Coordination: Fonorow has experimented with three approaches to interior ducts/AHUs:

- Modified Trusses (no longer uses)
- Fur Down Chases (test homes)
- "Encapsulated Ducts" (continuing experiments)

In the *modified truss* approach, the bottom chord is altered in the center to create either a rectangular or a trapezoidal fur-up chase that bridges from bedrooms, over the hallway, to the other bedrooms and bisects open living spaces. Supply runs are contained within the house/chase air barrier. Logistically, installers have to work around the interior walls to hang and seal the air barrier. This cumbersome and time consuming process, plus the extra cost of the truss package, made this approach undesirable. This experience has been confirmed by two other Florida builders in independent studies under the DOE Building America program. Mercedes Homes reported difficulty with modified trusses in a Building America study in Melbourne (Energy Design Update, March 2001). Fallman Design and Construction (Lake County, Florida) recently experienced both extra cost and added labor using a modified truss design that did not bridge between rooms. Bentwood has experienced similar challenges with the fur-up approach applied to rafter and joist framing.

In the *furred down chase* approach, supply run outs passing through the chase side (an interior wall) create an air path from the chase to the attic. To block this air path, Fonorow uses an air tight drywall (ATD) technique to seal between top plate and the drywall. An energy specialist, trained by Fonorow, staples 1/3 of a strip of Seal Sill (Dow) to the top plate of all walls, not just those forming the sides of the chase. This thin, compressible, closed cell foam strip was designed to block air flow under exterior wall sole plates in slab-on-grade construction. Essentially it blocks air flow from one edge of the strip to the other. Dry wall gaskets are available for this installation also. With either, the drywall must be set in place at the top plate rather than being set below the top plate and slid into place (typical installation). The chases occur in hallways and at the edges of rooms which often have 9'0" ceiling heights affording some extra room for the duct system.

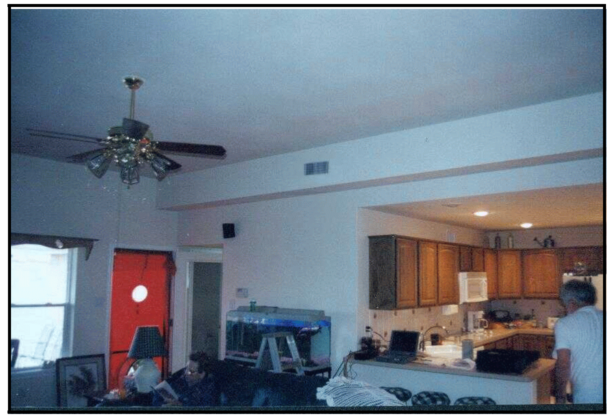
The *encapsulated duct* approach is intriguing. The duct system is installed in the attic, laying on the bottom chords of the trusses. The air handler is installed in an interior closet. After inspections and drywall, but before ceiling insulation is installed, the ducts are buried under a mound of expanding spray foam that forms an air barrier continuous with the ceiling drywall. The foam both seals and insulates the ducts.

In Florida, the ducts have to have insulation equal to the attic insulation to be considered "in the conditioned space" for energy code compliance and rating purposes. At R-5 per inch, an even shroud of 6"of foam insulation would constitute R-30. This would also seal any penetrations into the chase for wiring, plumbing, cable, phone, and security systems, a common occurrence, and protect it from future installations. This approach bears further scrutiny and exploration. Specifically, a way to ensure that an even layer of foam has been applied is needed.

Design and Construction Details

The above findings and additional practical advise for building interior duct chases/ AHU closets can be found in the FSEC Professional Paper FSEC-PF-365-0. Black and while drawings suitable for copying and blueprinting Appendix C.

Figure 11 *Bentwood Custom Homes*



Typical architectural fur down at the edge of a room.
Left: the air barrier (drywall) is installed and sealed, duct work is strapped in place, and framing for the chase sides and bottom is installed.
Right and below: the sides and bottom of the chase are finished with drywall at the same times as the rest of the house.

Typical fur up in the attic
Left: Compromise of both the thermal barrier and the air barrier. Insulation has blown or fallen away from sides and top. Part the chase side was removed for plumbing installation.
Right: Well sealed air barrier and continuous thermal barrier. Spray foam provides both despite wiring penetrations into the chase.

IV. RESULTS AND DISCUSSION

Task 2 -- Field Testing

Tasks Final Statement of Work (10/14/99)		Mile Stones Form 4600.3A		Success Criteria Technical Proposal Appendix A Section B	Planned Completion	Actual Completion
2	Field Testing	6	Test Houses	Test 20-40 of the partner builders' homes to determine effectiveness and identify deficiencies	3/30/00	3/21/00 (20) 6/00 (4 more)

Measurement Caveat
The researchers encountered unexpected physical obstacles which are likely to confront any other building scientist testing homes with interior duct chases/AHU closets.

These limit the usefulness of current testing procedures in assessing duct leakage to the outside. Interior ducts/AHUs frequently appear as part of an energy efficiency package and sometimes play a role in securing financing under programs such as Energy Efficient Mortgages, Energy Star Homes, and possibly tax credits for energy efficiency improvements. Reaching the specified duct tightness target is crucial to realizing energy savings, and the tightness must be verified to qualify for, at least, the Energy Star Homes financing.

Right now, building scientists use standard duct testing methods to quantify the leakage of interior ducts/AHUs to unconditioned spaces. The basic premise of this protocol, referred to as CFM25out, is to eliminate the duct leakage entering the house. For ducts installed in attics and crawl spaces, this leaves only leakage to unconditioned spaces. To accomplish this, a duct tester and a blower door are used simultaneously to equalize the pressure in the Ducts/AHU and the pressure in the house, thus eliminating air flow between the two. The blower door is used to bring the house to ±25 pascals WRTOUT and the Ducts/AHU are brought to 0 pascals WRThouse. In this condition, air will not flow between the Ducts/AHU and the house. Leakage can be assumed to involve only the unconditioned air surrounding them.

With interior ducts/AHUs, the ducts usually reside in a chase which may or may not be fully isolated from the surrounding unconditioned spaces. The researchers assert that results of the standard protocol for CFM25out do not reveal anything about the nature of leakage from interior ducts/AHUs because the air surrounding the duct/AHU system is not unconditioned. Technically, it is not "out".

Since the chase is not brought into pressure equalization with the Ducts/AHU and the house, standard CFM25out measures leakage into the chase as well as leakage into unconditioned spaces. Table 5 illustrates this point by showing that a CFM25out result of 100cfm in an interior Ducts/AHU system could be leakage into the chase rather than leakage into the attic. Leakage into the chase is generally considered harmless, but that assumption is only true if the chase is inside the conditioned space.

Table 5
Conventional CFM25out Testing Implications for Interior Ducts/AHUs

	Induced Pressure (pascals)			**Result (cfm)**	
	House WRTout	**Ducts WRThouse**	**Chase WRThouse**	**CFM25out**	**Implications**
Ducts in attic or crawl space	±25 pa	0	NA	0	No leakage into unconditioned spaces.
Ducts in attic or crawl space	±25 pa	0	NA	100	100cfm of leakage into unconditioned spaces under test conditions.
Interior Ducts/AHU	±25 pa	0	Inaccessible	0	No leakage into chase
Interior Ducts/AHU	±25 pa	0	Inaccessible	100	100 cfm leakage into ***chase or outside*** under test conditions.

The testing protocol developed for this project brings the chase into pressure equalization with the Ducts/AHU and the house. The protocol was to pressurize the house to +25pa WRTout, then the ducts and the chase were brought to 0pa WRThouse using one duct tester at the return grill and one in the doorway of the air handler closet to pressurize the duct chase/AHU closet. However, this proved impossible in all but a few cases due to air flow blockages such as framing, air barriers, and inaccessibility. Visual inspection clearly revealed that duct chase/AHU closets can still be directly connected to unconditioned spaces. This was confirmed in the few homes where the modified CFM25out test could be performed.

Some researchers will argue that air deposited in or taken from the chase is house air. The logic behind this is compelling. If the Ducts/AHU pours air into the chase and it exits the chase into the attic, that is leakage across the house air barrier, not the chase/AHU closet air barrier. If the integrity of the chase air barrier can be evaluated, either through during the whole house testing (CFM50) or dedicated chase testing (ChaseCFM25out), then measuring both Ducts/AHU and chase leakage may indicate the relative success of an interior Ducts/AHU strategy. For example, if the standard CFM25out measurement for an interior Ducts/AHU is 100 and the ChaseCFM25out is 0, then all of the Ducts/AHU leakage is staying inside the conditioned space. Likewise, if the ChaseCFM25out is 100, then none of the Ducts/AHU leakage is staying inside the conditioned space.

For homeowners, lenders, utilities, the IRS, and anyone else concerned with the performance of an interior Ducts/AHU system, this may be a valid approach for evaluation. However, this approach is only feasible if builders adhere to a construction method that allows free flow of air through duct chase/AHU closet as well as providing adequate access to conduct the test. The free flow of air, however, may be a fire code violation. This requires *thorough* review.

Alternatively, if the chase is strongly connected to the house in each segment (if framing/air barriers are present), then the chase would essentially be part of the house, not a separate space. Under these circumstances, the air pressure in the chase would be the same as the house. This approach was briefly considered, however, it would have required researchers to cut holes in the chase. Homeowners had not agreed to invasive measures and there was no way of determining where the chases were segmented by framing or partial air barriers.

In new construction, a pressure relief strategy for the chase to house air barrier (in each segment of the chase) could over come this problem. Pressure relief could be provided with a dummy supply register or return grill.

Testing and Results

With this caveat explained, the following pages detail the measurements that were made at the test homes which produced some indications helpful in answering the original question: *Are construction techniques currently being used to build interior duct chases and AHU closets isolating the conditioned air from unconditioned spaces?*

Test 1 *What is the pressure in the* ***duct chase/AHU closet*** *under normal operation of the air handler?* (Pressure measurements were also taken in the attic, house, supply, and return.)
Test 2 *Is the* ***duct chase/AHU closet*** *(chase and air handler closet) zone isolated from adjacent unconditioned spaces?*
Test 3 *How much is the duct chase/AHU closet leaking to/from the unconditioned space?*
Test 4 *How much is the* ***Ducts/AHU*** *leaking?*

On-Site Pre-testing Activities

Briefly explain the project and the test to the homeowner and/or other builder representatives if present. Set up blower door and duct tester equipment and prepare home for testing using standard building science safety and health precautions.

Test 1: What is the pressure in the ***duct chase/AHU closet*** *under normal operation of the air handler?*

With the air handler fan operating, researchers used a small sensor (thin cylinder less than 1/16" in diameter), air tight tubes, and pressure gauges (APT or manometers) to measure the pressure differential in several locations with respect to the outside (WRT outside). These data (Table 6) were used in Test 3 to set the pressure at which duct leakage under operating conditions would be measured.

Table 6 Test 1 Results
Operating Pressures with Air Handler Unit (AHU) Operating

	Ducts and air	House WRTout pascals	duct chase/AHU closet	Attic WRThouse pascals	Supply WRThouse pascals	Return WRThouse pascals
NC-G823-0003	U					
NC-G824-0003	U				42	
NC-G826-0003	U				42	
NC-G830-0003	U					
NC-J2821-0003	U				42	
NC-E12-0003	C	0.0	3.5	0.0	55	-11.5
NC-G829-0003	C	-1.5	0	0	77	-19
NC-G831-0003	C	-1.5	2.4	0.6	72	-16
NC-J2819-0003	C	-2.5	4	0	80	-15
NC-L1113-0003	C	Too Windy	0.5	-0.3	42	-17.7
TX-B107-0003	C	Too Windy	2.3	0	70	-25
TX-H502-0003	C	Too Windy	-1.5	-1.5	25	-23
TX-L1000-0003	C	Too Windy	-16	Too Windy	20	-18
TX-BC150-0003	C	Too Windy	0	0	9	-3.5
TX-D128-0003	C	Too Windy	0	0	70	-35
TX-P907-0003	C	Too Windy	0	0	35	-11
TX-T122-0003	C	Too Windy	N/A	Too Windy	30	8
TX-W104-0003	C	Too Windy	0	0	25	-18
FL-SW55-0007	C	0.7	0.2	0.3	48	-19
FL-SW56-0007	C	0.3	0.5	0.3	74	-11
FL-NW6-0007	C	0.2	0	0.1	40	-28
FL-GN-0000	C	0.1	0	0	32	-58
***U = Ducts in Unconditioned Space C = Ducts in Conditioned Space**						

Test 2: Is the ***duct chase/AHU closet*** *(chase and air handler closet) zone isolated from adjacent unconditioned spaces? Is the* ***duct chase/AHU closet*** *isolated from adjacent unconditioned spaces?*

Researchers again measured pressure differentials, this time while pressurizing the house with a blower door (large, calibrated fan assembly) to +50 Pascal (Pa) WRTOUT, and whole house leakage in cubic feet per minute at a test pressure of +50 pascals (CFM50) and leakage normalized by conditioned area (ACH50). Table 7 summarizes the possible test results and implications and Table 8 shows the results.

The testing protocol stated that "if the Ducts/AHU is completely isolated from unconditioned spaces, then the pressure in the duct chase/AHU closet WRTOUT will also be +50 pa (0pa WRThouse)" because the duct chase/AHU closet is holding the same pressure as the house. The protocol further states, "If this result appears, then the builder has successfully accomplished the task of placing the Ducts/AHU system in the conditioned space. No further tests will be conducted."

The protocol assumed that the duct chase/AHU closet was fully open to the house and that "if the pressure the [duct chase/AHU closet] WRTOUT was between 0 and +50 Pa [then duct chase/AHU closet] is *communicating* with the unconditioned space." This would warranting further testing to determine how much and where unconditioned air enters and exits the duct chase/AHU closet.(see Tests 2-4). Researchers clearly documented that most of the duct chase/AHU closets were not well connected to the house (see Measurement Caveat) which also returns a result between 0 and +50 pascals as shown in Table 8.

Table 7 - Test 2 Possible Results and Implications

As Stated in the Testing Protocol			Learned from Field Work
IF	**AND**	**THEN**	**ELSE**
House Pressure WRTOUT =	**duct chase/AHU closet Pressure WRThouse =**	**Implication**	**Implication**
+50pa	0pa	duct chase/AHU closet isolated from attic.	
+50pa	0pa < X < -50pa	duct chase/AHU closet is exchanging air with the attic.	duct chase/AHU closet may not be fully communicating with house.
+50pa	-50pa	duct chase/AHU closet is completely outside.	

Table 8 - Test 2 Results
Whole House Air Tightness and Zonal Pressures (House=50 pa WRTout)

	Conditioned Area (ft2)	Volume (ft3)	CFM50 (cfm)	ACH 50 (cfm/ft3)	Pressure WRT house (pascals)			
					Chase	Attic	Supply	Return
NC-G823-0003	1014	8112	1478	10.9	Ducts in Unconditioned Space			
NC-G824-0003	1176	9408	1118	7.13				
NC-G826-0003	960	7680	869	6.79				
NC-G830-0003	962	7696	904	7.05				
NC-J2821-0003	1024	8192	1136	8.32				
NC-E12-0003	1060	8480	1204	8.2	-14.5	-50	0	0
NC-G829-0003	1176	9408	1331	8.49	-10	-52	-0.2	0
NC-G831-0003	1121	8968	1172	7.84	-17	-39	-0.2	-0.2
NC-J2819-0003	1060	8480	1341	9.49	-6.5	-50	0	0
NC-L1113-0003	1228	9824	1979	12.1	-22.2	-48.7	0	0
TX-B107-0003	843	7587	504	3.99	-1.1	-50	0	0
TX-H502-0003	1820	16380	1140	4.18	-38	-48	-0.17	0
TX-L1000-0003*	1931	16414	1723	6.3	-9	-45	-1	-9
TX-BC150-0003	1247	12470	866	4.17	-5.5	-48	-0.2	-0.6
TX-D128-0003	1416	12744	1005	4.73	-38	-48	0	0
TX-P907-0003	1455	15278	1057	4.15	-8	-50	0	0
TX-T122-0003	2040	20000	1309	3.93	0	-48	0	0
TX-W104-0003	2340	23400	1666	4.27	-4.2	-48	0	0
FL-SW55-0007	1230	9840	1060	6.46	-20	-49	0	No Return
FL-SW56-0007	1230	9840	972	5.93	-21.3	-50	0	No Return
FL-NW6-0007	1230	9840	1200	7.32	-23	-49	0	No Return
FL-GN-0000	980	8820	630	4.29	0.5	-49	0	0

Test 3: *If the [duct chase/AHU closet] pressure does not measure 0 or +50 pascals in Test 2, how much is the duct chase/AHU closet leaking to/from the unconditioned space?*

Until recently, software for producing Home Energy Ratings gave interior ducts/AHUs credit for having no leakage based on the assumption that interior ducts/AHUs do not leak to or from unconditioned spaces. Test 3 was designed to determine the validity of that assumption under current construction practice.

The testing protocol stated, "In the case that the result from *Test 2* is neither 0 nor +50 Pa WRTOUT outside, researchers will evaluate the air tightness of the [duct chase/AHU closet]" From Table 8, note that only two houses (highlighted) meet the criteria of 0pa WRThouse. However, six were tested for duct chase/AHU closet air tightness. The others were not tested either because the duct chase/AHU closet would not hold the test pressure (couldn't be pressurized) or because there was an air barrier blocking air flow from the air handler closet into the chase (see *Measurement Caveat* above).

In the six houses, researchers measured both total leakage and leakage to outside of the duct chase/AHU closet (Test 3a), using the standard CFM25out test procedure for the duct chase/AHU closet, not the Ducts/AHU system (Table 9). For the ChaseCFM25out test, the Ducts/AHU system pressure *was not* regulated; hence, air could move between the Ducts/AHU system and duct chase/AHU closet. Researchers conducted modified leakage tests (Test 3b) in four homes that *did* eliminate air flow between the Ducts/AHU system and duct chase/AHU closet. These are designated as Chase&DuctCFM25total" (pressure equalized in Ducts/AHU system and duct chase/AHU closet using two duct testers) and Chase&DuctCFM25out" (pressure equalized in Ducts/AHU system, duct chase/AHU closet, and house). For both tests, the duct tester fan flow required to achieve pressure equalization was measured for both the Ducts/AHU system and duct chase/AHU closet. Results are shown in Table 10. Note that in all four cases, the Ducts/AHU leakage measured in Chase&DuctCFM25out was less than 15cfm, significantly less than the standard CFM25out test reported next in *Test 4*.

Table 9 - Test 3a Results
Leakage at Test and Operating Pressures Duct Chase/AHU Closet Only

	Duct Chase/AHU Closet Leakage at Test Pressure		**Duct Chase/AHU Closet Leakage at Operating Pressure**	
	Total	To Outside	Total	To Outside
NC-G829-0003	242	137	511	286
NC-G831-0003	467	260	934	521
NC-J2819-0003	346	200	774	
TX-L1000-0003	1006	527	Chase/AHU CLOSET is Return - Testing Discontinued	
TX-BC150-0003	957	467	532	248
FL-GN-0000	170	49	Operating Pressure was 0	

Table 10 Test 3b Results
Leakage at Test and Operating Pressures

Duct Chase/AHU Closet and Ducts/AHU Combined

	Chase&DuctCFM25total		Chase&DuctCFM25out	
	Ducts/AHU	Chase/AHU Closet	Ducts/AHU	Chase/AHU Closet
NC-G829-0003	59	209	13	137
NC-G831-0003	73	405	0	254
NC-J2819-0003	15	314	0	190
FL-GN-0000	14	140	8	23

Characterizing Leakage Magnitude

The magnitude of duct chase/AHU closet leakage to unconditioned spaces can be evaluated in two ways (Table 11). An absolute equivalent leakage area (ELA) can be calculated in square inches based on the measured leakage. A normalized leakage area (Qn), which is useful for comparing different sized houses, can be calculated by dividing the measured leakage by the house's conditioned area.

Equivalent Leakage Area

From Appendix D of the Minneapolis Duct Tester Manual, Calculating an Equivalent Leakage Area from Duct Tester Test Results, the equivalent leakage area associated with a given pressure and flow rate is equal to the duct system leakage rate divided by 1.06 times the square root of the duct system pressure. This formula uses calculation procedures from the Canadian General Standards Board CGSB149.10-M86. For this study, duct chase/AHU closet leakage has been substituted for duct leakage in the ELA formula to assess the integrity of the duct chase/AHU closet air barrier.

$$\text{ChaseELA (square inches)} = \frac{\text{Chase\&DuctCFM25out,chase}}{1.06 \text{ X } (\text{Chase Pressure})^{1/2}}$$

Relative Leakage Magnitude

The State of Florida training manual for certifying Class I Home Energy Raters defines normalized air distribution system leakage area, Qn, as "the total volumetric air leakage rate of the air distribution system to and from outdoors when the air distribution system is [de]pressurized to 25 pascals, normalized to the [conditioned] floor area of the house. Specifically, Qn = CFM25/(conditioned floor area)." Again, for this study, duct chase/AHU closet leakage has been substituted for duct leakage in the Qn equation to assess the relative tightness of the duct chase/AHU closet.

$$\text{ChaseQn} = \frac{\text{Chase\&DuctCFM25out,chase}}{\text{Conditioned Area of the House}}$$

The target Qn in Florida for "substantially leak free ducts" is 0.03, meaning that measured leakage (in cfm) is equivalent to 3% of the conditioned floor area (in square feet).

Table 11
Absolute and Relative Leakage Duct Chase/AHU Closet
Duct Chase/AHU Closet and Ducts/AHU System Combined

	Duct Chase/AHU Closet Effective Leakage Area (ELA)	Duct Chase/AHU Closet Qn
	$\frac{\text{Chase\&DuctCFM25out,chase}}{1.06 \text{ X } (\text{ChasePressure})^{1/2}}$	$\frac{\text{Chase\&DuctCFM25out,chase}}{\text{Conditioned Area}}$
NC-G829-0003	25.8	0.12
NC-G831-0003	47.9	0.23
NC-J2819-0003	35.8	0.18
FL-GN-0000	4.3	0.02

*Test 4: How much is the **Ducts/AHU** leaking?*

If interior duct chase/AHU closets did not leak, theoretically Ducts/AHU leakage would not make a significant difference in energy use or indoor air quality. This stance is debatable on grounds that conditioned air moving in unplanned ways interferes with the balanced delivery to and removal of air from each space in the house. But when the duct chase/AHU closet is shown to leak, as all the tested duct chase/AHU closets did, then the tightness of the duct/AHU system again becomes the focus of energy and indoor air quality concerns. Of course, the conditioning system still garners the benefit of the higher thermal protection. Results for the standard duct leakage tests (Test 4a) in each home are shown in Table 12.

For some of the houses, researchers adopted a modified version of ASHRAE Standard 152 (Test 4b) drafted by John Andrews of Brookhaven National Laboratory, technical advisor for this project (Appendix B). Specifically:

A. If CFM25out,supply + CFM25out,return < (0.03 X conditioned floor area)
   Then, use the measured supply and return leakage.
   And for (air handler flow) flow, use the lesser of (0.7 * floor area) or 400 cfm/ton of rated cooling capacity.

B. If CFM25out,supply + CFM25out,return > (0.03 * conditioned floor area)
   Then, measure the supply and return leakage rates separately using Annex C of Standard 152P, i.e., separating the duct/AHU system using a barrier.

For condition B, researchers removed the air handler fan and covered the return air intake with masking to isolate the return portion of the system. The supply side of the air handler was similarly masked to isolate the supply portion of the system. Again note that only the house and duct system were brought into pressure equilibrium for this test, consistent with standard CFM25 testing.

North Carolina systems were not split. All Florida homes met condition A, needing no further testing. Five systems in Texas houses were split, Table 13.

Table 12 - Test 4 Results
Standard Duct Leakage
Duct/AHU System Only

	Area	Standard CFM25 Total	Standard CFM25 Out	Standard Duct Qn
NC-G823	1014	157	90	0.09
NC-G824	1176	104	57.5	0.05
NC-G826	960	92.5	64.5	0.07
NC-G830	962	164	70.5	0.07
NC-J2821	1024	157	61.5	0.06
NC-E12	1060		45	0.04
NC-G829	1176	97	30	0.03
NC-G831	1121	167	56.5	0.05
NC-J2819	1060	124	39	0.04
NC-L1113	1228	205.5	53	0.04
TX-B107	843	126.5	11	0.02
TX-H502	1820	278	78	0.04
TX-L1000	1931	642	323	0.17
TX-BC150	1247	559.5	193.5	0.16
TX-D128	1416	545	70	0.05
TX-P907	1455	255	71	0.05
TX-T122	2040	834	280	0.14
TX-W104	2340	365	100	0.04
FL-SW55	1230	99	28	0.02
FL-SW56	1230	130	30	0.02
FL-NW6	1230	104	35	0.03
FL-GN	980	111	20	0.02

Table 13 - Test 4b Results
Standard Duct Leakage
Supply and Return Measured Separately

	Standard (Table 12)	Supply Side		Return Side	
	Qn	CFM25tot,sup	CFM25out,sup	CFM25tot, ret	CFM25out,ret
TX-BC150-0003	0.16	217	0	480	195
TX-D128-0003	0.05	513	68	186	25
TX-P907-0003	0.05	205	57	112	38
TX-T122-0003	0.14	194	0	890	280
TX-W104-0003	0.04	235	10	198	30

Return Leakage
These results suggest that the air barrier in the AHU closets and return plenums need more attention. This was the case in Texas Homes T122 and BC150. Here the return plenum consisted of rough framing (no air barrier) under the air handler platform. During whole house testing, air flowed down the unfinished walls indicating an air path to the attic. This was evidenced by attic insulation in the return plenum. Shortly after this field test, perhaps as a result of it, the Partner Builder abandoned this approach in favor of ducted returns.

The approach used in the North Carolina houses appears reliable for new construction with a return plenum under an AHU platform. The whole AHU closet is lined with drywall (air barrier) and sealed at the edges and seams before the air handler platform is built.

Supply Leakage
Supply leakage was also present though to a lesser extent. One Texas house, D128, exhibited predominantly supply leaks suggesting that the duct chase/AHU closet air barrier needed more sealing. The Partner Builder developed a strategy for reducing the supply leakage and implemented retrofits several weeks later.

The duct chase was a fur up, rather than a fur down, built on top of the ceiling rafters. The chase was covered with an air barrier on the attic side of the framing. This air barrier stopped at the ceiling joists creating a gap between it and the ceiling finish along the entire length of the chase including the top of the air handler closet. Air flow through those holes was evidenced by disturbances in the insulation.

The Builder's retrofit included filling the gap with wood and sealing the entire chase (from the attic) with spray foam. These steps were taken at the Builder's own expense. Resulting improvement is discussed under Task 4.

Task 3 – Full Development of Refined Details if Needed
No formal drawings were made of the Texas retrofit strategy because it is purely a retrofit and not a detail to be incorporated into new construction. No other specific refinements were recommended or retested.

Researchers found several common air barrier breeches. These, along with summaries of each Partner Builder's design and construction strategies, were summarized in an FSEC Professional Paper (FSEC-PF-365-01) and newsletter style publication. Each Partner Builder was given an opportunity to review both documents. Both have been finalized and are available from the Florida Solar Energy Center.

Task 4 – Field Validation of Refinements
In August, researchers revisited the Texas house to evaluate the effectiveness of retrofits made to the fur up chase and air handler closet.

The retrofit included coating the duct chase (which was a "fur up" resting on the ceiling joists) and the top of the air handler closet from the attic with expanding spray foam insulation. This sealed wiring and plumbing penetrations as well as the framing air paths into the return plenum of the AHU closet.

A difficult detail in this home involved the gap between the ceiling drywall and the duct chase itself, resulting in a 3.5" high gap between every joist in the attic. When retrofitting, the builder had the gaps filled with 2 X 4 blocking. However, the technician installing the foam only covered the sides of the chase and not the new blocking, leaving a crack at all four edges of the blocking. (This points out the impact of sub-contractors not understanding the intent of the detail.)

Keeping in mind the pitfalls of conventional CFM25 testing for interior duct/AHU systems, the results were indicative of success, reducing Ducts/AHU system leakage to the outside 36%, from 70 CFM25out to 46.5 CFM25out. The Qn was reduced from 4.9% to 3.3%.

In subsequent construction including the one new house researchers visited, the builder switched to a sealed air handler closet and a ducted return, rather than an open plenum, to significantly reduce return leaks.

Task 6 -- Technology Transfer
Researchers completed the newsletter style document for distribution to energy research, home building, and design professionals. From this colorful summary, readers may request the FSEC Professional Paper (FSEC-PF-365-01) which contains more details on how to implement this strategy. The Department of Energy and each Partner Builder were given an opportunity to review both documents. Contact the Florida Solar Energy Center for copies. Both will be made available on FSEC's web site, www.fsec.ucf.edu, key word interior ducts.

Conference Presentations
The research was very favorably received at the American Council on an Energy Efficient Economy (ACEEE) Summer Study in August. Approximately 50 people inquired about the work during a 2 hour poster session.

At the 2001 Affordable Comfort Conference in Minneapolis in April, the research was again presented to favorable reception. Approximately 50 attended the session. 19 evaluations are summarized in Table 14.

Table 14
Presentation Evaluations - 2001 Affordable Comfort Conference
Forced Air Strategies for High Performance Housing

	Excellent				**Poor**
Category	**5**	**4**	**3**	**2**	**1**
Accurate content/knowledge	8	11	1	0	0
Communicated effectively	9	9	1	1	0
Well organized/well planned	10	8	2	0	0
Responsive to participant's needs	9	10	0	0	0
Total	**36**	**38**	**4**	**1**	**0**

V. CONCLUSION

Researchers conducted standard building science tests as well as tests designed to evaluate the degree of separation between the Ducts/AHU system and adjacent unconditioned and wall cavities. Originally, researchers planned to use infrared imaging to document common breeches in both the air barrier and the thermal barrier designed to isolate the Ducts/AHU system from unconditioned air; however, this proved impractical because of insufficient temperature differences, attic insulation, as well as being unnecessary because visual inspection was often sufficient to locate holes, missing insulation, and unplanned air flow.

Interior Duct Chase/AHU Closet Design

Without exception, the Partner Builders made provisions in the design specifically to ease construction of and/or take advantage of the aesthetic of the duct chase. There included:

- Aligning hallways with closets, cabinets, and plant shelves to simplify the path of the duct chase.(All)
- Adjusting ceiling heights and hallway widths to accommodate correctly sized ducts OR adjusting duct sizing, materials, and design to fit in the duct chase and be easier to install.(All)
- Allotting interior space for the air handler.(All)
- Developing the aesthetic value of the duct chase. (Texas, North Florida, South Florida.)
- Developing interior wall sections that reduce leakage to the attic. (North Florida)

Interior Duct Chase/AHU Closet Construction

Building interior ducts/AHUs requires a shift in the construction process. Contractors must begin to establish the house's air barrier earlier in the building process, before the rough-in of the electrical, plumbing, and mechanical system. Even in simple homes this creates a new set of responsibilities that must absorbed by the traditional trades such as framers and drywallers (as in the Texas homes) or by a new trade such as an energy specialist (as in the North Florida homes). The responsibilities include:

- Laying out the duct chase during rough framing to ensure a clear path free of interior wall framing from the air handler closet to every space requiring supply air.
- Ensuring that a continuous air barrier is installed on all surfaces of the duct chase/AHU closet that separate it from unconditioned spaces including interior wall cavities, attics, crawlspaces, garages, floor cavities, plumbing chases, and any other space not receiving supply air.
- Ensuring that all penetrations in the air barrier are filled with a code approved sealant prior to ceiling insulation installation
- Ensuring that all code mandated ceiling height requirements are met.
- Coordinating the sub-contractors involved with duct chase/AHU closet
- Solving unexpected conflicts

In Texas, North Carolina, and South Florida, the duct chase/AHU closet air barrier was routinely compromised by supply "runouts" (from the main supply to the supply boot) that penetrated the duct chase sides. To prevent exchange with unconditioned spaces, all duct chase/AHU closet air barrier joints must be sealed, including the duct chase, return air plenum and platform (if present), and the air handler closet.

A major factor in duct chase/AHU closet leakage appears to be penetrations for wiring and plumbing runs. Plumbers, electricians, phone, cable, and alarm installers view the duct chase as a dropped ceiling, not as an airtight cavity, and use it for access throughout the house. Trade coordination is critical to preserve the intent of the duct chase/AHU closet and to avoid (or at least seal) penetrations in the air barrier. Supervision of the duct chase/AHU closet construction most effectively falls at the general contractor level.

Interior Duct Chase/AHU Closet Performance

Researchers found that the thermal barrier covering the duct chase and top of the air handler closet was to intact, in most of the homes. The duct chase/AHU closet air barrier, however, was typically compromised. Ducts/AHUs housed in leaky duct chase/AHU closets are not isolated from unconditioned spaces and reap only the thermal benefit of interior ducts/AHUs.

> Due to several instances of unexpected, significant leakage in the duct chase/AHU closet air barrier, especially near the air handler, **the researchers recommend that builders implement the interior duct chase/AHU closet details documented here only in conjunction with a comprehensive Ducts/AHU sealing strategy using mastic and avoid using the duct chase as a surrogate duct for supply or return.**

Many of the air barrier breeches were obvious from visual inspection, others became apparent though testing. Common leak sites were where:

- Duct work (supply run outs) passed through interior walls
- Wiring or plumbing penetrations in the duct chase were not sealed
- Joints in the air handler closet were inadequately sealed

Measuring Interior Duct/AHU System Performance and Rating Homes with Interior Ducts/AHUs

Changes in Home Energy Rating Software have eliminated the artificially high "credit" for interior ducts/AHUs by allowing raters to input measure leakage for these systems. The current methodology for measuring leakage to the outside (CFM25out) is valid only if the air pressure in the duct chase/AHU closet can be equalized with the house and the ducts/AHU system (see *Measurement Caveat* in IV. RESULTS AND DISCUSSION).

Unfortunately, researchers found that most of the duct chase/AHU closets could not be (de)pressurized because of framing and/or air barrier obstructions. Thus the value of entering the measured leakage is diminished by the inaccuracy of the test. At this time however, building scientists have little choice. Invasive measures such as cutting a hole to better connect the duct chase/AHU closet with the house add time and cost to the standard testing process as well as being objectionable to homeowners.

If builders constructed duct chase/AHU closets to be purposely connected to the house, these problems could be avoided. This might take the form of pressure relief registers in each segment to allow the duct chase/AHU closet to be pressurized by pressurizing the whole house. Another approach might be to delay installation of the mechanical system until after drywall finishing. However, this might seem to encourage using the duct chase as an unducted return path, similar to a panned joist which is strongly discouraged. As researchers saw, this would be folly since the Duct chase/AHU closets are not necessarily tighter than any other building cavity.

This matter needs to be addressed by ASHRAE Standard 152p. As this detail gains popularity, more building scientists and home energy raters will face these challenges.

Quantitative Analysis

Researchers conducted standard CFM25out tests in all the houses as part of the testing protocol. Based on those tests, researchers found the following:

In the North Caroline homes, those with interior ducts/AHUs averaged a normalized leakage of 0.04 (CFM25out/conditioned area = Qn) while those with attic and crawl space ducts averaged 0.068, a 40% improvement.

At one of the Texas houses, the return plenum was formed by unfinished and unsealed rough framing drawing in unconditioned air from the attic under the AHU's significant negative pressure. Retrofit measures included sealing the top of the AHU closet as well as the duct chase from the attic with expanding spray foam. Normalized leakage dropped from 0.048 to 0.033, a 36% improvement.

Conversely, one of the Texas homes has the best Qn to the outside (1.3%) in all the testing. It was a small home with a through-the-wall package unit on an interior wall and no return duct work The builder's *supply* ducts were consistently put together with mastic and tight.

Interior duct chase/AHU closet design and construction is a viable option for reducing the impact of duct/AHU leakage as well as heat transfer, but it requires careful planning and trade cooperation. The benefits reach from the mechanical contractor to the builder to the homeowner as the ducts/AHU system is easier to install, maintains comfort for less money, and requires less maintenance and repair.

VII. REFERENCES AND RECOMMENDED READING

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VIII. LIST OF ACRONYMS AND ABBREVIATIONS

ach	Predicted or measured number of whole-house, complete air changes per hour under natural conditions.
ACH50	Number of whole-house, complete air changes per hour at a test pressure of 50 pascals with respect to the outside. Calculated using the measured CFM50 as follows: (CFM50 X 60)/Conditioned Volume.
AHU	Air Handler Unit
cfm	Cubic feet per minute
CFM25total	Duct tester fan flow required to achieve 25 pascals pressure in the ducts/AHU.
CFM25out	This test eliminates air flow between the ducts/AHU and the surrounding space. It requires a duct tester and second calibrated fan. The duct tester measures fan flow required to achieve 25 pascals pressure (WRTout) in the ducts/AHU. The second calibrated fan is used to equalize the pressure between the ducts/AHU and the surrounding space.
ChaseCFM25	Duct tester fan flow required to achieve 25 pascals pressure in the duct chase/AHU closet.
Chase&DuctCFM25	This test eliminates air exchange between the ducts/AHU and the duct chase/AHU closet. Two duct testers are used simultaneously. One measures the flow required to achieve 25 pascals pressure in the duct chase/AHU closet (Chase&DuctsCFM25chase) . The other measures flow required to achieve 25 pascals pressure in the ducts/AHU (Chase&DuctsCFM25duct).
CFM50	Fan flow in cubic feet per minute required to achieve 50 pascals pressure in whole house.
FlaHERO	Florida Home Energy Resources Organization. Gainesville (FL) based business founded and operated by Ken Fonorow, whose builders participated as Partner Builders.
FSEC	Florida Solar Energy Center
HFH	Habitat for Humanity
WRT	With Respect To. Describes the reference location that a pressure differential is being measured against.

Appendix A: Testing Results

Interior Duct System Project: Basic Information and Characteristics									
House ID	Area (LxW)	Volume	CFM50	ACH 50	Split/Gas?	Ducts CFM25 Total	Ducts CFM25 Out	Ducts % Leakage to Out (Qn)	Duct Location
NC-G823-0003	1014	8112	1478	10.9	No/No	157	90	8.9%	U
NC-G824-0003	1176	9408	1118	7.13	No/No	104	57.5	4.9%	U
NC-G826-0003	960	7680	869	6.79	No/No	92.5	64.5	6.7%	U
NC-G830-0003	962	7696	904	7.05	No/No	164	70.5	7.3%	U
NC-J2821-0003	1024	8192	1136	8.32	No/No	157	61.5	6.0%	U
NC-E12-0003	1060	8480	1204	8.2	No/No	0	45	4.2%	C
NC-G829-0003	1176	9408	1331	8.49	No/No	97	30	2.6%	C
NC-G831-0003	1121	8968	1172	7.84	No/No	167	56.5	5.0%	C
NC-J2819-0003	1060	8480	1341	9.49	No/No	124	39	3.7%	C
NC-L1113-0003	1228	9824	1979	12.1	No/No	205.5	53	4.3%	C
TX-B107-0003	843	7587	504	3.99	No/No	126.5	11	1.3%	C
TX-H502-0003	1820	16380	1140	4.18	No/No	278	78	4.3%	C
TX-L1000-0003*	1931	16413.5	1723	6.3	No/Yes	642	323	16.7%	C
TX-BC150-0003	1247	12470	866	4.17	Yes/No	559.5	193.5	15.5%	C
TX-D128-0003	1416	12744	1005	4.73	Yes/No	545	70	4.9%	C
TX-P907-0003	1455	15278	1057	4.15	Yes/No	255	71	4.9%	C
TX-T122-0003	2040	20000	1309	3.93	Yes/No	834	280	13.7%	C
TX-W104-0003	2340	23400	1666	4.27	Yes/No	365	100	4.3%	C
FL-SW55-0007	1230	9840	1060	6.46	No/No	99	28	2.3%	C
FL-SW56-0007	1230	9840	972	5.93	No/No	130	30	2.4%	C
FL-NW6-0007	1230	9840	1200	7.32	No/No	104	35	2.8%	C
FL-GN-0000	980	8820	630	4.29	No/No	111	20	2.0%	C

Interior Duct System Project: Operating Pressures

	Duct Locatio	House Op AHU On WRTout (pa)	Chase Op AHU On WRThouse	Attic Op AHU On WRThouse	Supply Op AHU On WRThouse	Return Op AHU On WRThouse (pa)
NC-G823-0003	U					
NC-G824-0003	U				42	
NC-G826-0003	U				42	
NC-G830-0003	U					
NC-J2821-0003	U				42	
NC-E12-0003	C	0.0	3.5	0.0	55	-11.5
NC-G829-0003	C	-1.5	0	0	77	-19
NC-G831-0003	C	-1.5	2.4	0.6	72	-16
NC-J2819-0003	C	-2.5	4	0	80	-15
NC-L1113-0003	C	Windy	0.5	-0.3	42	-17.7
TX-B107-0003	C	Windy	2.3	0	70	-25
TX-H502-0003	C	Windy	-1.5	-1.5	25	-23
TX-L1000-0003*	C	Windy	-16	Windy	20	-18
TX-BC150-0003	C	Windy	0	0	9	-3.5
TX-D128-0003	C	Windy	0	0	70	-35
TX-P907-0003	C	Windy	0	0	35	-11
TX-T122-0003	C	Windy	N/A	Windy	30	8
TX-W104-0003	C	Windy	0	0	25	-18
FL-SW55-0007	C	0.7	0.2	0.3	48	-19
FL-SW56-0007	C	0.3	0.5	0.3	74	-11
FL-NW6-0007	C	0.2	0	0.1	40	-28
FL-GN-0000	C	0.1	0	0	32	-58

Interior Duct System Project: Zonal Pressures House = +50WRTout				
	Chase	Attic WRThouse (pa)	Supply WRThouse (pa)	Return WRThouse (pa)
	House = +50	House = +50 WRTout	House = +50 WRTout	House = +50 WRTout
NC-G823-0003				
NC-G824-0003				
NC-G826-0003				
NC-G830-0003				
NC-J2821-0003				
NC-E12-0003	-14.5	-50	0	0
NC-G829-0003	-10	-52	-0.2	0
NC-G831-0003	-17	-39	-0.2	-0.2
NC-J2819-0003	-6.5	-50	0	0
NC-L1113-0003	-22.2	-48.7	0	0
TX-B107-0003	-1.1	-50	0	0
TX-H502-0003	-38	-48	-0.17	0
TX-L1000-0003*	-9	-45	-1	-9
TX-BC150-0003	-5.5	-48	-0.2	-0.6
TX-D128-0003	-38	-48	0	0
TX-P907-0003	-8	-50	0	0
TX-T122-0003	0	-48	0	0
TX-W104-0003	-4.2	-48	0	0
FL-SW55-0007	-20	-49	0	No Return
FL-SW56-0007	-21.3	-50	0	No Return
FL-NW6-0007	-23	-49	0	No Return
FL-GN-0000	0.5	-49	0	0

Interior Duct System Project: Duct Leakage at Test Pressure					
	Ducts Total @25 (cfm)	Chase ΔP WRT house (pa) during Ducts Total	Ducts Out @25 (cfm)	Chase ΔP WRT house (pa) during Ducts Out	% Leakage to outside (cfm/sqft)
	House=0 WRT out Ducts =	House=0 WRT out Ducts = 25 WRT house	House=25 WRTout Ducts = 0 WRT house	House=25 WRTout Ducts = 0 WRT house	
NC-G823-0003	157		90		8.9%
NC-G824-0003	104		57.5		4.9%
NC-G826-0003	92.5		64.5		6.7%
NC-G830-0003	164		70.5		7.3%
NC-J2821-0003	157		61.5		6.0%
NC-E12-0003	0		45		4.2%
NC-G829-0003	97		30		2.6%
NC-G831-0003	167	1.3	56.5	-6.5	5.0%
NC-J2819-0003	124	2.2	39	-4	3.7%
NC-L1113-0003	205.5		53		4.3%
TX-B107-0003	126.5	2.7	11	-1	1.3%
TX-H502-0003	278		78		4.3%
TX-L1000-0003*	642	0	323	-8	16.7%
TX-BC150-0003	559.5		193.5	-3	15.5%
TX-D128-0003	545		70		4.9%
TX-P907-0003	255	1.6	71	-2.8	4.9%
TX-T122-0003	834		280		13.7%
TX-W104-0003	365		100		4.3%
FL-SW55-0007	99	1.3	28	-0.8	2.3%
FL-SW56-0007	130	1.3	30	-0.8	2.4%
FL-NW6-0007	104	0.7	35	-10	2.8%
FL-GN-0000	111		20		2.0%

Interior Duct System Project: Duct Leakage with System Split

				Ducts Total @25 (cfm) split **SUPPLY**	Chase ΔP WRT house (pa) during Ducts Total @25 split	Ducts Total @25 (cfm) split **RETURN**	Chase ΔP WRT house (pa) during Ducts Total @25 split	Ducts Out @25 (cfm) split **SUPPLY**	Chase ΔP WRT house (pa) during Ducts Out @25 split	Ducts Out @25 (cfm) split **RETURN**	Chase ΔP WRT house (pa) during Ducts Out @25 split **RETURN**
	Ducts Total @25p	Ducts Out @25p	Split/Gas	House=0 WRT out Ducts = 25 WRT house	House=0 WRT out Ducts = 25 WRT	House=0 WRT out Ducts = 25 WRT house	House=0 WRT out Ducts = 25 WRT house	House=25 WRTout Ducts = 0 WRT	House=25 WRTout Ducts = 0 WRT	House=25 WRTout Ducts = 0 WRT house	House=25 WRTout Ducts = 0 WRT house
NC-G823-0003	157	90	No/No								
NC-G824-0003	104	57.5	No/No								
NC-G826-0003	92.5	64.5	No/No								
NC-G830-0003	164	70.5	No/No								
NC-J2821-0003	157	61.5	No/No								
NC-E12-0003	0	45	No/No								
NC-G829-0003	97	30	No/No								
NC-G831-0003	167	56.5	No/No								
NC-J2819-0003	124	39	No/No								
NC-L1113-0003	205.5	53	No/No								
TX-B107-0003	126.5	11	No/No								
TX-H502-0003	278	78	No/No								
TX-L1000-0003*	642	323	No/Yes								
TX-BC150-0003	559.5	193.5	Yes/No	217	0	480	2.5	0	0	195	-2.5
TX-D128-0003	545	70	Yes/No	513		186		68		25	
TX-P907-0003	255	71	Yes/No	205		112		57	-3.5	38	
TX-T122-0003	834	280	Yes/No	194		890		0		280	
TX-W104-0003	365	100	Yes/No	235		198		10		30	
FL-SW55-0007	99	28	No/No								
FL-SW56-0007	130	30	No/No								
FL-NW6-0007	104	35	No/No								
FL-GN-0000	111	20	No/No								

Interior Duct System Project: Duct Leakage at Operating Pressure

	Ducts Total @Sup Operating Pres (cfm)	Chase ΔP WRT house (pa) during Ducts Total @Sup	Ducts Out @Sup Operating Pres (cfm)	Chase ΔP WRT house (pa) during Ducts Out @Sup	Ducts Total @Sup (cfm) split **SUPPLY**	Ducts Total @Sup (cfm) split **RETURN**	Ducts Out @Sup (cfm) split **SUPPLY**	Ducts Out @Sup (cfm) split **RETURN**
	House=0 WRT out Ducts=SOP WRT house	House=0 WRT out Ducts=SOP WRT house	House=SOP WRTout Ducts= 0 WRT house	House=0 WRT out Ducts=SOP WRT house	House=0 WRT out Ducts=SOP WRT house	House=0 WRT out Ducts=SOP WRT house	House=SOP WRTout Ducts= 0 WRT house	
NC-G823-0003								
NC-G824-0003	146		81					
NC-G826-0003	133		94					
NC-G830-0003	255		110					
NC-J2821-0003	188		90					
NC-E12-0003	277		75					
NC-G829-0003	225		69					
NC-G831-0003	370	4.2	132					
NC-J2819-0003	307	7	90					
NC-L1113-0003	303		80					
TX-B107-0003	250	9	39	-6				
TX-H502-0003	278		78					
TX-L1000-0003*	242	0	101	-8				
TX-BC150-0003	360		134		130		0	
TX-D128-0003	can't reach		148					
TX-P907-0003	342	2.5	105		336		61	
TX-T122-0003	944		350		224	970	0	350
TX-W104-0003	365		100					
FL-SW55-0007	155	2.2	52	-18.5				
FL-SW56-0007	312	3.2	72	-32				
FL-NW6-0007	141	1	47	-17.5				
FL-GN-0000	127							

Interior Duct System Project: Chase Leakage					
	Chase Total @25 (cfm)	Chase Out @25 (cfm)	Chase % Leakage to outside (cfm/sqft)	Chase Total @Operating Pressure (cfm)	Chase Out @Operating Pressure (cfm)
	House=0 WRT out Chase = 25 WRT house	House=25 WRTout Chase = 0 WRT house		House=0 WRT out Chase=SOP WRT house	House=Supply OP WRTout Chase= 0 WRT house
NC-G823-0003	no chase	no chase	no chase	no chase	no chase
NC-G824-0003	no chase	no chase	no chase	no chase	no chase
NC-G826-0003	no chase	no chase	no chase	no chase	no chase
NC-G830-0003	no chase	no chase	no chase	no chase	no chase
NC-J2821-0003	no chase	no chase	no chase	no chase	no chase
NC-E12-0003	no access	no access	no access	no access	no access
NC-G829-0003	242	137	11.6%	511	286
NC-G831-0003	467	260	23.2%	934	521
NC-J2819-0003	346	200	18.9%	774	
NC-L1113-0003	no access	no access	no access	no access	no access
TX-B107-0003	no access	no access	no access	no access	no access
TX-H502-0003					
TX-L1000-0003*	1006	527	27.3%	chase is return	chase is return
TX-BC150-0003	957	467	37.4%	532	248
TX-D128-0003	can't reach	can't reach	can't reach	can't reach	can't reach
TX-P907-0003	can't reach	can't reach	can't reach	can't reach	can't reach
TX-T122-0003					
TX-W104-0003	too complex	too complex	too complex	too complex	too complex
FL-SW55-0007	no access	no access	no access	no access	no access
FL-SW56-0007	no access	no access	no access	no access	no access
FL-NW6-0007	no access	no access	no access	no access	no access
FL-GN-0000	170	49	5.0%		

Interior Duct System Project: Chase + Duct Leakage								
	Chase&Ducts Total @25 (cfm25tot **DUCT**)	Chase&Ducts Total @25 (cfm25tot **CHASE**)	Chase&Ducts Out @25 (cfm25out **DUCT**)	Chase&Ducts Out @25 (cfm25out **CHASE**)	Chase&Ducts Total@SOP (cfmSOPtot **DUCT**)	Chase&Ducts Total@SOP (cfmSOPtot **CHASE**)	Chase&Ducts Out @Sup Op (cfmSOPout **DUCT**)	Chase&Ducts Out @Sup Op (cfmSOPout **CHASE**)
	House = 0 WRT out Duct=Chase = +25 WRT house	House = 0 WRT out Duct=Chase = +25WRT house	House=Duct=Chase= +25 WRTout	House=Duct=Chase= +25 WRTout	House = 0 WRT out Duct=Chase= SOP WRT house	House = 0 WRT out Duct=Chase= SOP WRT house	House = SOP WRTout Chase = 0 WRT house	House = SOP WRTout Chase = 0 WRT house
NC-G823-0003	no chase	no chase	no chase	no chase	no chase	no chase	no chase	no chase
NC-G824-0003	no chase	no chase	no chase	no chase	no chase	no chase	no chase	no chase
NC-G826-0003	no chase	no chase	no chase	no chase	no chase	no chase	no chase	no chase
NC-G830-0003	no chase	no chase	no chase	no chase	no chase	no chase	no chase	no chase
NC-J2821-0003	no chase	no chase	no chase	no chase	no chase	no chase	no chase	no chase
NC-E12-0003	no access	no access	no access	no access	no access	no access	no access	no access
NC-G829-0003	59	209	13	137	125	404.5	25	281
NC-G831-0003	73	405	0	254	85	781	0	521
NC-J2819-0003	15	314	0	190	288	700	0	443
NC-L1113-0003	no access	no access	no access	no access	no access	no access	no access	no access
TX-B107-0003	no access	no access	no access	no access	no access	no access	no access	no access
TX-H502-0003								
TX-L1000-0003*	chase is return	chase is return	chase is return	chase is return	chase is return	chase is return	chase is return	chase is return
TX-BC150-0003								
TX-D128-0003	can't reach	can't reach	can't reach	can't reach	can't reach	can't reach	can't reach	can't reach
TX-P907-0003	can't reach	can't reach	can't reach	can't reach	can't reach	can't reach	can't reach	can't reach
TX-T122-0003								
TX-W104-0003	too complex	too complex	too complex	too complex	too complex	too complex	too complex	too complex
FL-SW55-0007	no access	no access	no access	no access	no access	no access	no access	no access
FL-SW56-0007	no access	no access	no access	no access	no access	no access	no access	no access
FL-NW6-0007	no access	no access	no access	no access	no access	no access	no access	no access
FL-GN-0000	14	140	8	23				

Appendix B: Final Test Procedure and Addendum

Final Test Procedure and Addendum

Revision of Task 2 -- Field Testing

The Recipient shall send a team of two researchers to conduct testing at each partner builder's location. The Recipient shall implement the following testing protocol:

Pre-testing Activities
Briefly explain the project and the test to the homeowner and/or other builder representatives if present.

Set up blower door and duct tester equipment and prepare home for testing using standard building science safety and health precautions.

Conduct Test 1: What is the pressure in the duct chase under normal operation of the air handler?
Using a small sensor (thin cylinder less than 1/16" in diameter), researchers shall measure the differential pressure in the duct chase with respect to the outside (WRT outside) while the air handler is operating. If possible, sensor measurements shall be taken in several locations within the duct chase to ensure data are representative of the overall duct chase system. These data shall be recorded for use in Test 3.

Note: All pressure and flow measurements shall be read using digital manometers.

Conduct Test 2: Is the duct chase (including the air handler closet) isolated from adjacent unconditioned spaces?
Researchers shall again measure duct chase differential pressure, this time while pressurizing the house with a blower door (large, calibrated fan assembly) to +50 Pascal (Pa) with respect to outside atmospheric pressure. If ducts are completely isolated from the unconditioned space, then the pressure in the chase WRT outside will also be +50 Pa. If this result appears, then the builder has successfully accomplished the task of placing the ducts in the conditioned space. No further tests will be conducted.

> Ducts completely isolated from unconditioned space: P_{chasee} $WRT_{outside}$ = +50 Pa
>
> If the pressure in the duct chase WRT outside is between 0 and +50 Pa, that means that the duct chase is "communicating" with the unconditioned space. Further testing is needed to determine how much unconditioned air is entering the duct chase, or how much conditioned air is exiting, and where (see Tests 2-4).
>
> Ducts are communicating with the unconditioned space: P_{chasee} $WRT_{outside}$ < +50 Pa
>
> Note that if the pressure reads 0 Pa WRT outside then the duct chase is completely outside. That means all duct leakage is associated with unconditioned air, just as if the ducts were in the attic or crawlspace instead of the specially designed duct chase.

Conduct Test 3: How much is the ***chase*** *leaking to/from the unconditioned space?*

In the case that the result from test 2 is neither 0 nor +50 Pa WRT outside, researchers will evaluate the air tightness of the duct chase. Researchers will measure the total leakage of the duct chase (including the air handling unit (AHU) closet) as well as the leakage to the outside of the chase.

Total leakage of the chase will be assessed by reading the pressure across the duct tester fan required to pressurize the duct chase to +25 Pa WRT outside. Since the duct tester is a calibrated device, this pressure is analogous to a flow rate. This measurement shows the combined leakage to both the conditioned and the unconditioned spaces. This test will be conducted at several differential pressures including the operating pressure found in Test 1. This set of testing pressures will remain the same for each test conducted. The duct chase pressurization will be accomplished by first masking off all the supply and return registers, then installing a duct tester in the door of the AHU closet. This set up looks like a blower door set up but uses a blower door curtain with an opening is sized to fit the smaller duct tester fan. Results from this test will quantify total leakage of the chase at +25 Pa WRT outside as well as total chase leakage at operating conditions.

The next test will eliminate leakage into/from the conditioned space. With the duct tester configuration still in place, the whole house will be pressurized to +25 Pa WRT outside using a blower door. This will eliminate the pressure difference across the chase wall and hence air flow between the two spaces. Again, this will be a multipoint test including the operating pressure as described in Test 2. The flow measured will quantify chase leakage to the outside/unconditioned space at the test pressure as well as under operating conditions.

While the house is in the second configuration of this test, infrared scanning will be used to determine where the chase is leaking to the unconditioned space. Infrared images will be used to document the predominate leak sites. Leakage patterns will be characterized and addressed in refinement of the details. Infrared images will also be used to show changes in the air exchange pattern when the leak site has been eliminated. If the leak site(s) are accessible, the refinements will be implemented and changes in air flow documented. If leaks are not accessible, the refinements will be incorporated into subsequently built homes and evaluated in a second visit. Infrared scanning will be done from the adjacent unconditioned space (i.e. attic) and/or the conditioned spaces adjacent to the duct chase. The infrared camera will likely be an Inframetrics color IR camera recorder. This model has a detachable (from the base) camera element that allows great freedom of movement. The backup camera is an Agema model which is also small enough to take in an attic. Under these test conditions, leakage will be from or to the unconditioned space through penetrations in the duct chase or at the point where the duct chase opens to the conditioned space at the register. As long there is a temperature difference, the leakage should be apparent with the infrared images. The case of leakage through penetrations in the top of the duct chase (attic floor) leakage *would* only be apparent from the attic or inside the chase. Another possible method of assessing where the duct chase is communicating with the unconditioned space would be to use a titanium tetrachloride smoke, a common diagnostic aid.

At the conclusion of this test, researchers know the effective leakage area of the chase to the unconditioned space as well as the rate of unconditioned air entering the duct chase under both test and operating conditions. They will also know the predominate leak sites and have a good foundation on which to develop refinements to the current construction details.
The equivalent leakage (ELA) in square inches is equal to the duct system leakage rate divided by 1.06 times the square root of the duct system pressure.

$$\text{ELA (square inches)} = \frac{\text{Duct System Leakage Rate (cfm)}}{1.06 \times (\text{Duct System Pressure})^{1/2}}$$

From Appendix D of the Minneapolis Duct Tester Manual, "Calculating an Equivalent Leakage Area from Duct Tester Test Results." This formula uses calculation procedure in Canadian General Standards Board CGSB149.10-M86.

*Test 4 How much is the **conditioning system** leaking?*
This test essentially repeats Test 3 but seeks to evaluate the *conditioning system* (meaning ducts, registers, and all associated equipment) rather than the *duct chase*. Researchers will measure the total leakage and the leakage to the outside of the conditioning system.

See Addendum below (*Apply Low Leakage Criterion*) for additional testing conducted at the recommendation of John Andrews at Brookhaven National Lab in accordance with AHSRAE Draft Standard 152P.

Total leakage will be measured by leaving the supply and return registers covered but pressurizing the duct system rather than the chase with a duct tester connected to the return grill. Leakage to the outside will be measured by bringing the duct system, the duct chase and the house all to the same pressure (+25pa WRT outside) creating only one leakage path: the duct system to the outside.

Addendum: Based on recommendations from technical consultant John Andrews, Brookhaven National Lab.

Apply Low Leakage Criterion to See Whether Further Measurements are Needed
Determine tentative supply and return leakage rates by dividing the measured CFM25out equally between the supply and return sides of the system, unless there are no return ducts, in which case apply it all to the supply side. That is,

CFM25out,sup = 0.5 CFM25out
CFM25out,ret = 0.5 CFM25out — if there are return ducts. This includes a platform return that is contiguous with the exterior envelope.

or

CFM25out,sup = CFM25out
CFM25out,ret = 0 — if the equipment is in the conditioned space and the return is simply a grille at the equipment.

Calculate tentative supply and return leakage rates:

Supply leakage: $Q_{s,out} = CFM25_{out,sup} \times (P_{pan}/25)^{0.6}$
Return leakage: $Q_{r,out} = CFM25_{out,ret} \times (P_{ret}/50)^{0.6}$

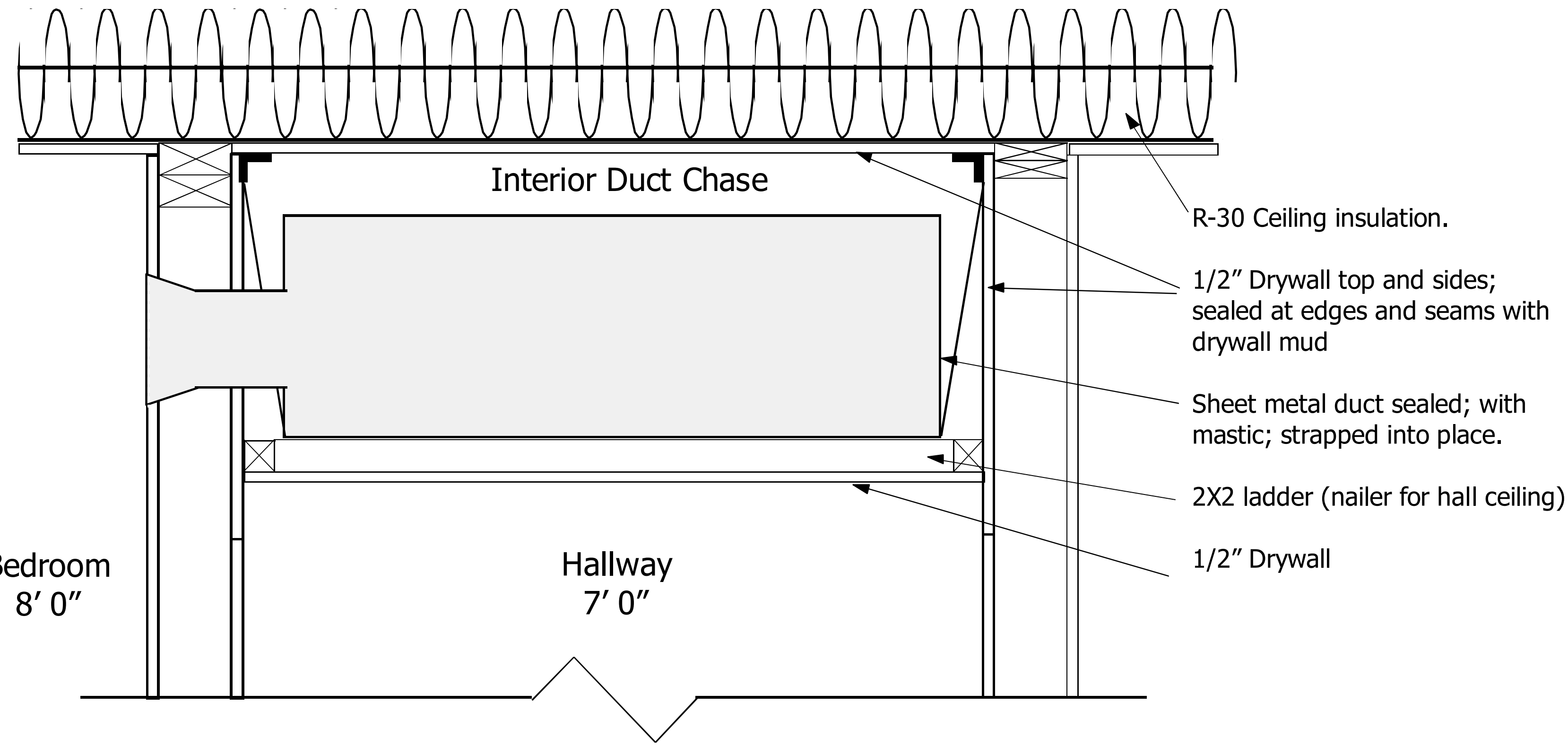
Note: The denominator in the return case is 50 and not 25 because the assumed operating pressure is one-half the plenum pressure (Pret/2) and this is in turn divided by 25.

Criterion:

A. If $Q_{s,out} + Q_{r,out} < 0.03$ X floor area, use these as the measured leakage values. For fan flow in this case, use the lesser of 0.7 X floor area or 400 cfm/ton of rated cooling capacity.

B. Otherwise, measure the supply and return leakage rates separately using Annex C of Standard 152P, i.e., with separating the system using a barrier. In this case, measure the fan flow using Annex B.

Appendix C: Black and White Drawings



<u>Assembly Notes for Interior Duct Chase and Interior Air Handler Closet, Details D1-D3:</u>

1. After laying out the path of the duct chase, cover the top and sides of the chase and the air handler closet with drywall.
2. Extend side drywall down to top of door rough opening. Seal drywall at all seams and edges with drywall mud, any code-approved sealant may be substituted. Seal the joint in the handler closet where the drywall meets the sub-floor with drywall mud,
3. Mark location of finished ceiling and ceiling framing. Mark openings for returns and supplies, build air handler platform, cut out rough openings in chase and air handler closet for duct work.
4. Install duct work with strapping. Bottom of duct work must be above height of finished ceiling framing in all hallsand rooms. Set air handler.
5. ALL WIRING OR PLUMBING PENETRATIONS IN THE CHASE AND AIR HANDLER CLOSET MUST BE SEALED.
6. Construct 2X2 "ladder" to support finished ceiling and provide nailing surface to allow drywall installation to cover entire chase and airhandler closet.

Note: All details shown here developed by Durham County Habitat for Humanity, Durham, NC. Illustration providedby the Florida Solar Energy Center, Cocoa, FL

D 1

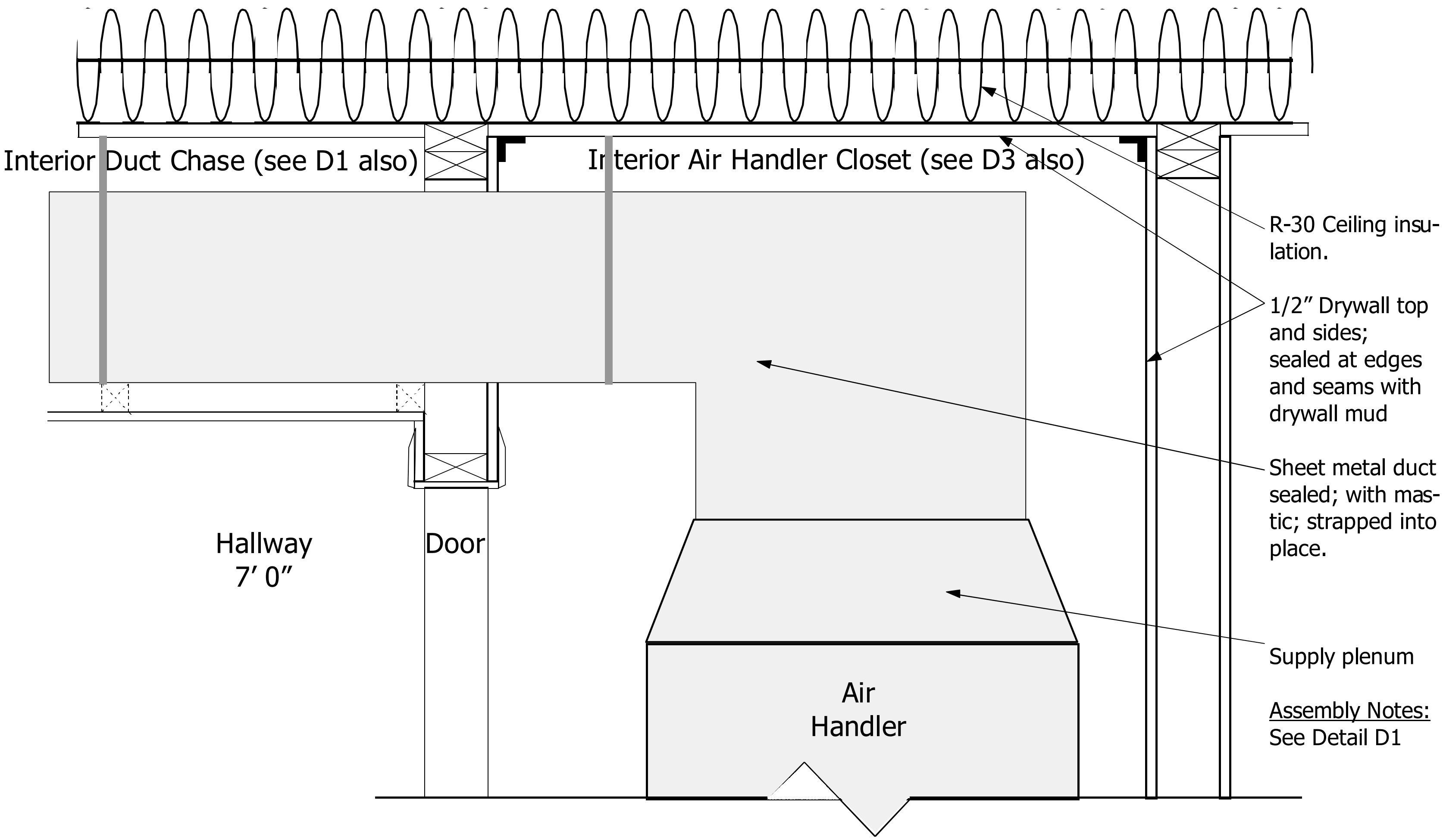
Interior Duct Chase - Section

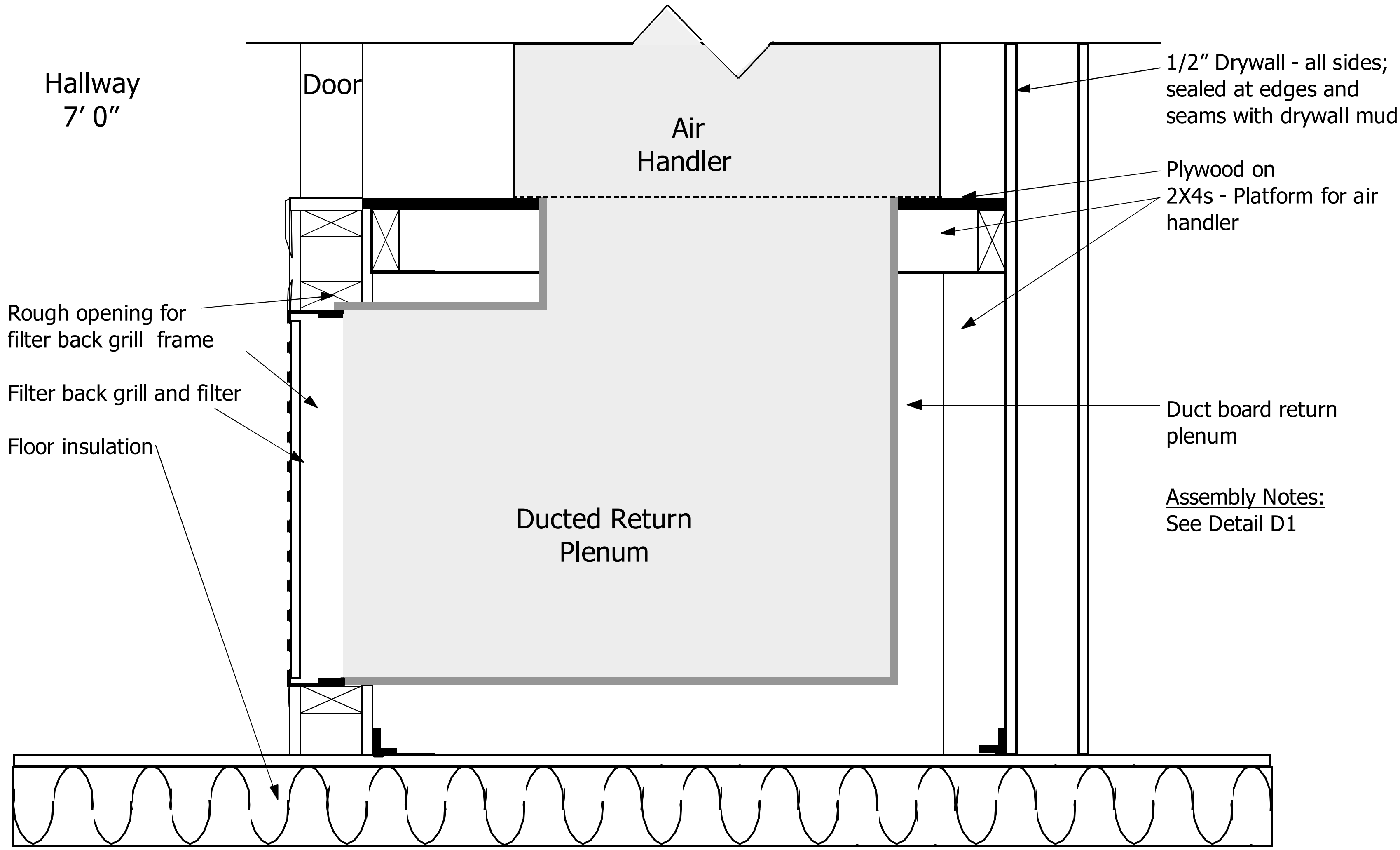
Scale 1/8" = 1"

D 2

Interior Air Handler Closet - Section - Side View of Upper Closet

Scale 1/8” = 1”





D
3

Interior Air Handler Closet - Section - Side View of Lower Closet

Scale 1/8” = 1”