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Compact Buried Ducts in a Hot-Humid Climate House

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Definitions

ACCA	Air Conditioning Contractors of America
BA	Building America Program
ccSPF	Closed-cell spray polyurethane foam (insulation)
CFM25	Cubic feet per minute at 25 Pascals pressure
CFM25/100SFcfa	Cubic feet per minute at 25 Pascals pressure per 100 square feet of conditioned floor area
FPM	Feet per minute
PVC	Polyvinyl chloride
RH	Relative humidity
t	Ton

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Executive Summary

Using buried ducts—heating and cooling air-distribution ducts that are insulated, installed close to the ceiling in a vented attic, and covered with attic insulation to minimize energy loss—can be an energy-efficient method to provide conditioned air distribution and a practical alternative to installing ducts in conditioned space or constructing unvented attics. Using compact ducts—a duct layout that minimizes the overall duct length and area—can further reduce energy losses caused by conduction, leakage, and duct pressure drop. Combining the two strategies into a system of compact buried ducts provides a high-performance and cost-effective solution for delivering conditioned air throughout a building.

This report outlines research activities that are expected to facilitate the adoption of compact buried duct systems by builders. The results of this research will be scalable to many new house designs in most climates and markets, which can lead to wider industry acceptance and approval by those who administer building codes and energy-efficiency programs.

The primary research question regarding buried ducts is whether there is potential for condensation at the outer jacket of the duct insulation in humid climates during the cooling season. Current best practices for buried ducts rely on encapsulating the insulated ducts with closed-cell spray polyurethane foam insulation to control the condensation and improve the air sealing. The concept of an encapsulated buried duct has been analyzed and shown to be effective in hot-humid climates by CARB (Shapiro, Magee, and Zoeller 2013; Shapiro, Zoeller, and Mantha 2013). Previous research by Home Innovation Research Labs (Home Innovation) resulted in two buried duct designs with reduced duct encapsulations that have been successfully installed, tested, and monitored in mixed-humid climates (Energy and Environmental Building Alliance 2013).

Home Innovation is a U.S. Department of Energy Building America team that conducted this project. The project's goal is to develop an alternative buried duct system that performs effectively as ducts in conditioned space—ducts that are durable, energy efficient, and cost-effective—in hot humid climates (International Energy Conservation Code warm-humid Climate Zone 3A). Three goals distinguish this project from buried duct research by Building America:

1. Develop design criteria for buried ducts that use common materials and do not rely on encapsulation using spray foam or disrupt traditional work sequences.
2. Establish design criteria for compact ducts and incorporate the buried duct criteria to further reduce energy losses and control installed costs.
3. Develop heating, ventilating, and air-conditioning design guidance for performing accurate heating and cooling load calculations for compact buried ducts.

The results of this research indicate that a compact buried duct layout can be a practical alternative to installing ducts inside conditioned space (inside the air barrier), which often presents a challenge for many house configurations—including the single-story slab-on-grade design for this project. Key project findings include the following:

- Based on the readings from numerous sensors installed to monitor the duct surface and attic conditions, no condensation has been observed at the buried ducts. (Common R-8 insulated ducts were covered with R-30 attic insulation.) Monitoring is ongoing.
- Conventional duct-sealing methods resulted in a low leakage rate for the attic ducts when tested during the rough-in stage. Final testing indicated a higher leakage rate than expected; this was attributed to a lack of sealing of the supply register boots and return grille box at the ceiling.
- The buried ducts delivered colder air during cooling than the attic ducts that were not buried. (On average the air was nearly 7°F colder.) The lowered delivery temperature results in increased energy savings and improved occupant comfort.
- A compact duct layout can improve the performance of any duct system wherein the design criteria are carefully considered in accordance with industry standards. For this project, the attic duct area was reduced by 32% for supply ducts and 75% for return ducts compared to builder standard practice; both significantly contributed to the overall energy savings. (See also the last bullet point below.)
- The compact buried duct layout was practical to install, although effective quality control is required to ensure uniform insulation coverage above the buried ducts.
- Existing industry standard heating and cooling load calculation software can be used to accurately represent predicted energy savings for compact buried duct layouts. Additional features can be implemented in the software to facilitate the analysis and design of these types of systems.
- This project outlined a cost-effective energy-savings solution for hot-humid climates. Simulations predicted a positive annual cash flow of $239, a simple payback of 3.1 years, and a simple return on investment of 32%. If cost savings from monetizing the reduced duct area and smaller capacity systems are included, the proposed solution could realistically be a no-cost option.
- Simulations predicted 21% annual heating/cooling site energy savings compared to conventional insulated attic ducts. The compact duct component contributed approximately 13% of this energy savings, and the buried duct component contributed approximately 8%.

1 Problem Statement

1.1 Introduction

Using buried ducts—heating and cooling air-distribution ducts that are insulated, installed close to the ceiling in a vented attic, and covered with attic insulation to minimize energy loss—can be an energy-efficient method to provide conditioned air distribution and a practical alternative to installing ducts in conditioned space or constructing unvented attics. Using compact ducts—a duct layout that minimizes the overall duct length and area—can further reduce energy losses caused by conduction, leakage, and duct pressure drop. This report outlines research activities that are expected to facilitate the adoption of compact buried duct systems by builders. The results of this research will be scalable to many new house designs in most climates and markets, leading to wider industry acceptance and approval by building codes and energy-efficiency programs.

Ideally, air-distribution ducts and equipment should be installed in conditioned space within the building thermal enclosure and air barrier to significantly reduce heating and cooling energy losses compared to ducts installed in unconditioned spaces such as vented attics or crawl spaces and garages. However, installing ducts in conditioned space can lead to design and construction challenges for some house configurations, particularly for slab-on-grade houses and two-story houses with complicated framing or open floor plans. Adapting house designs with interior ducts may require the addition of mechanical rooms, duct chases, dropped ceilings, soffits, or floors. The additional framing and associated air sealing may not be considered cost-effective by builders, bulkheads that conceal ducts may not be acceptable to buyers, and air-distribution performance can be adversely affected due to increased duct lengths and bends. Building a sealed, unvented attic to create a space for the ducts and the equipment within the thermal air boundary is a viable approach, but it may not be cost-effective because of the increased air sealing and insulation area, especially for higher roof slopes. Installing ducts in attics has been time-tested and found to be convenient; it has enabled the standardization of duct layout and minimized many of the objections to installing ducts in conditioned space. However, installing conventional ducts in attics (above the attic insulation) results in a significant energy penalty.

A buried duct system has the potential to balance the convenience of attic ducts with the thermal benefits of interior ducts. The primary concern with buried ducts is whether there is potential for condensation at the outer condensing surface of the duct insulation in humid climates during the cooling season. Current best practices for buried ducts developed through the U.S. Department of Energy Building America Program (BA) rely on encapsulating the insulated ducts with closed-cell spray polyurethane foam (ccSPF) insulation to control the condensation and improve the air sealing. The concept of an encapsulated buried duct has been analyzed and shown to be effective in hot-humid climates based on research performed by the Consortium for Advanced Residential Buildings (Shapiro, Magee, and Zoeller 2013; Shapiro, Zoeller, and Mantha 2013). Additional research on systems with buried attic ducts by Home Innovation Research Labs (Home Innovation) resulted in two alternative buried duct designs with reduced duct encapsulations that have been successfully installed, tested, and monitored in mixed-humid climates (Energy and Environmental Building Alliance 2013).

The purpose of this research project is to develop a new attic buried duct system that performs as effectively as ducts in conditioned space—ducts that are durable, energy-efficient, and cost-effective—in a hot-humid climate (International Energy Conservation Code warm-humid Climate Zone 3A). Three goals distinguish this project from previous buried duct research by BA:

- Develop design criteria for buried ducts that use common materials and do not rely on encapsulation using spray foam or disrupt traditional work sequences.
- Establish design criteria for compact duct layouts, and incorporate the buried duct criteria to further reduce energy losses and control installed costs.
- Develop heating, ventilating, and air-conditioning design guidance for performing accurate heating and cooling load calculations.

Previous BA research conducted by Home Innovation successfully demonstrated compact buried duct systems in mixed-humid climates (described in Section 1.2.4). The results of that research provided a high level of confidence to proceed with this current effort. With support from BA, Home Innovation partnered with K. Hovnanian Homes to further investigate compact buried duct applications for hot-humid climates. A compact buried duct system was installed in a single-family house in the hot-humid climate of Lady's Island, Beaufort County, South Carolina (International Energy Conservation Code warm-humid Climate Zone 3A). This report presents the design, testing, and monitoring of that duct layout.

1.2 Background

1.2.1 Overview

Heating and cooling duct layouts vary widely by climate, region, builder, and house design. Some builders successfully install equipment and ducts in conditioned space for their entire portfolio of house designs. However, in many markets equipment and ducts are still most commonly installed in vented attics above the attic insulation even though this practice is known to decrease the energy efficiency of the space-conditioning system (Roberts and Winkler 2010). Rather than making large, expensive modifications to existing floor plans, some builders in these markets convert the vented attic to an unvented attic and leave the duct system unchanged. Alternatively, the buried duct approach is an accepted practice in some dry climates (California Energy Commission 2005), but it is not common in humid climates.

Installing ducts in conditioned space reduces energy losses due to conduction and leakage to the outdoors. The resultant reduced heating and cooling loads can contribute to selecting heating, ventilating, and air-conditioning equipment that has a smaller capacity. Locating the ducts in conditioned space may also improve air quality by minimizing pollutants drawn from the attic, crawl space, or garage. Interior ducts may also leak air to the outdoors—for example, through house leakage points at rim areas, chases, or soffits—although increasingly tighter building enclosures minimize these losses. Ducts in conditioned space may also improve the building airtightness by eliminating house leakage at the envelope penetrations for registers and grilles and at leaking ducts. Basements are an ideal location for equipment and ducts in conditioned space, but routing ducts to a second floor can still be problematic.

In some cases, installing ducts in conditioned space can adversely affect airflow performance. For example, one approach is to install a supply trunk at the ceiling of a central hallway serving supply registers on high interior walls in the adjacent rooms (Burdick 2013). These supply registers may provide unacceptable air mixing (due to inadequate air throw from the diffuser), drafts (if air blows onto people in the occupied zone of the room), and noise (if the selected diffuser results in too high an air velocity in an attempt to increase the throw) (Ridouane 2011, Ridouane and Gawlik 2011). Similarly, compact return ducts must be designed to attenuate noise from the air handling unit and minimize noise due to excessive air velocity and turbulence. For some house designs, installing ducts in conditioned space could also result in a duct layout with excessive duct length or a number of elbows that in turn could result in reduced system and/or diffuser airflow, increased fan power, or the need to design a less restrictive duct system by increasing duct sizes (which may lead to other house design problems). Concealed interior ducts can also limit opportunities to use air-balancing dampers to more evenly distribute airflow to rooms.

Building a sealed, unvented attic creates a convenient space for the ducts and equipment, but this approach adds unoccupied volume within the building thermal enclosure and may not be cost-effective. Sealed attics are most commonly constructed by applying spray polyurethane foam insulation at the interior of the roof deck. Spray polyurethane foam insulation tends to be expensive, and the increased surface area to insulate (because of the sloped roof and the attic walls at the gable ends, porches, and garages) further increases installed costs. Additionally, the installed thickness of the insulation is frequently less than building code prescriptive values and may further limit energy savings.

1.2.2 Buried Ducts

Buried duct systems, though beneficial in reducing energy losses, must be particularly well sealed to prevent chronic condensation problems. As mentioned, condensation is a concern in humid climates during the cooling season. The outer surface of the duct insulation is required to be a vapor retarder (International Code Council 2012). Condensation can occur at this condensing surface when the temperature drops to the dew point temperature, and it can potentially lead to water accumulation and building damage. Burying ducts under higher levels of insulation lowers the temperature at this condensing surface during the cooling season. In humid climates that have higher average dew point temperatures, the common R-8 duct insulation, which is buried under the attic insulation, may not be sufficient to prevent the temperature at the outer surface of the duct insulation from falling to the dew point temperature. Duct leakage can aggravate the potential for condensation when cold, conditioned air leaks onto condensing surfaces. Additionally, conditioned air leakage through the exterior vapor barrier at tears or seams has the potential to allow condensation in the attic insulation surrounding the duct or for warm, moist air from the attic to enter the duct insulation and condense at the duct. Encapsulating the ducts entirely using ccSPF adds insulation value and moves the condensing surface outward, and it effectively controls duct leakage. When using ccSPF as a thermal and air barrier, building codes generally require an ignition barrier to protect spray foam in attics—for instance, minimum 1.5-in. mineral fiber or cellulose insulation—unless the foam is approved for use without an ignition barrier (International Code Council 2012). Encapsulation does have implementation uncertainties:

- Applying ccSPF generally requires specialized crews and stringent safety procedures.
- The installed thickness of ccSPF may deviate from the desired design thickness, particularly at areas that are difficult to reach such as below the bottom of trunks.
- The installation sequence has trade-offs: duct encapsulation before the drywall improves access to the ducts and allows concurrent air sealing at the rim areas (or other areas, to capture an economy of scale), but duct encapsulation after the drywall allows concurrent air sealing at the top plates, duct registers and grilles, and other penetrations at the ceiling. Either approach requires a second trip for the installer of the spray foam or additional air-sealing steps.

Previous BA research examined buried ducts for new and existing houses. Research results indicate that the thermal performance of buried ducts can be comparable to ducts in conditioned space (Griffiths et al. 2004). Testing and monitoring insulated R-6 ducts entirely encapsulated using 1-in. ccSPF (R-7) and covered with attic insulation in a hot-humid climate indicated that condensation was not likely (Consortium for Advanced Residential Buildings 2009). Insulated R-4.2 ducts encapsulated with 1.5-in. ccSPF were also shown to prevent condensation in a hot-humid climate. Additionally, effective duct and attic insulation values were calculated with respect to nominal insulation values (Shapiro, Magee, & Zoeller 2013). The U.S. Department of Energy Zero Energy Ready Home program allows buried ducts as an exception to the requirement that ducts are “located within the home’s thermal and air barrier boundary” such that ducts must be insulated with minimum R-8 duct insulation, encapsulated with minimum 1.5-in. ccSPF, covered with minimum 2-in. blown-in attic insulation, and tested to achieve a maximum 3 CFM25/100SFcfa total duct leakage (U.S. Department of Energy 2013).

1.2.3 Compact Ducts

The term *compact ducts* describes a heating and cooling air-distribution duct layout with reduced duct area and duct total effective length (linear feet and fittings)—both in the attic and in conditioned space. Compared to conventional duct layouts, a compact duct layout reduces duct pressure losses, improves airflow performance, and reduces fan power. Less duct area in the attic reduces conduction and leakage energy losses to the outdoors. Less duct area can contribute to a lower installed cost, particularly for the insulated ducts in the attic.

Home Innovation has developed general design guidance for compact duct layouts for earlier buried duct projects. The primary considerations for compact duct design are furnace or air handling unit location, return duct design, supply duct design and performance, and noise control. A summary of this guidance is provided in Section 3.3 of this report.

1.2.4 Compact Buried Ducts

Previous BA research by Home Innovation working with production builder K. Hovnanian Homes resulted in two compact buried duct systems with limited duct encapsulations installed in mixed-humid climates (Energy and Environmental Building Alliance 2013). For both systems, the attic ducts were deeply buried (covered with at least 3.5 in. of attic insulation). The first system design was featured in a single-story, slab-on-grade, new-construction test house in Monmouth, New Jersey, in 2009, with the following results (see Appendix A for additional information):

- Compact central return (single return with a short return trunk) and furnace in mechanical closet (both in conditioned space), and bedroom transfer grilles to provide a low-resistance return-air path
- Attic supply duct details: metal trunk and metal register boots both with R-8 duct insulation, flexible R-8 supply branch ducts, and ccSPF installed after the drywall at the trunk and boots (but not over the flex duct branches)
- Duct-leakage test result, attic ducts only, before encapsulation: 1.0 CFM25/100SFcfa
- Monitoring results: no condensation measured or observed at sensors installed at the condensing surfaces of the trunk, boots, or flexible branches
- Duct area compared to standard builder design: 70% less return and 28% less supply.

The second buried compact duct system was installed in Upper Marlboro, Maryland, in 2012. This two-story test house had an air handling unit in the basement and a vertical duct chase to the attic (see Appendix B for more information), and it was evaluated with the following highlights:

- Compact central return, in conditioned space, and bedroom transfer grilles
- Compact attic supply duct layout: registers installed in the ceiling near the interior walls to minimize the length and area of the supply branch ducts
- Attic supply duct details: double R-8 branches (R-16), metal register boots with R-8 duct insulation, metal trunk with 2-in. ccSPF
- Duct-leakage test result, attic ducts only: 1.9 CFM25/100SFcfa.
- Monitoring results: no condensation measured at the attic duct sensors.

1.3 Relevance to Building America

The goals for this project align well with the BA goals to develop market-ready solutions that improve energy efficiency, durability, quality, affordability, and comfort. The BA energy-efficiency goal is 30%–50% whole-house energy savings compared to the BA B10 benchmark, based on 2009 energy codes, for new construction or compared to pre-retrofit energy use for existing houses (“Building America Program” 2012).

This project builds upon previous BA research on buried ducts. If successful, the results of this research would be quickly scalable to many house designs in most climates and markets. The results will primarily benefit the new-construction market, but they could also benefit the existing-house retrofit market.

1.4 Cost-Effectiveness

Similar to conventional ducts installed above the attic insulation in a vented attic, buried ducts offer a large degree of flexibility regarding duct location, and they can be convenient to install. The furnace or air handling unit is ideally installed in conditioned space below the ceiling, so a mechanical room would be required for houses without a basement. Ideally, the buried duct approach should be combined with a compact duct approach that minimizes total duct area in the attic and in the conditioned space. These measures, on balance, would reduce the installed cost and operating costs of a buried duct system to improve cost-effectiveness.

For this project, the test house was a single-story, slab-on-grade, single-family house with 2,222 ft^2 of conditioned floor area (SFcfa). See Appendix C for floor plan. The 2 x 4, 16-in. on-center frame wall cavities have R-13 fiberglass batt insulation. Attic insulation is R-38 blown fiberglass. The roof is dark asphalt shingles. The selected heating/cooling system is an air-source heat pump (seasonal energy efficiency ratio: 13; heating and seasonal performance factor: 8).

This project features a compact duct system. The air handling unit was installed in a mechanical closet. The central return is in the ceiling of an adjacent hall and connected to the return plenum by a short jump duct (duct board, R-8.7, in the attic). Transfer grilles (for the two front bedrooms) and a short jump duct (flexible duct, R-8, in the attic, for the owner suite) provide the return-air paths for the bedrooms. The ducts are installed in the attic close to the ceiling plane. The ducts in the front of the house are buried using R-30 blown attic insulation mounded over the ducts (see Appendix D for duct layout). The supply trunks in the attic (duct board where buried, flexible duct where not buried) serve flexible branch ducts (R-8 except one R-12). Most of the supply registers are installed in the ceiling near an interior wall.

Energy modeling using the Air Conditioning Contractors of America (ACCA) Manual J software was performed for a number of example duct layouts for the test house. These results are summarized in Table 1 (duct layout descriptions follow the table). Manual J requires selecting the duct criteria (inputs). Duct inputs include location (e.g., vented attic, encapsulated attic, or in conditioned space), configuration (e.g., trunk and branch or radial, perimeter, or middle of the room supply register locations), insulation, and level of sealing with corresponding duct leakage (CFM/SF duct[1]). The software calculates the duct loss and gain based on the criteria and duct area. The duct area is a default percentage of the conditioned floor area based on the selected duct configuration. Manual J does not allow an input for air handling unit location and also does not break out air handling unit leakage.

The cost analysis at the end of this section was based on the simulated energy savings (from Table 1) and estimated incremental installed costs provided by the builder and heating, ventilating, and air-conditioning trade partner.

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[1] Duct leakage CFM and CFM/100SFcfa are not software outputs.

Table 1. Estimated Energy Savings for Example Duct Layouts

Duct layout	Duct layout description	Duct location	Duct configuration: T&B=trunk&branch; P=perimeter; M=middle of room; C=close to AHU	Duct insulation	Duct sealing	Duct leakage (CFM/SFduct)	Duct area (SF)	Duct leakage (CFM)	Duct leakage (CFM/100SFcfa)	Duct heat loss (%)	Duct sensible gain (%)	Duct heat loss/sens. gain/latent gain (Btuh)	House heat loss/sens. gain/latent gain at design conditions (Btuh)	Annual heating/cooling site energy, includes fan (kwHr)	Heating/cooling site energy savings compared to #1 (%)	Estimated annual operating cost ($)
#1	conventional attic ducts									27.4	58.7	7080	35511	9503	0.0	1330
	supply	attic	T&B - P	R-8	average	0.12	527.3	63.3	2.8			8867	26851			
	return	attic	T&B	R-8	average	0.24	196.9	47.3	2.1			2439	6899			
#2	conventional based on #1 except notable duct sealing									23.6	50	6106	34538	9066	4.6	1269
	supply	attic	T&B - P	R-8	notable	0.09	527.3	47.5	2.1			7540	25524			
	return	attic	T&B	R-8	notable	0.15	196.9	29.5	1.3			1680	6140			
#3	compact based on #1									17.8	35.3	4592	33024	8500	10.6	1190
	supply	attic	T&B - M	R-8	average	0.12	358.6	43.0	1.9			5332	23316			
	return	attic	T&B - C	R-8	average	0.24	91	21.8	0.9			1423	5883			
#4	compact based on #3 except notable duct sealing									15.4	30.6	3977	32408	8250	13.2	1155
	supply	attic	T&B - M	R-8	notable	0.09	358.6	32.3	1.4			4613	22597			
	return	attic	T&B - C	R-8	notable	0.15	91	13.7	0.6			991	5452			
#5	compact based on #4 except return ducts are in conditioned space (ics)									13.9	23.1	3578	32010	7997	15.8	1120
	supply	attic	T&B - M	R-8	notable	0.09	358.9	32.3	1.4			3486	21470			
	return	ics	T&B - C	R-8	notable	0.15	91	13.7	0.6			782	5242			
#6	buried ducts based on #1 except extreme duct sealing									10.4	19.1	2687	31118	7829	17.6	1096
	supply	attic	T&B - P	R-30	extreme	0.06	527.3	31.6	1.4			2890	20874			
	return	attic	T&B	R-30	extreme	0.06	196.9	11.8	0.5			942	5402			
#7	compact buried ducts based on #4 except extreme duct sealing									6.8	11.7	1792	30193	7490	21.2	1049
	supply	attic	T&B - M	R-30	extreme	0.06	358.9	21.5	0.9			1766	19750			
	return	attic	T&B - C	R-30	extreme	0.06	91	5.5	0.2			570	5030			
#8	compact buried ducts based on #7 except return in conditioned space (ics)									6.3	9	1617	30048	7395	22.2	1035
	supply	attic	T&B - M	R-30	extreme	0.06	358.9	21.5	0.9			1362	19346			
	return	ics	T&B - C	R-30	extreme	0.06	91	5.5	0.2			474	4934			
#9	encapsulated attic (ea) based on #2											4267	32698	8159	14.1	1142
	supply	ea	T&B - P	R-8	notable	0.09	527.3	47.5	2.1	16.5	20.7	3128	21112			
	return	ea	T&B	R-8	notable	0.15	196.9	29.5	1.3			1680	6140			
#10	inside conditioned space (ics)									0	0	0	28431	6921	27.2	969
	supply	ics	T&B - P	R-8	notable	0.09	527.3	47.5	2.1			0	17984			
	return	ics	T&B	R-8	notable	0.15	196.9	29.5	1.3			0	4460			

Duct Layout #1 represents a conventional attic duct installation wherein the ducts are installed above the attic insulation in a vented attic. This layout is the baseline, worst-case layout for energy comparisons. The duct area estimated by the software is the best case. The actual duct area is typically greater when the ducts are installed high in the attic near the roof deck. Layout #2 is the same as #1 except for the higher level of duct sealing. (For this example, the duct leakage now complies with the most recent building code maximum of 4 CFM25/100SFcfa).

Layout #3 represents a compact duct layout that compared to #1 has 38% less duct area and 42% less duct leakage, and it is now within 4 CFM25/100SFcfa, even at the same level of duct sealing (average). Layout #4 is the same as #3 except with improved duct sealing.

Layout #5 is the same as #4 (compact and well-sealed ducts) except that the return ducts are in the conditioned space. This layout represents a 15.8% heating/cooling energy savings compared to the conventional attic ducts (#1).

Based on previous BA research for buried ducts, a duct R-value of 30 was considered reasonable to use for the cost analysis. Layout #6 represents a buried conventional configuration at 17.6% annual heating and cooling energy savings. Layout #7 best represents the duct system for this project: a buried compact configuration with improved duct sealing at 21.2% energy savings. Layout #8, the same as #7 except that the return ducts are in conditioned space, shows a 22.2% energy savings.

Layout #9 represents an encapsulated attic. Manual J distinguishes an encapsulated attic (insulated at the roof deck and not vented) form an unvented attic (insulated at the ceiling and not vented). The attic is an interstitial space and generally not conditioned. This layout shows duct losses because the attic temperature is 10°F warmer in summer and 10°F cooler in winter compared to indoor temperatures. The estimated incremental cost to encapsulate the attic for this project exceeded $16,000 (2,712 ft^2 of roof deck, with 6-in. closed-cell spray foam [ccSPF], and 520 ft^2 of gable wall, with 2-in. ccSPF, at $0.95/board-foot). Even if the energy savings had been greater than 14.1%, this option was not considered cost effective for this project.

Layout #10 represents ducts in conditioned space and shows the greatest energy savings at 27.2%. Duct losses to the outdoors are common (e.g., through leaky rim areas and framed chases and cavities) even where ducts are in conditioned space, but this has become less likely as thermal-air barriers are improving. The incremental cost can range from insignificant (e.g., a single-story house with a full basement) to cost prohibitive (e.g., a single-story, slab-on-grade house with numerous chases, framed and air sealed, to conceal ducts). A two-story, slab-on-grade house may fall in between.

For this project, Layout #7, the estimated annual heating and cooling savings was $281 compared to the baseline, Layout #1 ($1,330–$1,049). The estimated incremental cost was $732 ($720 material and labor to build the mechanical closet, less $400 to eliminate the pull-down attic stairs, air handling unit platform, and overflow condensate pan, plus $412 additional blown insulation to mound over the buried ducts).The resultant incremental annual mortgage was $42. This resulted in a positive annual cash flow of $239, a simple payback of 3.1 years, and a simple return on investment of 32.2%.

No cost reductions were taken for the reduced duct area, and no cost was added for the duct-sealing effort. (The contractor's standard practice relied on conventional methods using mastic.) For future projects, if the cost savings from monetizing the reduced duct area and smaller capacity systems are included, the proposed solution could realistically be a no-cost option. Further, a two-story house with first-floor ducts in conditioned space would tend to provide energy savings closer to the case where all ducts are in the conditioned space (e.g., approximately 25%, between the 22.2% and 27.2% estimated heating and cooling energy savings shown in Table 1).

1.5 Trade-Offs and Other Benefits

Buried ducts allow for a standard duct layout approach without excessive and custom design changes. The primary non-energy trade-off associated with this research is the durability concern due to the potential for condensation at the duct surfaces in the attic. Implementing a compact duct layout can be beneficial with and without buried ducts. The research results may also be useful when a relatively small portion of a house would benefit from the buried duct approach such as a room above a garage or a one-story room on a slab connected to a two-story house. The energy savings could be small in these types of cases, but the buried duct approach could provide less costly options for building code and above-code program compliance.

2 Experiment

2.1 Research Questions

Buried ducts must be particularly well sealed and insulated to minimize energy losses and prevent condensation. The buried duct system for this project incorporates a compact duct design to further reduce energy losses and installed costs. Based on the stated purpose and goals (Goal 1: buried ducts design criteria; Goal 2: compact ducts design criteria; and Goal 3: heating, ventilating, and air-conditioning design guidance for energy calculations), this project addresses the following research questions:

1. What is the minimum level of duct insulation to prevent condensation at the outer jacket of buried ducts in hot-humid and mixed-humid climates? (Addresses Goal 1)
2. What duct-leakage rate for buried ducts will minimize energy loss and the risk of condensation due to duct leakage? (Goal 1)
3. What are the design considerations for compact duct layouts? (Goal 2)
4. What are the specific compact duct and buried duct design criteria for this test house? (Goals 1 and 2)
5. What is the design guidance for performing accurate heating and cooling load calculations for compact and buried ducts, and what inputs would be required for energy-modeling programs? (Goal 3)
6. Is this compact buried duct system cost-effective? (Purpose)
7. What are the building code and energy program acceptance barriers to this design? (Purpose)

2.2 Technical Approach

The technical approach is described below for each research question. (The numbers below correspond to the research question numbers.)

1. This research effort includes modeling to predict the minimum level of duct insulation required to prevent condensation. Additionally, sensors were installed in an existing house (a builder model home) in a nearby community to monitor and better understand the dynamic moisture conditions within the attic and attic insulation. This empirical data was compared to modeled results and previous BA research results as the final design criteria for the test house were developed. After the ducts were installed at the test house, sensors were installed to monitor potential condensation. (See Section 3 for further discussion.)
2. A target duct-leakage rate for the entire duct system and also for the attic ducts only was identified based on current industry standards. (Specific rates are identified in Section 3.) A duct-leakage test performed at the rough-in stage allowed for additional "touch-up" sealing and retesting as needed. The test at the rough-in stage measured attic ducts only, without the air handling unit, measured from the open supply plenum and return plenum at the ceiling plane. A final duct-leakage test, with the air handling unit and registers and grilles installed, measured total duct leakage from the central return. The target duct-

leakage rates were used for building load calculations and modeling (research question 5). Additionally, duct-leakage testing was helpful to evaluate the duct-sealing methods for this test house (research question 4).

3. Home Innovation previously developed general design guidance for compact duct layouts. A summary of this guidance is provided in Section 3.3. The compact duct criteria developed in this project was assembled based on previous work by Home Innovation and other BA teams to provide a more complete understanding of specific design concerns. The compact duct design criteria addressed industry standards to achieve effective air mixing (to avoid stratification and stagnant zones) and avoid unacceptable drafts and noise.
4. The specific design criteria for this project were based on the answers to research questions 1 and 2 for the buried duct component and research question 3 for the compact duct component. The criteria included details for duct insulation, attic insulation, duct-sealing methods, and register and grille selection and location. For this project, the compact duct layout was designed in accordance with ACCA Manual J (ACCA 2006), Manual T (ACCA 1992), Manual S (ACCA 2004), and Manual D (ACCA 2009a). The performance of compact ducts designed and installed based on the proposed criteria will be validated at the test house by observation at start-up and by feedback from the occupants.
5. Current Manual J software was used to calculate the heating and cooling loads of the test house for a number of different duct configurations: duct locations, layouts, and levels of duct sealing for conventional attic ducts (ducts above attic insulation), ducts in conditioned space, compact ducts, buried ducts, and compact buried ducts. The actual duct area, and duct leakage, and the theoretical effective R-values of the buried duct, were evaluated to determine the effect of these to the simulated loads. Changes to the energy-modeling software were identified that would improve the accuracy for compact buried ducts.
6. The compact buried duct system for this project was compared to duct layouts in conditioned space; conventional, vented attic ducts (ducts above the attic insulation); and ducts in an encapsulated (semi-conditioned) attic. The cost analysis was based on simulated energy savings for this test house and installed costs provided by the builder and heating, ventilating, and air-conditioning trade partner.
7. Testing and monitoring data were evaluated for compliance with building codes and energy programs.

2.3 Measurements

The tests and measurements required for this experiment are detailed in Table 2 and Table 3. The equipment needed for this experiment is identified in Table 4. Upon completion, the test house will be sold and occupied. The test house will be monitored through the 2015 cooling season. The monitoring equipment was installed by Home Innovation.

Table 2. Performance Testing

Test	Details	Data
Duct-Leakage Tests		
Rough-In Test 1	Test attic ducts only without air handling unit. Connect duct blaster to open supply plenum at the ceiling. Reseal and test as required.	CFM25 attic
Rough-In Test 2	After drywall and sealing, register boots at drywall, before attic insulation and air handling unit	CFM25 attic and outdoors
Final Test	With air handling unit and registers and grilles	CFM25 attic and outdoors
Airflow Tests		
Final Test	Airflow at air handling unit	CFM
Final Test	Airflow at registers and grilles	CFM
Final Test	Pressure differential at transfer grilles	Pascals (Pa)

Table 3. Performance Monitoring

Measurement	Details	Data
Condensation potential and thermal performance	Sensors in the airstream within the supply trunk and selected supply register boots	Temperature and relative humidity (RH)
Condensation potential	Sensors at selected condensing surfaces (outer jacket of duct insulation) in the attic	Temperature and RH

Table 4. Testing and Monitoring Equipment

Measurement	Equipment Needed	Equipment Range/Accuracy
Duct-Leakage Tests	Minneapolis Series B Duct Blaster system	10–1,500 CFM/greater of ±3% or 1 CFM
	Minneapolis DG700 manometer	-1,250–1,250 Pa/greater of ±1% or 2x resolution
	Minneapolis Model 3 Blower Door system	85–6,300 CFM/na
Airflow Test at Registers and Grilles	Alnor 6200 flow hood	10–500 CFM/±(3%+5CFM)
Airflow Test at Air Handling Unit	Trueflow flow grid	365–2,100 CFM/±7% of reading
	DG700 manometer	See above
Temperature and RH	Omnisense S-900-1 wireless sensors	Temperature: -40°C–85˚C/±0.4˚C, 2˚C max
		RH: 0%–100%/±3.5%, ± 5% max

The Omnisense wireless sensors measure temperature and RH, and a wireless gateway with built-in cellular collects and sends that data to the manufacturer's website. The sensor and battery are housed in a plastic box that is approximately 2.5-in. wide, 1.5-in. high, and 1-in. deep; the sensor is located flush to one of the 2.5-in. x 1.5-in. surfaces. Home Innovation currently has hundreds of these wireless sensors installed around the country. (These sensors are also capable of measuring wood moisture content.)

To monitor for potential condensation, sensors were installed in the airstream and at the outer jacket of the duct insulation of the selected supply trunk duct, branch ducts, and register boots. (See Appendix E for sensor locations.)

The sensor in the airstream near the air handling unit was not installed directly above the air handling unit to avoid the radiative component of the air handling unit and because the airstream is not well mixed at this point. A sensor was installed in the supply trunk after the first elbow and at a distance of two duct diameters downstream of that elbow (ACCA 2009b). The airstream is considered well mixed at this point and at points downstream for temperature measurements (versus velocity pressure measurements that would require traverse measurements). To validate this assumption, Home Innovation conducted an experiment: temperatures were taken within a supply trunk (16-in. x 8-in. duct in the Home Innovation lab; "traverse" measurements at 1-in., 4-in., and 7-in. depths and corresponding 1-in., 4-in., 8-in., 12-in., and 15-in. widths) using a calibrated temperature probe. With the cooling system operating, all readings were within 0.2°F, confirming temperature uniformity within the duct. Additionally, sensors installed at different locations within the duct provided consistent results, and the direction the sensor was facing did not appear to impact the result.

For sensors installed on the condensing surfaces of the ducts, Home Innovation was concerned that a sensor attached directly to the duct may not obtain an accurate RH measurement. Home Innovation investigated the effect of spacers between the sensor and the duct surface, and as a result these wireless sensors will be installed with a 1/8-in. spacer.

For sensors installed within the attic insulation, the sensor tree material at the test house was polyvinyl chloride (PVC) trim, and the sensor boxes were installed on the PVC using spacers to minimize thermal conduction and the influence of moisture.

Table 4 provides the listed uncertainty for RH and temperature measurements for the wireless Omnisense sensors based on the sensor manufacturer specifications. Dew point temperatures were calculated using the measured temperature and RH. Based on the dew point uncertainty analysis for the conditions of this project, the range of uncertainty of the dew point data presented in this report is ±3°F. The accuracy of the temperature data presented in this report is considered ±1°F.

3 Analysis

A discussion of the analysis is provided below for each of the research questions.

3.1 Research Question 1

What is the minimum level of duct insulation to prevent condensation at the outer jacket of buried ducts in hot-humid and mixed-humid climates?

The methods used to determine the minimum R-value to prevent condensation of buried ducts were hygrothermal modeling, monitoring moisture conditions at an existing house near the test house (South Carolina model home), and installing and monitoring a modified duct design at a test house (South Carolina test house). Hygrothermal modeling software (WUFI) was used to predict condensation at the outer jacket of the buried duct insulation; the National Renewable Energy Laboratory provided support for this project by modeling moisture dynamics using data from the model home in South Carolina and from Home Innovation's Maryland house (described in Section 1.2.4). No condensation was measured or observed at the condensing surfaces of the buried ducts at the Maryland and New Jersey houses. This data was compared to empirical data to determine if the modeling accurately represents the conditions around the ducts.

As mentioned, sensors (see Section 2.3 for a description of the sensors) were installed in an existing model home in a nearby community to capture the dynamic moisture conditions within the attic and attic insulation. The air handling unit is in a mechanical closet below the ceiling, and the ducts are in the attic above the insulation except at the supply plenum and register boots. Sensor locations include "sensor trees" within the R-30 attic insulation (sensors at 1 in., 3.5 in., 6 in., and 8.5 in. above the ceiling), supply airstream (measured near the register boot), in the attic on the insulated supply register boot (3.5 in. above the ceiling), in the attic above the attic insulation, at the thermostat, and outdoors. At the model home, the sensor tree material that the attic insulation sensors were attached to was wood (pine 1-in. x 3-in. trim).[2]

The WUFI model was adjusted to better match the monitored field data from the Maryland test home (both the rectangular trunk duct and round branch duct) and South Carolina model home (attic insulation sensor trees). Figure 1 plots the measured and modeled RH for one round buried supply duct at the Maryland home to demonstrate general hourly correlation between the measured and modeled data (within the ±3.5% RH accuracy of the sensor).

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[2] At the test house, the sensor tree material was PVC trim, and the sensors were installed on the PVC using spacers to minimize thermal conduction and the influence of moisture.

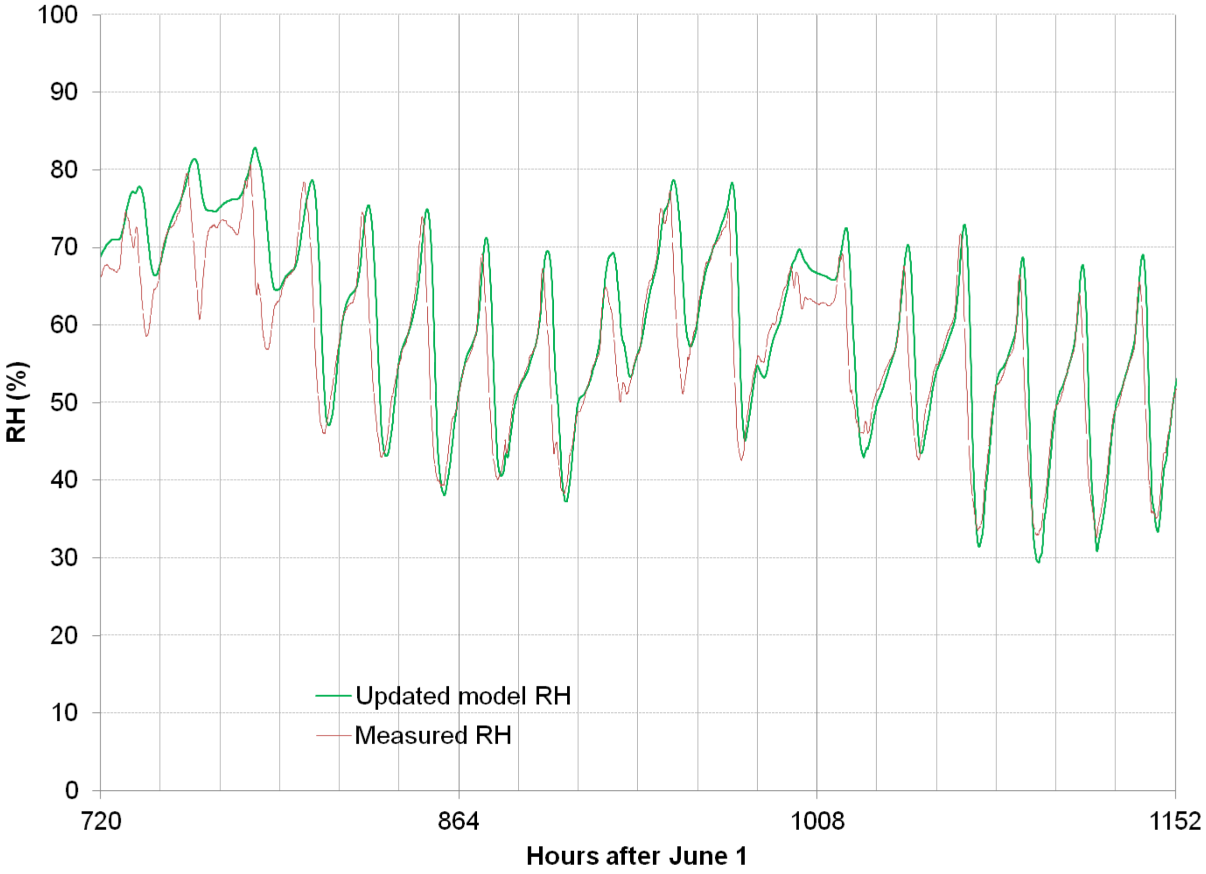

Figure 1. Measured and modeled RH of the Flex supply duct at the condensing surface for a summer period. ***Image by the National Renewable Energy Laboratory***

Figure 2 plots the measured and modeled temperature and dew point for the sensor trees in the South Carolina model home during a 48-hour period. (The upper black line shows the measured attic ambient value, and the lower black line shows the measured indoor value.) Although the hourly correlation is demonstrated, the modeled temperature (left chart) is lower than measured near the ceiling and higher than the measured near the top of the insulation during higher daytime temperatures. T This result is the same for the nighttime periods. The modeled and measured dew point temperatures are closely aligned nearer the ceiling, but the modeled dew points are higher than the measured dew points at locations in the insulation closer to the attic space. This holds true for both the daytime and nighttime periods.

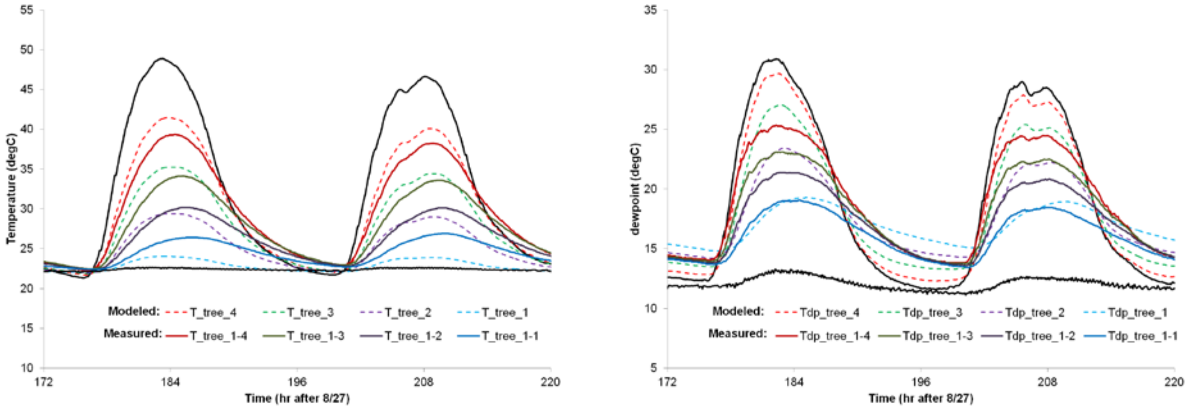

Figure 2. Measured and modeled temperatures and dew points of the attic insulation tree at the South Carolina model home. ***Image by the National Renewable Energy Laboratory***

Comparing the modeling results to the measured data indicated general agreement: sensor accuracy is ±0.4°C for temperature, ±3.5% for RH, and approximately ±1.7°C for dew point. However, further measurements are needed to more closely align the hourly data.

Figure 3 plots a histogram of a round buried duct, with various duct insulation levels, for Maryland and South Carolina during the cooling season, from June through September. A maximum design target of 90% RH at the duct condensing surface is reasonable as a design limit because at 90% RH the dew point is less than 5°F away from the dew point at any given temperature.[3] However, a case can be made that insulation is sufficient as long as it never reaches 100% RH. Duct insulation of R-8 appears to be sufficient in Maryland, but it is questionable in South Carolina (particularly considering the sensor accuracy for RH).

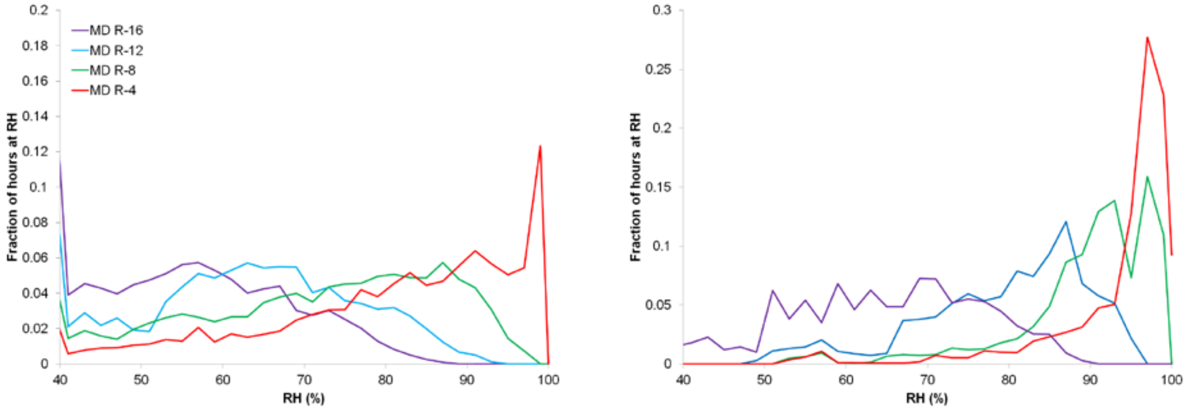

Figure 3. Histograms of the (left) round buried duct in Maryland and (right) South Carolina. (Note: The legend R-value is the same for both graphs.) ***Image by the National Renewable Energy Laboratory***

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[3] Refer to the psychometric chart for the relationship between the temperature, relative humidity, and dew point.

Data from the South Carolina model home were revealing. Figure 4 shows the dynamic nature of the dew points within the attic and attic insulation and at one insulated duct supply register boot near the ceiling surface. The dew point temperature at the boot fluctuates rapidly when the temperature is affected by the operation of the cooling system. Figure 5 plots data for that supply register boot. The boot temperature (sensor installed on the insulated boot, within the R-30 attic insulation, at 3.5 in. above the ceiling) is at times below the dew point of the corresponding attic insulation tree sensor (also 3.5 in. above the ceiling), but it is always above the dew point temperature at the boot sensor (normally by at least 5°F). Further, moisture was not felt or observed at that boot during a site visit by Home Innovation during this period. Home Innovation observed this dynamic for the New Jersey and Maryland projects as well.

Although hygrothermal modeling and previous BA research indicate that R-8 duct insulation for round ducts is questionable, particularly in a hot-humid climate, no condensation was measured or observed at R-8 branch ducts and supply register boots during the monitoring of the South Carolina model home and the projects in Maryland and New Jersey. Based on this field data, duct insulation was selected for the buried ducts in the test house for this project: four R-8 flexible round branch ducts, one R-12 flexible round branch duct, and R-8.7 rigid rectangular duct board supply and return trunks. The buried ducts were located in the front of the test house, and the remaining ducts that were located in the rear of the house were not buried. The R-12 branch duct and R-8.7 duct board trunk (condensation is less likely on the flat surface) were specified for additional data points in the event that condensation was observed on the R-8 branch ducts.

Sensors (37 total) were installed to monitor the temperature, RH, and dew point of the ambient conditions (11 sensors), condensing surfaces (20 sensors), and airstreams (6 sensors). See Appendix D for the duct layout and Appendix E for the sensor locations. The ambient conditions include outdoors, indoors at thermostat, indoors at the ceiling just below the attic tree, attic insulation tree, and attic; three attic sensors also measured wood moisture content of the truss framing. Condensing surfaces include selected trunk, branch, takeoff, and boot locations. These sensors monitor for potential condensation during the cooling season. If the dew point temperatures are below the surface temperatures, then condensation is not expected to be a performance concern for this design. The airstream sensors can provide data on the temperature rise (summer) from the plenum to the diffuser boots, indicating conduction losses and ultimately duct efficiency. These data can be compared to typical attic duct systems.

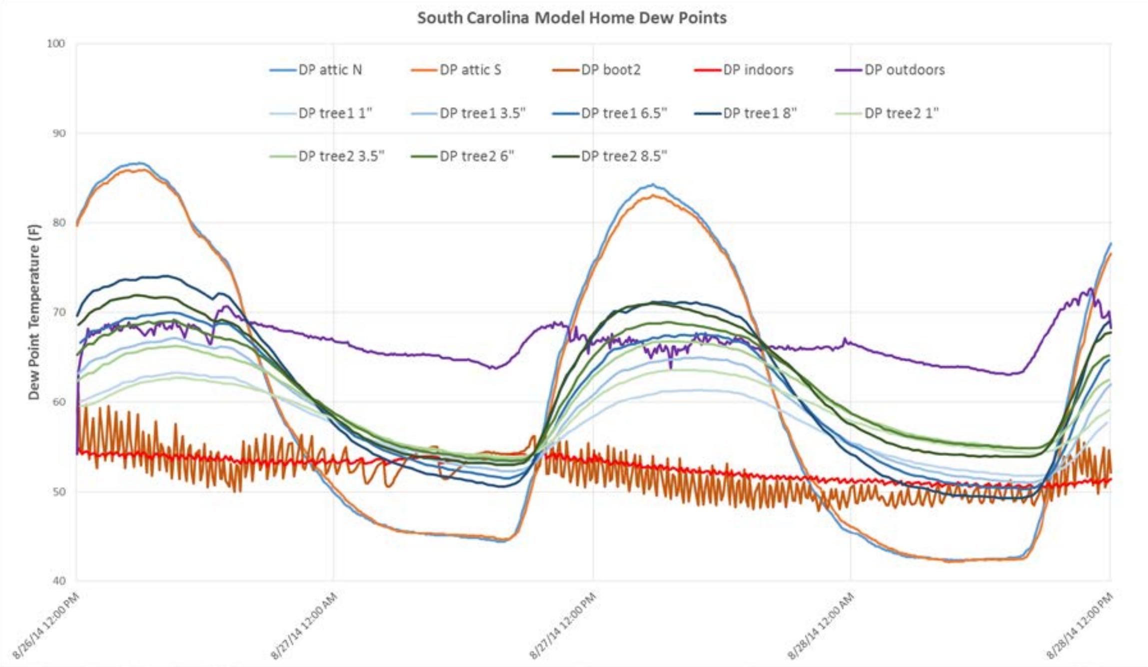

Figure 4. South Carolina model home dew point temperature dynamics

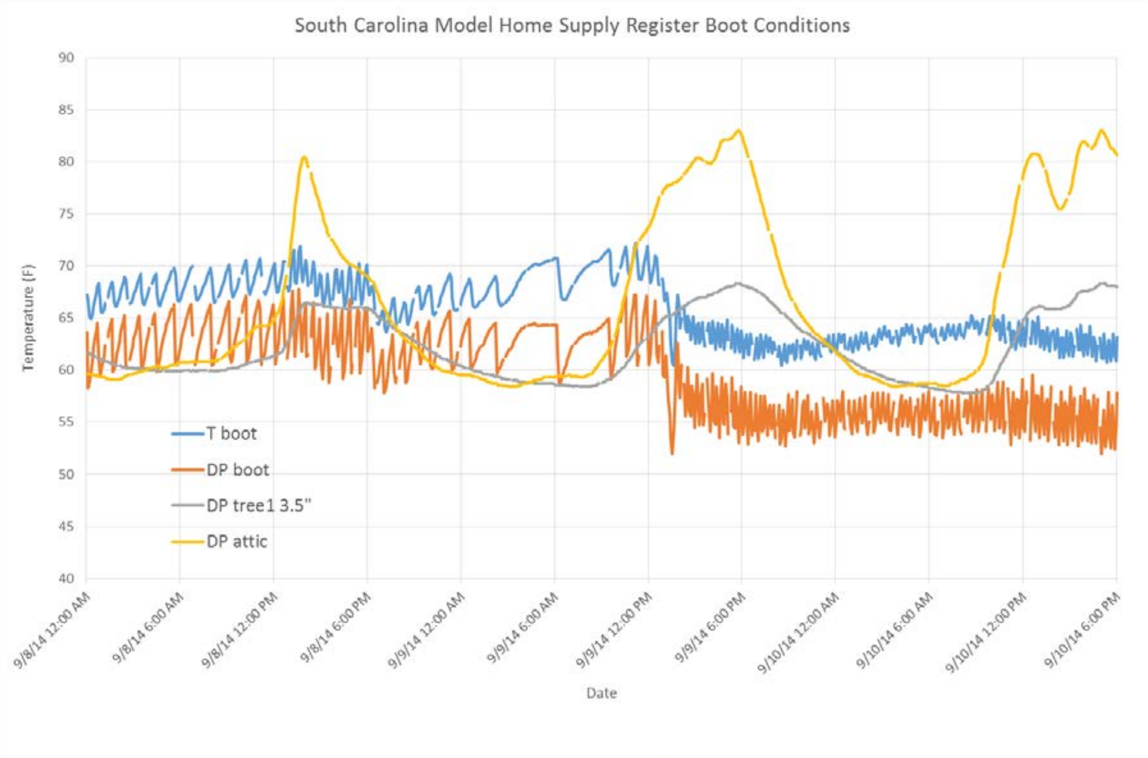

Figure 5. Duct supply register boot conditions

3.2 Research Question 2

What duct-leakage rate for buried ducts will minimize energy loss and the risk of condensation due to duct leakage?

The target total duct-leakage rate for this project was maximum 3 CFM25/100SFcfa. This rate satisfies current requirements for the U.S. Department of Energy Zero Energy Ready Home program and exceeds the ENERGY STAR® program and 2012 International Energy Conservation Code requirements. The target leakage rate for the attic ducts only was 1 CFM25/100SFcfa. Isolating the attic ducts for leakage testing was important for this project because leakage here represents energy loss outside the building envelope, may cause or contribute to condensation, and may contribute to house pressure balance concerns (e.g., infiltration and indoor air quality). A leakage rate of 1 CFM25/100SFcfa corresponds to approximately 2% of system airflow for this project (23 CFM for this 2,222 ft^2 house/1,200 CFM [400 CFM/ton] = 1.9%). This leakage rate for only the attic ducts allows for a total leakage target of 5% of system airflow (generally considered airtight) to take into account the air handling unit (maximum leakage rate of 2% of design airflow, per code) and a compact central return duct. The metal trunk duct, metal boots, and flexible branch ducts at the New Jersey project (Section 1.2.4) were sealed conventionally using duct mastic and tested within 1 CFM25/100SFcfa before encapsulation of the trunk and boots.

3.3 Research Question 3

What are the design considerations for compact duct layouts?

This section provides an overview of design considerations and guidance for compact duct layouts in residential buildings. The term *compact* ducts describes a heating and cooling air-distribution duct layout with reduced duct area and reduced total effective length (the linear feet of duct plus equivalent length of duct fittings) compared to conventional duct layouts.

A compact duct layout can improve any duct system. Less duct area reduces conduction and leakage energy losses, which is particularly important where ducts are not inside conditioned space. A lower total effective length improves the duct design friction rate (used to size ducts). Reducing the number of fittings also helps to lower the total effective length. (One duct elbow can be the equivalent of 15–35 ft of duct.) A lower total effective length reduces duct pressure losses, improves airflow performance, and reduces fan power. Compact ducts can contribute to lower installed costs, lower operating costs, and improved occupant comfort.

The primary design categories for compact ducts are furnace/air handling unit location, return duct design, and supply duct design. Design considerations for each category include duct location, performance, and noise control. A compact duct layout should be considered early during the design phase of the project, particularly when house designs must be altered to accommodate mechanical rooms, central duct chases, or ducts within floors or bulkheads. Ideally, all ducts and equipment should be located in conditioned space to minimize energy losses, although a compact duct design can significantly reduce these losses when the ducts, or portions of the duct system, are not in conditioned space.

Ideally, the furnace/air handling unit should be located centrally to reduce the total effective length and duct area (supply and return ducts). For example, a 3-ton (t) air handling unit in the middle of the house serving two 1.5-t trunks will have less supply duct area than that air handling unit at one end of the house serving one trunk that initially must handle all 3 t. A central location can also improve airflow balance. For example, a central air handling unit with independent supply trunks serving specific zones (e.g., great room and kitchen, master suite, and other bedrooms) allows for air balance control at the air handling unit. This can be helpful when supply ducts and dampers are not accessible (within a floor or chase) or not easily accessible (attics).

The return duct system is the best and easiest opportunity, and it should be the top priority and first step to reduce total effective length and duct area. Ideally, locate a single, central return trunk near the air handling unit that serves one return grille per living level. A second return grille may be practical as well (e.g., in a master bedroom suite). The idea is to minimize or eliminate return branch ducts.

The compact central return relies on a low-resistance return-air path for bedrooms or other rooms with doors (excluding bathrooms, kitchens, closets, laundry rooms, and mechanical rooms). The simplest return-air path is a transfer grille that should have a baffle to minimize sound and light transfer. A jump duct through the ceiling or attic can be substituted if necessary. The return-air transfer grille or duct should be selected for a maximum pressure differential of 3 Pa across the closed door during heating or cooling system operation.

For compact supply duct systems, locate the supply registers to minimize supply branch duct length. The style and location of the supply registers must still provide acceptable air mixing (avoid air stratification and room stagnant zones) and prevent unacceptable noise and drafts. Drafts are generally not acceptable within the occupied zone of a room (within 6 ft above the floor and 2 ft from a wall).

Supply registers must be selected based on manufacturer product data. Previous BA work provides details on register selection (IBACOS 2013). For example, when registers are located at an interior wall or at the ceiling near an interior wall, they are typically selected for “throw” so that the supply air travels across the ceiling toward the exterior wall. Throw that equals the distance from the diffuser to the wall may be acceptable for cooling, but it may not be acceptable for heating because it may result in stratification. A throw that additionally includes some distance down the exterior wall will help avoid stratification during heating.

In rooms when a ceiling supply register is not available with sufficient throw within acceptable noise limits, a register can be located in the middle of the ceiling (still directed to an exterior wall) or near an interior wall (directed down, similar to a conventional ceiling diffuser—the supply air does not need to blanket the exterior walls in today’s tighter, more energy-efficient homes). Alternative supply register locations may result in a somewhat less compact design, but the priority is comfort—sufficient air mixing without unacceptable noise and drafts.

For supply ducts in vented attics, install ducts away from the roof deck; this reduces duct area and energy losses. Install ducts that will be buried closed to the ceiling plane, ideally before installing a sprinkler, plumbing, and electric rough-ins. Install ducts that will not be buried just above the attic insulation.

Noise control is a design requirement for any system, and it can be more critical for compact supply and return duct layouts (e.g., a central return adjacent to an air handling unit). Ducts should be sized and registers and grilles should be selected in accordance with manufacturer performance data and ACCA Manual D Table A1-1: Air Velocity for Noise Control and Appendix 13: Noise. Where the return grille is near the furnace, pay particular attention to air velocity limits, turbulence due to duct geometry (e.g., consider long radius elbows or turning vanes), and attenuation of blower noise and rumbling sounds (e.g., install a minimum of two elbows to reduce line-of-site noise, and consider a duct liner for the first 10 ft and first two elbows).

The compact buried duct layout of the New Jersey project (Section 1.2.4) provides an example of how a compact duct design can reduce duct area. The house was a single-story slab-on-grade design. The air handling unit and return duct were located in a mechanical closet inside the conditioned space. A single, central return grille was located in the hall next to the furnace closet. The short return trunk was sized to provide low air velocity and included two elbows and duct liner to further control noise. The supply duct layout was a conventional trunk and branch layout serving perimeter supply registers in the ceiling and installed close to the ceiling to be buried. Duct area in the attic was reduced by 70% for the return ducts and 28% for the supply ducts compared to builder standard practice. (Flexible ducts were installed high in the attic close to the roof deck; substituting supply registers near the interior walls would have further reduced the duct area.)

3.4 Research Question 4

What are the specific compact duct and buried duct design criteria for this test house?

The specific design criteria for this project were based on the answers to research questions 1 and 2 for the buried duct component and research question 3 for the compact duct component. The duct layout for this project is shown in Appendix D. The ducts in the front of the house were buried, and the ducts at the back of the house were installed just above the attic insulation and not buried. The specific design criteria for the compact buried ducts for this project are as follows:

- Air handling unit location
    - Locate air handling unit in mechanical closet (in conditioned space).
- Central return
    - Locate single return grille in the ceiling of the hall adjacent to the mechanical closet served by one trunk duct (attic jump duct).
    - Return trunk duct and plenum shall be R-8.7 duct board.
    - Provide return-air paths using transfer grilles for the two front bedrooms and one jump duct (flexible duct and metal grille boxes) for the owner suite.

  - Use a maximum design velocity of 500 feet per minute (FPM) for return ducts, 350 FPM for return grilles, and 300 FPM for transfer grilles.
- Supply ducts
  - Locate supply registers in the ceiling, near interior walls as practical.
  - Select registers (near interior walls) to provide a throw to include the distance to the exterior wall plus 4 ft.
  - Use a maximum design velocity of 700 FPM or NC30/35 rating to select the supply registers, 800 FPM for the supply trunks, and 700 FPM for the supply branches.
  - Install buried ducts as close to the ceiling as practical.
  - Supply trunk shall be R-8.7 duct board when buried and R-8 flex duct when not buried.
  - Supply branches are R-8 flexible duct throughout. Insulate one branch to R-12. Add supplemental R-8 insulation for one branch take-off at the trunk.
- Duct sealing
  - Seal duct board trunks and plenums at all seams using mastic over foil tape.
  - Seal metal boxes and supply register boots using tape before adding duct insulation.
  - Seal metal take-offs at the supply trunk and all boxes using mastic.
  - Seal flexible duct at fittings using mastic: apply duct mastic to fitting, slide inner core over fitting, and secure with a zip tie (beyond the ring of the flexible duct fittings) using a zip tie tensioner tool. Pull duct insulation and outer core over this connection, and secure it with a zip tie using a tensioner tool. Further seal this assembly using mastic.
  - Seal supply register boots and return boxes at the ceiling after drywall.
- Duct-leakage targets
  - At rough-in stage, before air handling unit: 1 CFM25/100SFcfa (23 CFM25)
  - Final, with air handling unit: 3 CFM25/100SFcfa (69 CFM25).
- Attic insulation
  - For ducts to be buried, install insulation depth markers (to mark the location of the ducts and ensure proper coverage) every 10 ft and at take-offs and register boots.
  - Install R-38 attic insulation (blown fiberglass).
  - Install R-30 attic insulation mounded over the buried ducts.

3.5 Research Question 5

What is the design guidance for performing accurate heating and cooling load calculations for compact and buried ducts, and what inputs would be required for energy modeling programs?

The design guidance to perform accurate heating and cooling load calculations for compact and buried ducts must consider duct area, duct leakage, and duct R-value. For the analysis below, the ACCA Manual J software (Wrightsoft 2015) default values can be found in Table 1 of this report.

The software calculates duct surface area as a percentage of conditioned floor area based on the selected duct configuration. The duct configuration selections are *trunk and branch* or *radial*, plus *perimeter* or *middle of room* for supply branches and *close to air handling unit* or not for return branches. For this project, the software calculated 528 ft^2 supply duct (for trunk and branch perimeter) and 197 ft^2 return duct. For the more compact duct layout, the software calculated 359 ft^2 supply duct (for trunk and branch middle of room) and 91 ft^2 return duct (close to the air handling unit).

The field-measured attic duct areas for this project (as built) were 430 ft^2 supply duct and 53 ft^2 return duct (including the owner suite jump duct). The supply area is likely larger than the estimated compact supply because this house's design is three rooms wide and results in longer branch ducts for some rooms. The builder standard design duct areas are 638 ft^2 supply and 214 ft^{2}return. This translates to a reduced duct area of 32% for the supply ducts and 75% for the return ducts compared to builder standard. In this case, the software is underestimating the energy savings because the builder standard actual duct area in the attic is larger than estimated. For accuracy, the software does allow the actual duct area to be substituted for default values.

For duct tightness, selecting the "extreme" input in the software corresponded well to the measured duct leakage during the rough-in stage testing, but the final duct-leakage testing was between the *extreme* and *notable* selections.

Duct insulation is generally rated using the nominal R-value of the insulation that is calculated for the insulation material lying flat. The effective R-value takes into account round duct geometry, inner and outer duct surface materials, and heat transfer between the duct and conditioned space. Previous BA research established effective R-values for round buried ducts (Shapiro, Magee, and Zoeller 2013; Shapiro, Zoeller, and Mantha 2013). For this project, a value of R-30 was selected in the software to best represent the average for all buried ducts.

3.6 Research Question 6

Is this compact buried duct system cost-effective?

The analysis of this research question was completed in Section 1.4, and the results are presented in Section 5.1.

3.7 Research Question 7

What are the building code and energy program acceptance barriers to this design?

Building code and above-code energy program acceptance is discussed in the conclusions.

4 Results and Discussion

4.1 Duct-Leakage Testing

As detailed in Section 3.2, the target duct leakage rates for this project were 3 CFM25/100SFcfa total (69 CFM25) and 1 CFM25/100SFcfa for the attic ducts only (23 CFM25). The total leakage target allowed for leakage of 2% of system air flow at the air handler (24 CFM25, or roughly another 1 CFM25/100SFcfa) and leakage of the return plenum below the ceiling plane.

Home Innovation measured 1.2 CFM25/100SFcfa (28 CFM25) for the attic supply ducts and supply plenum (without the air handling unit) during the rough-in stage. The only observed leakage was at the duct mask tape at the metal boot support cleats. (This area was specified to be sealed after the drywall.) The short central return trunk and jump duct serving the owner's suite were tested, but zero leakage was measured.

A second test at the rough-in stage, after the drywall and sealing the ceiling penetrations but before the attic insulation, was intended to capture the leakage around the supply register boots and return grille box at the ceiling and allow for resealing if necessary. This critical leakage area has significant leakage potential that can result in excessive measured leakage during testing even with an otherwise tight duct system. This second test at the rough-in stage was not performed due to scheduling conflicts.

Final duct leakage testing was reported by the energy rater as 91 CFM25 to outdoors and 128 CFM25 total. It was also reported that the supply register boots and return grille box may not have been sealed at the ceiling. In light of the test result during the rough-in stage that indicated a tight duct system in the attic, the higher than expected final duct leakage results are attributed to these HVAC ceiling penetrations not being adequately sealed. (As of this writing, re-sealing and re-testing are planned.) Based on the ACCA Manual J software, a measured duct leakage rate, for example, of 1.6 CFM25/100SFcfa (37 CFM25) to outdoors would have affected the estimated energy savings (Section 1.4, Table 1, Duct layout #7) as follows: annual heating/cooling site energy increased to 7613 kWHr (from 7490 kWHr), heating/cooling site energy savings compared to the baseline (Duct layout #1) decreased to 19.9% (from 21.2%), and estimated annual operating cost increased to $1066 (from $1049).

4.2 Comfort

The comfort level in the test house provided by the compact buried duct layout will be validated by testing and observation at start-up and by using feedback from the occupants. Observation during start-up indicated that the compact duct components of the design—a central return and most supply registers near the interior walls—appeared to be providing comfort throughout the house within normal noise levels and without drafts in the occupied zones of the rooms.

Testing showed that the pressure differentials across the closed bedroom doors were within 3 Pa (the limit for ENERGY STAR, Version 3) for the two front bedrooms with transfer grilles, but they approached 6 Pa for the owner suite with jump duct. The supply air temperatures at the registers for the buried ducts averaged 6.8°F cooler (during cooling) than the ducts that were not buried. This will provide a noticeable improvement in comfort as well as energy efficiency.

4.3 Condensation Monitoring

By early August, the new-construction test home was complete. Figure 6 shows a typical warm and humid weather period at the test house. The outdoor temperature approached 95°F, and the outdoor dew point approached 80°F. The attic temperature peaked near 120°F.

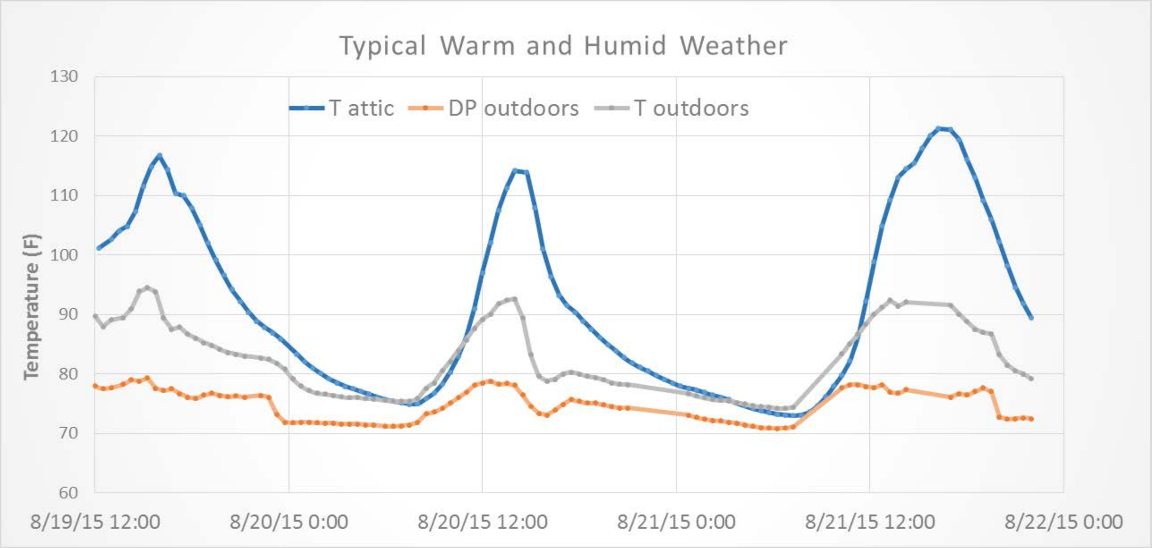

Figure 6. Typical warm and humid weather

Figure 7 shows the cooling system supply air temperature and the indoor temperature. The sensors send data every 30 minutes, so the plotted data frequently do not indicate the lowest supply air temperature (the cooling system cycles on and off 3–4 times per hour). Heating, ventilating, and air-conditioning service technicians measured and verified that the supply air temperature was consistently 54°F–55°F after the cooling system was operating for a few minutes.

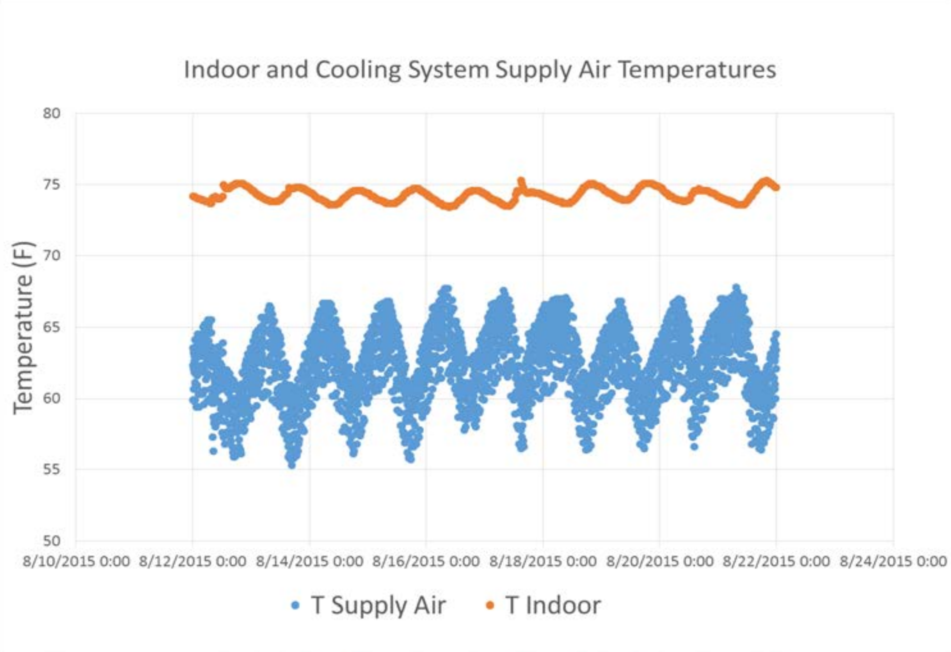

Figure 7. Indoor and supply air temperatures

Figure 8 shows the dynamic nature of the dew points within the attic and attic insulation. The attic dew point ranged from 60°F–85°F. (This dynamic was also observed during previous research by Home Innovation [Energy and Environmental Building Alliance 2013] and Consortium for Advanced Residential Buildings [Shapiro, Magee, and Zoeller 2013]). The dew points at the tree sensors within the attic insulation (3.5 in., 6 in., and 8.5 in. above the ceiling) varied by approximately 15°F during the day, but they were only a few degrees apart at night. (A sensor 1 in. above the ceiling failed.) Note that these dew points are mostly well below the outdoor dew point (shown in Figure 6). The indoor dew point was 57°F–59°F during this period. The assumption (in some prior research) that condensation is likely when the temperature at a duct insulation surface drops to the dew point of attic air or outdoor air is not necessarily true because of the dew point gradients within the attic insulation.

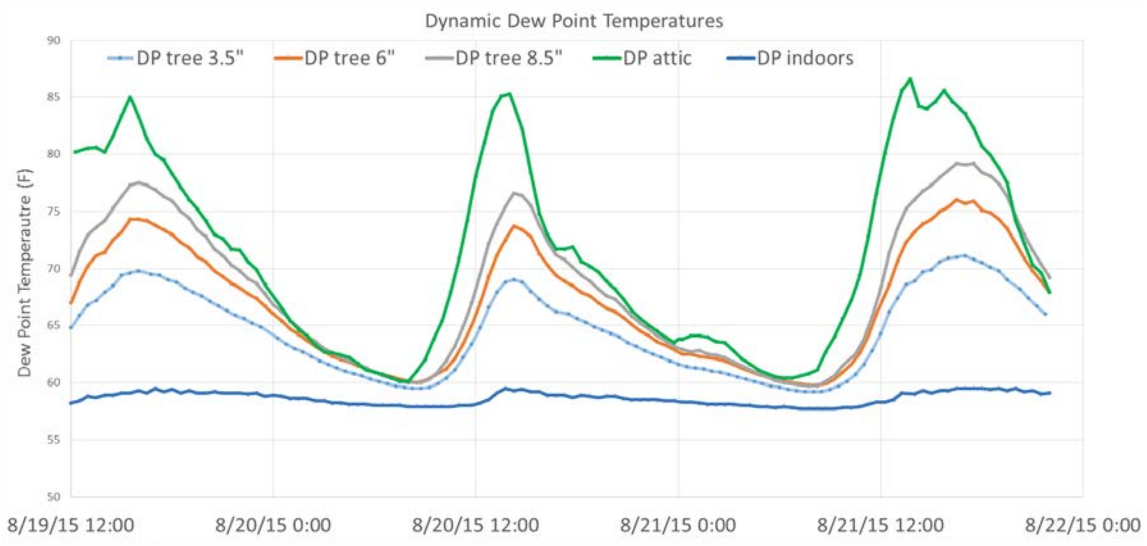

Figure 8. Dynamic dew point temperatures

Figure 9 shows the surface conditions of the 4-in.-diameter buried duct (flexible, R-8 insulated duct) serving the hall bath. The temperatures at the side and bottom of the duct were consistently above the dew point temperatures at the same location by at least 6°F–8°F. (A sensor installed at the top of this duct failed.) This difference is greater than the sensor uncertainty band of ±4°F (±1°F for temperature plus ±3°F for dew point temperature), indicating little condensation potential. Note that the sensor located at the bottom of the duct near the gypsum ceiling showed a much larger separation between the temperature and dew point, indicating a lower moisture level at this location.

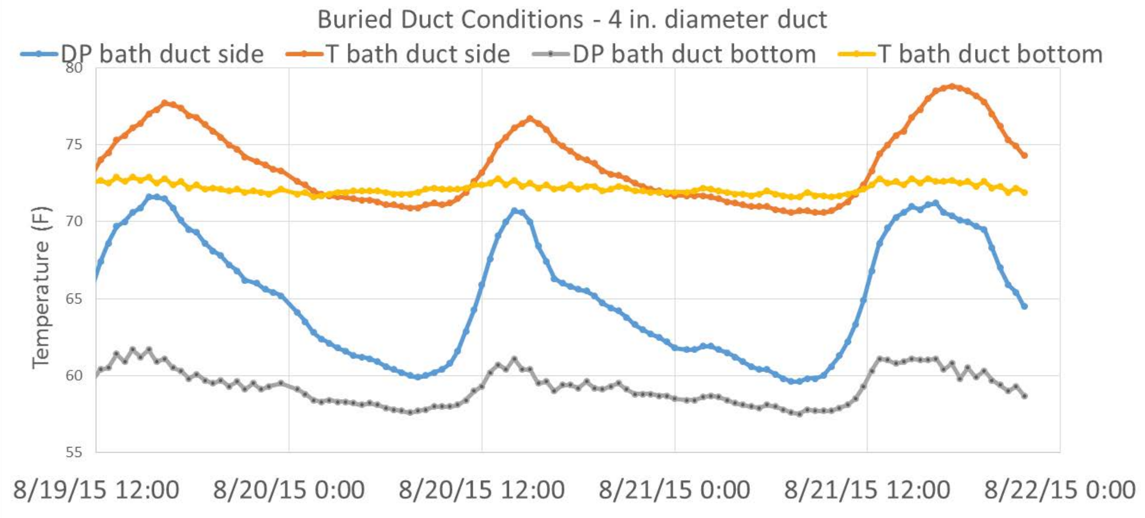

Figure 9. Buried duct conditions for the 4-in.-diameter duct

Figure 10 shows the duct surface temperature and dew point of the 6-in.-diameter buried duct serving the foyer. Again, the temperature was well above dew point, indicating little condensation potential.

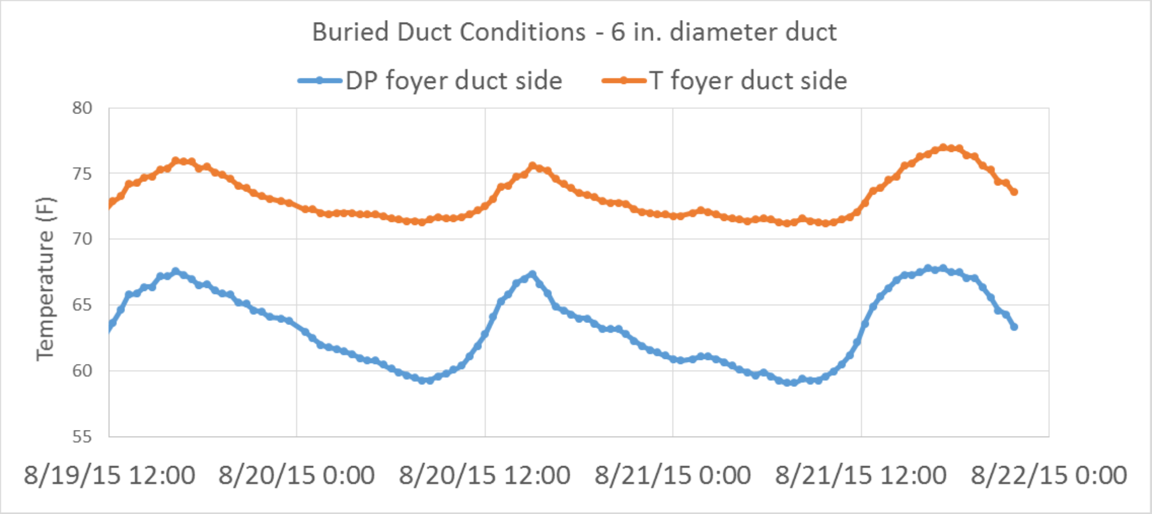

Figure 10. Buried duct conditions for the 6-in.-diameter duct

Figure 11 shows the surface conditions of two supply register boots (hall bath and foyer, above the R-8 duct wrap, both sensors 3.5 in. above the ceiling) and the dew point of the corresponding height insulation tree sensor (also 3.5 in. above the ceiling). Although the boot temperatures at times dropped below the dew point at the tree sensor, these remained well above the dew point temperatures at the boots. The boot dew points appeared to track the boot temperatures much more closely than the dew point within the attic insulation.

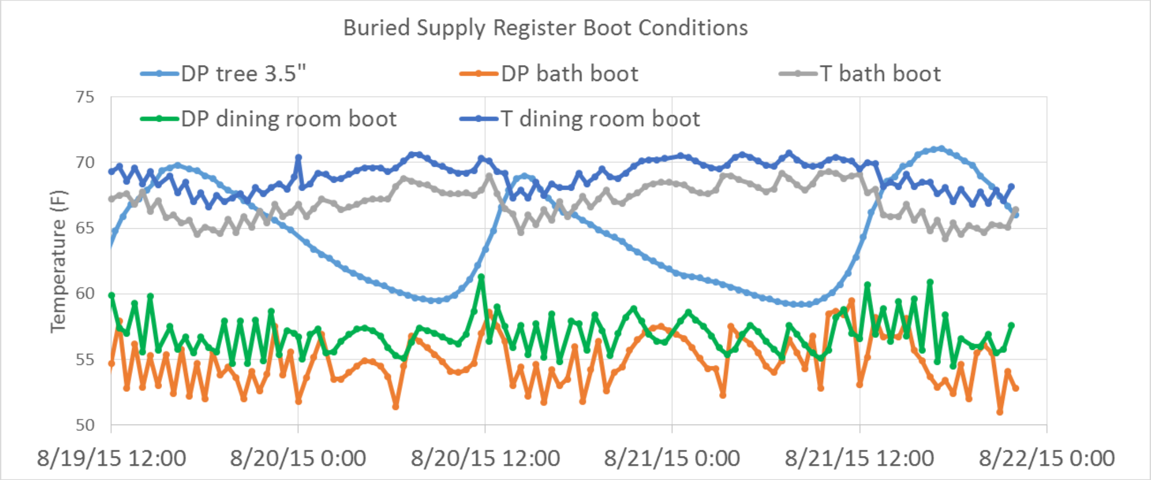

Figure 11. Buried supply register boot conditions

The dew point dynamics within the attic and attic insulation and when the duct surface dew points consistently tracked below the duct surface temperatures are not understood. A possible explanation may be because of the moisture-absorbing properties of some building materials in the attic (trusses, roof deck, insulation, and adjacent paper-backed gypsum ceiling).

5 Conclusions

5.1 Research Questions

1. What is the minimum level of duct insulation to prevent condensation at the outer jacket of buried ducts in hot-humid and mixed-humid climates?

The monitored data from the South Carolina test house indicates that R-8 duct insulation appears to be sufficient to prevent condensation. The monitored data was collected during a typical hot and humid summer but only for approximately one month (August), so monitoring results should not be considered conclusive until additional data has been collected for a longer period.

Previous BA research and the hygrothermal analysis for this project indicated that R-8 insulation for round ducts was marginal to prevent condensation in a humid climate. However, no condensation was measured or observed at the R-8 ducts during testing or monitoring for projects in the mixed-humid climates of New Jersey and Maryland. Further, this research did not measure or observe condensation at the R-8 ducts at the hot-humid climate model home in South Carolina, where during nearly a full summer of monitoring the attic insulation sensors predicted that there could be some condensation.

At the South Carolina test house, the attic dew point was below the outdoor dew point for most of the day, and the dew point gradient within the attic insulation tracked the attic dew but was well below the attic dew point. The monitored data indicates that the moisture characteristics near the ducts overall, based on the changing moisture characteristics within the attic and the variable temperatures near the duct, do not exhibit strong condensation risk.

2. What duct-leakage rate for buried ducts will minimize energy loss and the risk of condensation due to duct leakage?

Regarding energy loss, the leakage rate of 1 CFM/100SFcfa (about 2% of system airflow for this project) for the attic ducts was selected as a reasonable and achievable target. This was based on prior BA research projects that achieved this level using common sealing practices for conventional attic ducts (typically flexible duct trunks and branches with duct-board plenums and junction boxes). The measured duct-leakage rate at the rough-in stage (1.2 CFM25/100SFcfa) exceeded this design goal but only by 5 CFM. Even at a leakage rate of 1.6 CFM25/100SFcfa to outdoors the resultant energy penalty was considered small, indicating that a reasonable (with respect to energy use and constructability) target leakage rate for attic ducts would be 1–2 CFM/100SFcfa.

Regarding condensation due to duct leakage, the data collected do not allow an acceptable overall leakage rate to be determined with confidence. Any attic duct system, buried or not buried, has the potential for condensation due to duct leakage depending on the amount of leakage at any particular point. (For this project, condensation is possible away from the sensors.) Even the tightest duct system could have a leak large enough to create a condensation issue when the cold, conditioned air comes in contact with a condensing surface. Further, a duct-leakage test does not identify or measure the continuity of the outer jacket/vapor retarder of the duct insulation (except for duct board)—leakage here could allow ambient moisture into the duct insulation and lead to condensation (at the inner lining of the flexible duct or at the metal surface of fittings or metal duct).

3. What are the design considerations for compact duct layouts?

The design considerations for compact duct layouts are described in Section 3.3. A compact return duct layout is the most important first step to reduce duct area and total effective length. The supply register selection and location must balance the resultant duct area reduction with sufficient performance (air mixing without unacceptable drafts and noise).

4. What are the specific compact duct and buried duct design criteria for this test house?

The duct design criteria for this project are detailed in Section 3.4. One of the most straightforward criteria is the location of the air handling unit in conditioned space. This criterion not only reduces energy losses but facilitates regular maintenance (such as filter replacement). Another more obvious criterion is the optimization of the return duct through good design to significantly reduce the duct length and use of room crossover vents.

5. What is the design guidance for performing accurate heating and cooling load calculations for compact and buried ducts, and what inputs would be required for energy modeling programs?

For heating and cooling load calculations using Manual J software, the designer must consider nontypical adjustments for some inputs: duct area, duct leakage, and duct R-value. Current software calculates duct surface area as a percentage of conditioned floor area (depending on the selected duct layout). This approach may underestimate actual duct area reduction for compact layouts, so the designer should calculate actual duct areas for the most accurate results. For duct tightness, the designer should select levels that correspond to expected measured results, and the designer must understand the corresponding leakage rates for descriptions used in the software (e.g., *extreme* duct leakage corresponds to 0.06 CFM per square foot of duct). For duct insulation, the required input for buried ducts would be the effective R-value. Effective R-value varies with duct insulation, level of attic insulation above the ducts, and duct geometry. Effective R-values are based on modeling analysis and not on simple calculations. A designer can make a reasonable and conservative estimate based on prior BA research (R-30 for this project) (Shapiro, Zoeller, and Mantha 2013).

Although most software programs have inputs to change the location, insulation, and length of duct systems, these inputs may not result in estimated energy savings due to the lack of an adequate baseline. At this time, multiple estimates can be made in simulation software, one with a standard duct design and a second with the compact buried duct design, to estimate savings. Developing methodologies to take advantage of optimized attic duct designs remains a programmatic need for both code and above-code programs. Based on the analysis developed in Section 1.4, attic duct designs such as compact buried ducts may be compared to ducts located in conditioned space given sufficient criteria such as:

- Air sealing and testing to meet specified leakage levels
- R-8 duct insulation

- Buried ducts covered with R-30 attic insulation
- Air handling unit and return-air ducts located in conditioned space
- Room diffusers located at no more than one-half of the distance to the exterior wall.

6. Is this compact buried duct system cost-effective?

The cost analysis presented in Section 1.4 indicates that this compact buried duct layout is very cost-effective. The analysis included building a mechanical closet in conditioned space. (If a house design already included the air handling unit within conditioned space, this incremental cost would not be relevant.) No cost was added for the duct-sealing effort; the contractor's standard practice relied on conventional methods using mastic. No cost reductions for reduced duct area were taken even though duct area reduction was significant. The measured duct-leakage rate exceeded the design goal, but it barely affected the estimated energy savings. For future projects, if cost savings from monetizing reduced duct area (and potentially smaller capacity equipment) are included, the proposed solution could realistically be a no-cost option or even a net-cost savings.

7. What are the building code and energy program acceptance barriers to this design?

Four significant acceptance barriers apply to this design:

1. Further monitoring is required to confirm that R-8 duct insulation is sufficient to prevent condensation in all humid climates with a reasonable range of supply air temperatures.
2. All attic duct systems, buried and not buried, have the potential for energy loss and condensation due to duct leakage; selected sealing methods must be tested to show consistent leakage results.
3. The compact duct layout will vary by house design; consistently applying the compact duct layout criteria must result in acceptable comfort (air mixing without stagnant zones and without unwanted noise) to establish a track record of success.
4. The building code official may not permit buried ducts in vented attics until this practice, including specific design and testing criteria, becomes more common and is demonstrated to provide the necessary comfort and reliability of standard alternatives.

5.2 Key Findings

The results of this research indicate that a compact buried duct layout can be a practical alternative to installing ducts inside conditioned space (inside the air barrier), which often presents a challenge for many house configurations including the single-story slab-on-grade design for this project. Key project findings include:

- Based on the readings from numerous sensors installed to monitor duct surface and attic conditions, no condensation was measured or observed at the buried ducts. (Common R-8 insulated ducts that were covered with R-30 attic insulation.)
- Conventional duct-sealing methods resulted in a low leakage rate for the attic ducts when tested during the rough-in stage. Final testing indicated a higher leakage rate than expected; this was attributed to a lack of sealing of the supply register boots and return grille box at the ceiling.

- The buried ducts delivered colder air during cooling than the attic ducts that were not buried (on average nearly 7°F colder). The lower delivery temperature results in increased energy savings and improved occupant comfort.
- A compact duct layout can improve the performance of any duct system when the design criteria are carefully considered in accordance with industry standards. For this project, the attic duct area was reduced by 32% for supply ducts and 75% for return ducts compared to builder standard practice, both significantly contributing to the overall energy savings. (See also the last bullet point below.)
- The compact buried duct layout was practical to install, although effective quality control is required to ensure uniform insulation coverage above the buried ducts and to meet duct-sealing goals.
- Existing industry standard heating and cooling load calculation software can be used to accurately represent predicted energy savings for compact buried duct layouts. Additional features can be implemented in the software to facilitate the analysis and design of these types of systems.
- This project outlined a cost-effective energy savings solution for a hot-humid climate. Simulations predicted a positive annual cash flow of $239, a simple payback of 3.1 years, and a simple return on investment of 32%. If cost savings from monetizing the reduced duct area and smaller capacity systems are included, the proposed solution could realistically be a no-cost option.
- Simulations predicted 21% annual heating/cooling site energy savings compared to conventional insulated attic ducts. The compact duct component contributed approximately 13% of this energy savings, and the buried duct component contributed approximately 8%.
- Data in the report was taken at one house in a hot-humid climate during August of 2015 under the conditions, construction quality, and construction details for that house. Conditions, construction quality, and details that vary from those monitored in this report should be evaluated based on engineering principles and methods or empirical data.

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Appendices

Appendix A:
Home Innovation/K. Hovnanian Compact Buried Duct System 2009 (New Jersey Project)

The test house was a single-story, slab-on-grade design (Figure 13).

- Duct design details
    - Truss chase to accommodate the supply trunk (Figure 14)
    - Compact duct layout: a single central return with a short return trunk below the ceiling plane; bedroom transfer grilles; no elbows in attic supply trunk or supply branch ducts (Figure 15)
    - Deeply buried supply duct system in the vented attic
        - Metal supply trunk duct with R-8 duct insulation
        - Flexible R-8 insulated supply branch ducts
        - Metal supply register boots with R-8 duct insulation
        - Trunk and boots (but not flexible branches) encapsulated with 2-in. ccSPF (Figure 16)
        - Deeply buried with R-38 blown fiberglass insulation (Figure 17).
- Results
    - Duct area—compared to builder standard
        - 28% less supply duct area in the attic
        - 70% less return duct area
    - Duct-leakage testing
        - Rough: 1.0 CFM25/100SFcfa (25 CFM25) attic duct only—before encapsulation
        - Final: 3.4 CFM25/100SFcfa (85 CFM25) entire system, 0 CFM25 to outdoors
    - Condensation monitoring
        - Sensors installed at condensing surfaces of trunk, branches, and boots
        - None measured.

Figure 12.
Test house

Figure 13.
Truss chase with supply trunk

Figure 14. Supply duct layout

Figure 15.
Encapsulated supply trunk

Figure 16.
Ducts deeply buried in attic insulation

Appendix B:
Home Innovation/K. Hovnanian Compact Buried Duct System 2012 (Maryland Project)

Details

The purpose of this experiment was to assess if a particular buried duct design performed equivalently to ducts in conditioned space based on test results and monitored data. The test house was a two-story design in Upper Marlboro, Maryland, a mixed-humid climate, with a full basement and two independent heating and cooling systems (Figure 18). Each system had a natural gas furnace located in the basement. The first floor system had a conventional perimeter duct layout. The supply and return trunks for the second floor were installed within a vertical duct chase directly above the furnace. The supply trunk served buried ducts in the vented attic. The details for the second floor system are described below:

- Compact duct features
  - Central return trunk duct, without branch ducts, entirely in conditioned space below the ceiling plane, serving one grille each in the adjacent hall and adjacent master suite (Figure 19)
  - Transfer grilles for the remaining three bedrooms (Figure 20)
  - Supply register boots installed in the ceiling near interior walls to minimize supply branch lengths (Figure 21). Register size and style selected to provide adequate throw and air mixing without unacceptable drafts or noise.
- Buried ducts in the attic (second floor system)
  - Supply trunk duct: metal, sealed using mastic, no duct insulation before encapsulation (Figure 22)
  - Supply branch ducts: double flexible ducts—R-8 duct within another R-8 duct (Figure 23)
  - Supply register boots: metal, insulated with R-8 duct wrap
  - The trunk and branch take-offs at the trunk (but not the branches or register boots) were encapsulated with 2-in. ccSPF before drywall (Figure 24)
  - All attic ducts buried with at least 2 in. of blown fiberglass insulation (Figure 265).

The upstairs and downstairs duct systems were compared for thermal performance, duct leakage, and condensation potential. Sensors were installed to monitor temperature and relative humidity (RH). (Dee table below for specific sensor locations.)

- Sensors (15) at condensing surfaces of the buried ducts to monitor potential condensation
- Sensors (8) in airstreams to monitor thermal performance
- Sensors (4) to measure ambient conditions.

Figure 17. Buried duct in Project 2 test house

Figure 18. Central duct chase and return

Figure 19.
Bedroom transfer grilles

Figure 20.
Supply register boot near an interior wall

Figure 21.
Second-floor supply trunk and compact duct layout

Figure 22.
Flexible branch “duct within a duct”

Figure 23.
Encapsulated supply trunk before drywall

Figure 24.
Buried ducts

Testing and Monitoring Results

Duct-leakage test results are shown in Table 5. The supply plenum was left open just below the ceiling plane for rough testing. The attic ducts were tested before and after trunk encapsulation and drywall. The results were the same, indicating that the ccSPF did not contribute to duct tightness in this case. (Encapsulation after drywall potentially could have lowered duct leakage to the outdoors.) Final testing for the entire second-floor system showed duct leakage to the outdoors greater than the total leakage during the rough test, indicating leakage from the furnace and vertical supply and return trunks within the duct chase to the outdoors through the building enclosure. The final testing for the first floor and basement system showed that ducts in conditioned space can leak to the outdoors through the building enclosure.

Table 5. Buried Duct-Leakage Test Results in Design 2

Duct-Leakage Test	Details	Data
Rough 1—attic ducts only	Before ccSPF, before drywall	43 CFM25 (1.9 CFM25/100SFcfa)
Rough 2—attic ducts only	After ccSPF, before drywall	43 CFM25
Final—second-floor system	After house is complete	98 CFM25 to outdoors
Final—first-floor system	After house is complete	84 CFM25 to outdoors

Monitored data showed no signs of condensation at the sensor locations in the attic. Figure 26 plots the difference between the temperature and the dew point temperature during the worst-case two-week period during an entire cooling season. Figure 27 shows average temperatures during an entire cooling season and confirms that condensation is not likely for this design. Interestingly, the dew points varied within layers of the attic insulation and were also different compared to the attic and outdoors: the dew points at the boots and bottom of the flex ducts averaged 5°F–7°F less than the average attic dew point, and attic dew point averaged approximately 5°F less than the average outdoor dew point.

Monitored data showed that the buried ducts delivered conditioned air with less energy loss compared to the first-floor ducts in conditioned space (but of course these buried duct losses were to the attic and outdoors). Figure 28 plots the airstream temperature differential between the plenum and the supply registers for the longest and shortest branch ducts for the second floor (the lines represent the running averages) during the heating season. These second-floor differentials were much tighter (less) than the corresponding first floor data (not shown). The graph shows that the average plenum temperature was frequently lower than the average temperature at the supply registers. This indicates that as the furnace cycled off, the uninsulated plenum in the basement cooled faster than the insulated, buried ducts. The outdoor air ducted to the return plenum that provides supply-only mechanical ventilation likely contributed to this.

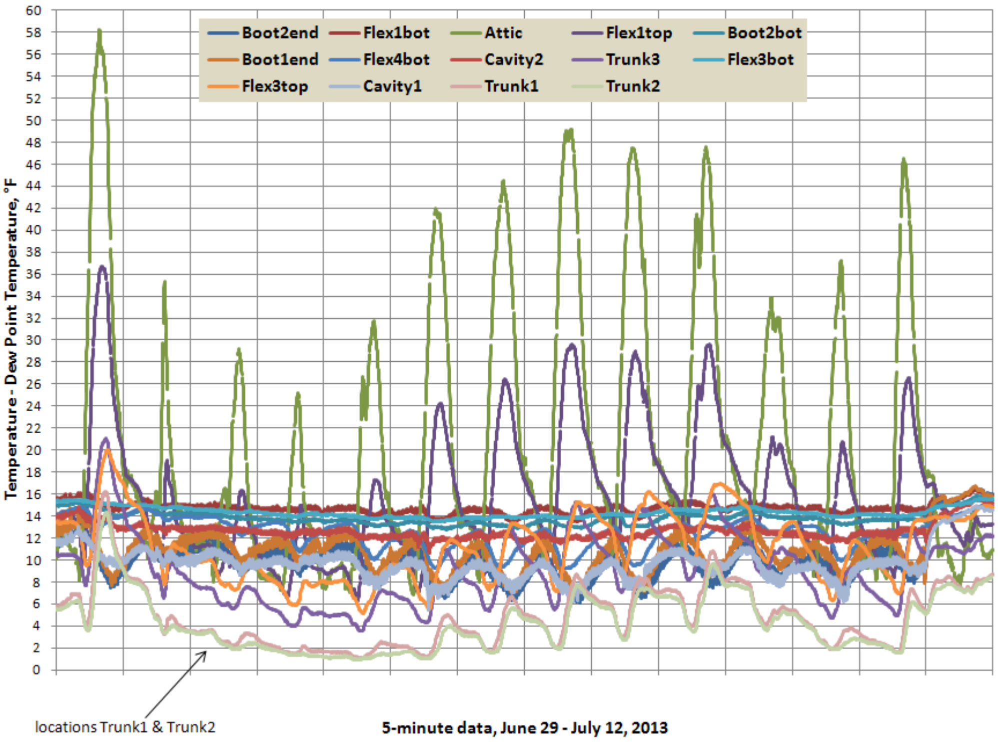


Figure 25. Condensation potential at condensing surfaces in the attic

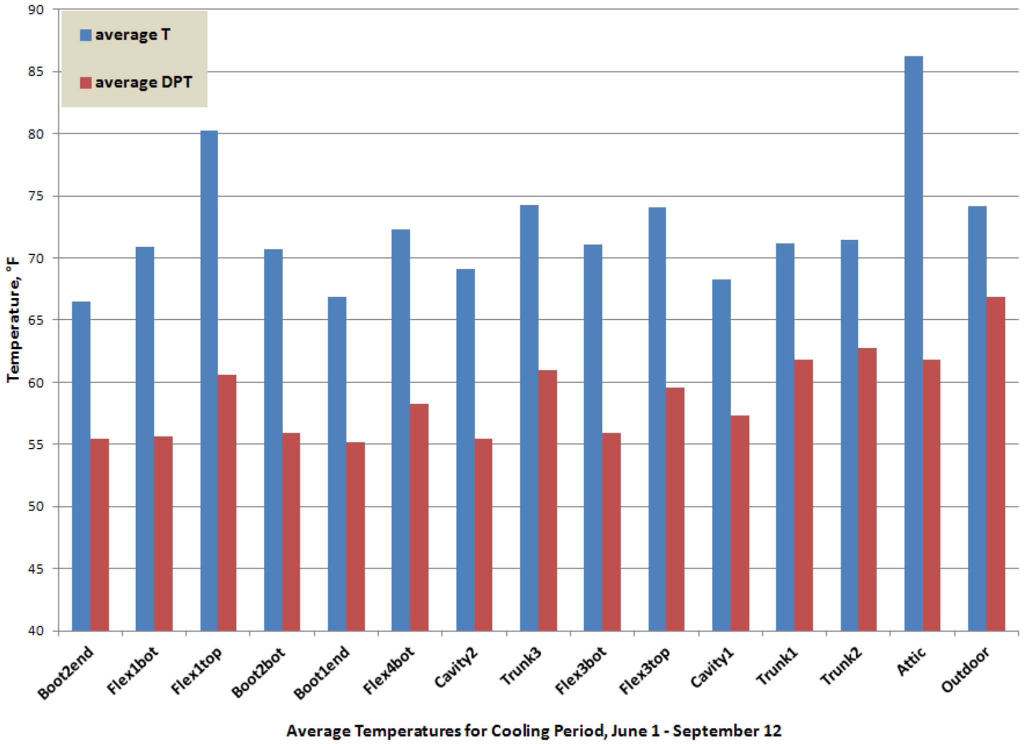


Figure 26. Seasonal average condensation potential

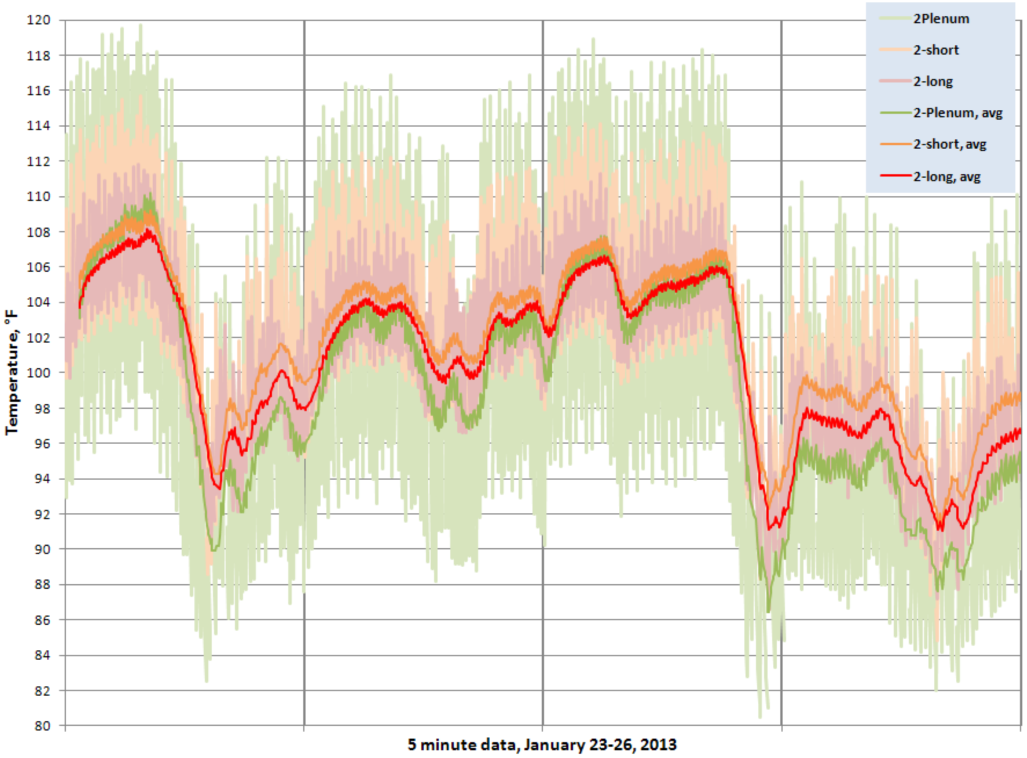
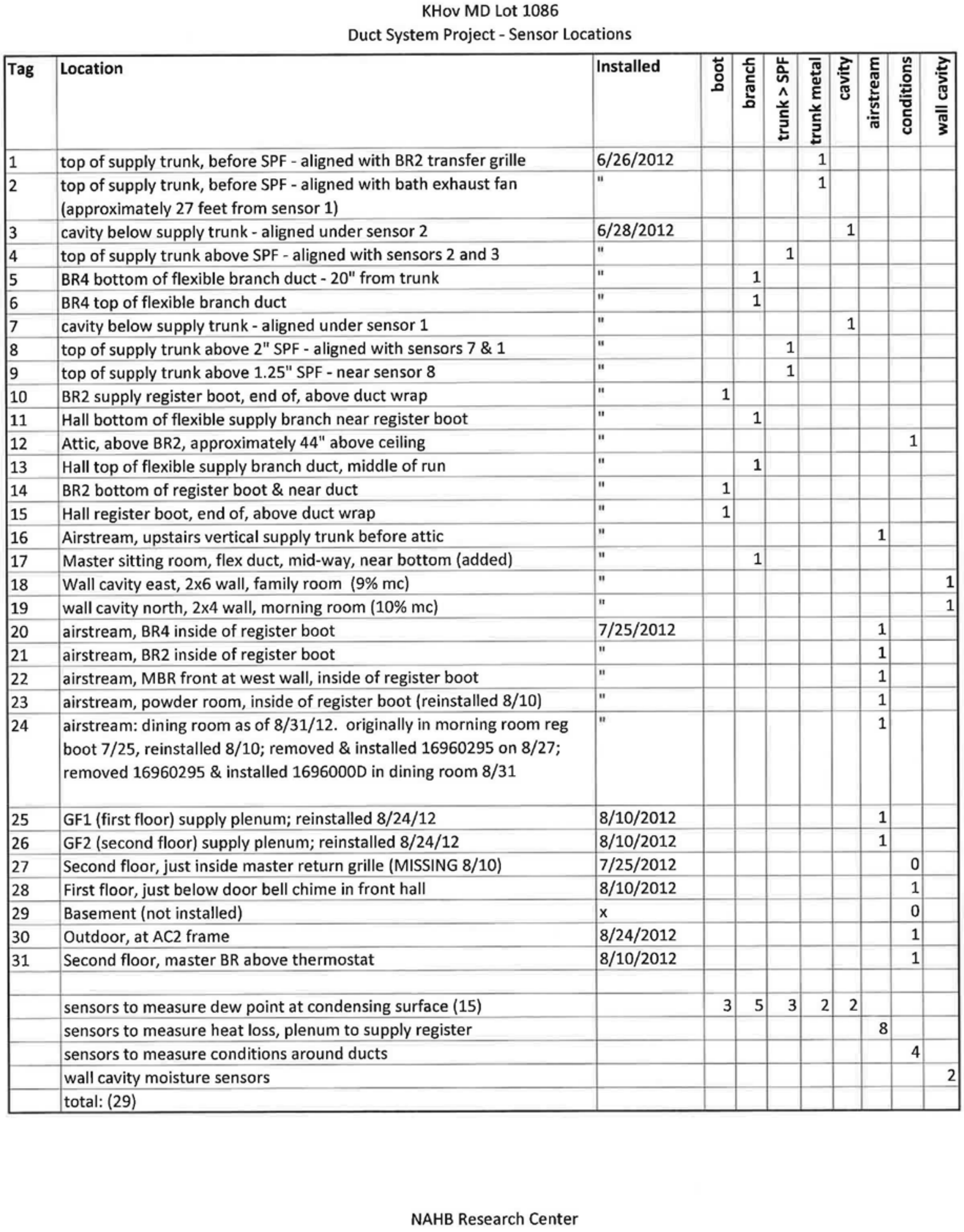


Figure 27. Thermal performance

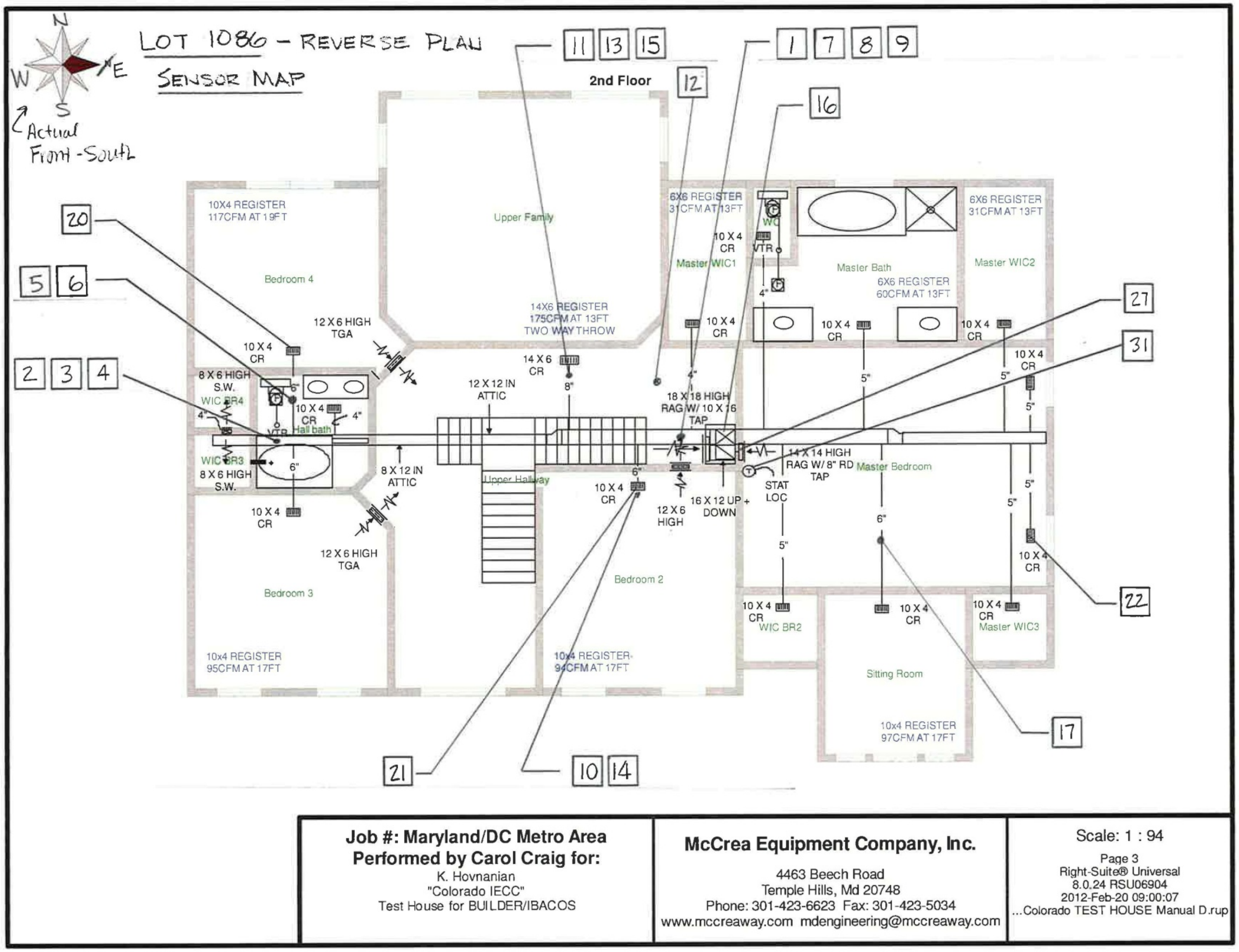
Table 6. Temperature and RH Sensor Locations



KHov MD Lot 1086
Duct System Project - Sensor Locations

Tag	Location	Installed	boot	branch	trunk > SPF	trunk metal	cavity	airstream	conditions	wall cavity
1	top of supply trunk, before SPF - aligned with BR2 transfer grille	6/26/2012				1				
2	top of supply trunk, before SPF - aligned with bath exhaust fan (approximately 27 feet from sensor 1)	"				1				
3	cavity below supply trunk - aligned under sensor 2	6/28/2012					1			
4	top of supply trunk above SPF - aligned with sensors 2 and 3	"			1					
5	BR4 bottom of flexible branch duct - 20" from trunk	"		1						
6	BR4 top of flexible branch duct	"		1						
7	cavity below supply trunk - aligned under sensor 1	"					1			
8	top of supply trunk above 2" SPF - aligned with sensors 7 & 1	"			1					
9	top of supply trunk above 1.25" SPF - near sensor 8	"			1					
10	BR2 supply register boot, end of, above duct wrap	"	1							
11	Hall bottom of flexible supply branch near register boot	"		1						
12	Attic, above BR2, approximately 44" above ceiling	"							1	
13	Hall top of flexible supply branch duct, middle of run	"		1						
14	BR2 bottom of register boot & near duct	"	1							
15	Hall register boot, end of, above duct wrap	"	1							
16	Airstream, upstairs vertical supply trunk before attic	"						1		
17	Master sitting room, flex duct, mid-way, near bottom (added)	"		1						
18	Wall cavity east, 2x6 wall, family room (9% mc)	"								1
19	wall cavity north, 2x4 wall, morning room (10% mc)	"								1
20	airstream, BR4 inside of register boot	7/25/2012						1		
21	airstream, BR2 inside of register boot	"						1		
22	airstream, MBR front at west wall, inside of register boot	"						1		
23	airstream, powder room, inside of register boot (reinstalled 8/10)	"						1		
24	airstream: dining room as of 8/31/12. originally in morning room reg boot 7/25, reinstalled 8/10; removed & installed 16960295 on 8/27; removed 16960295 & installed 1696000D in dining room 8/31	"						1		
25	GF1 (first floor) supply plenum; reinstalled 8/24/12	8/10/2012						1		
26	GF2 (second floor) supply plenum; reinstalled 8/24/12	8/10/2012						1		
27	Second floor, just inside master return grille (MISSING 8/10)	7/25/2012							0	
28	First floor, just below door bell chime in front hall	8/10/2012							1	
29	Basement (not installed)	x							0	
30	Outdoor, at AC2 frame	8/24/2012							1	
31	Second floor, master BR above thermostat	8/10/2012							1	
	sensors to measure dew point at condensing surface (15)		3	5	3	2	2			
	sensors to measure heat loss, plenum to supply register							8		
	sensors to measure conditions around ducts								4	
	wall cavity moisture sensors									2
	total: (29)									

NAHB Research Center



Job #: Maryland/DC Metro Area
Performed by Carol Craig for:
K. Hovnanian
"Colorado IECC"
Test House for BUILDER/IBACOS

McCrea Equipment Company, Inc.
4463 Beech Road
Temple Hills, Md 20748
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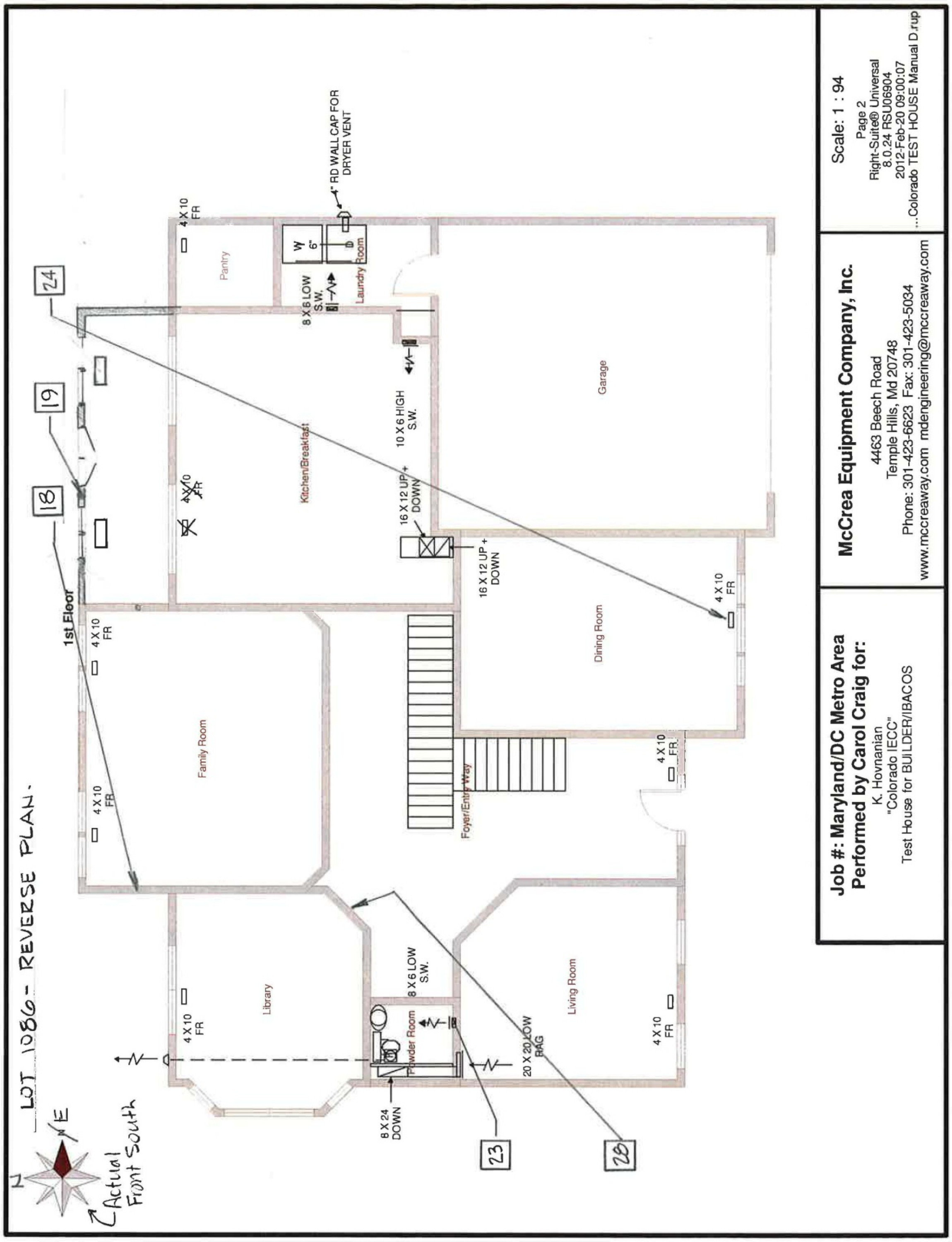
LOT 1086 - REVERSE PLAN.
1st Floor
N
E
Actual Front South
18
19
24
23
20
Pantry
Laundry Room
Kitchen/Breakfast
Garage
Family Room
Dining Room
Foyer/Entry Way
Library
Powder Room
Living Room
4 X 10 FR
4" RD WALL CAP FOR DRYER VENT
W
D
6"
8 X 6 LOW S.W.
10 X 6 HIGH S.W.
16 X 12 UP + DOWN
20 X 20 LOW RAG
8 X 24 DOWN
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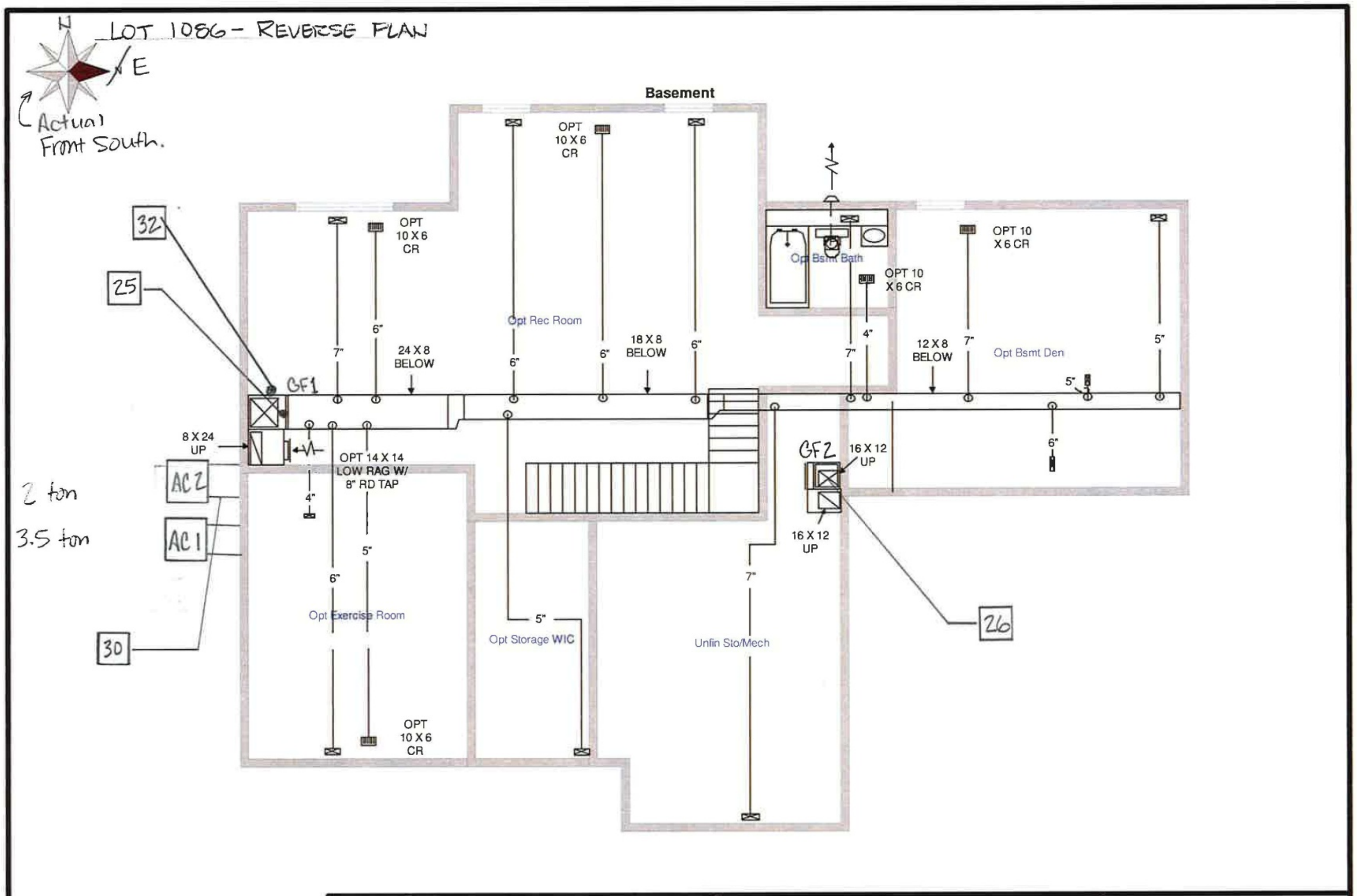

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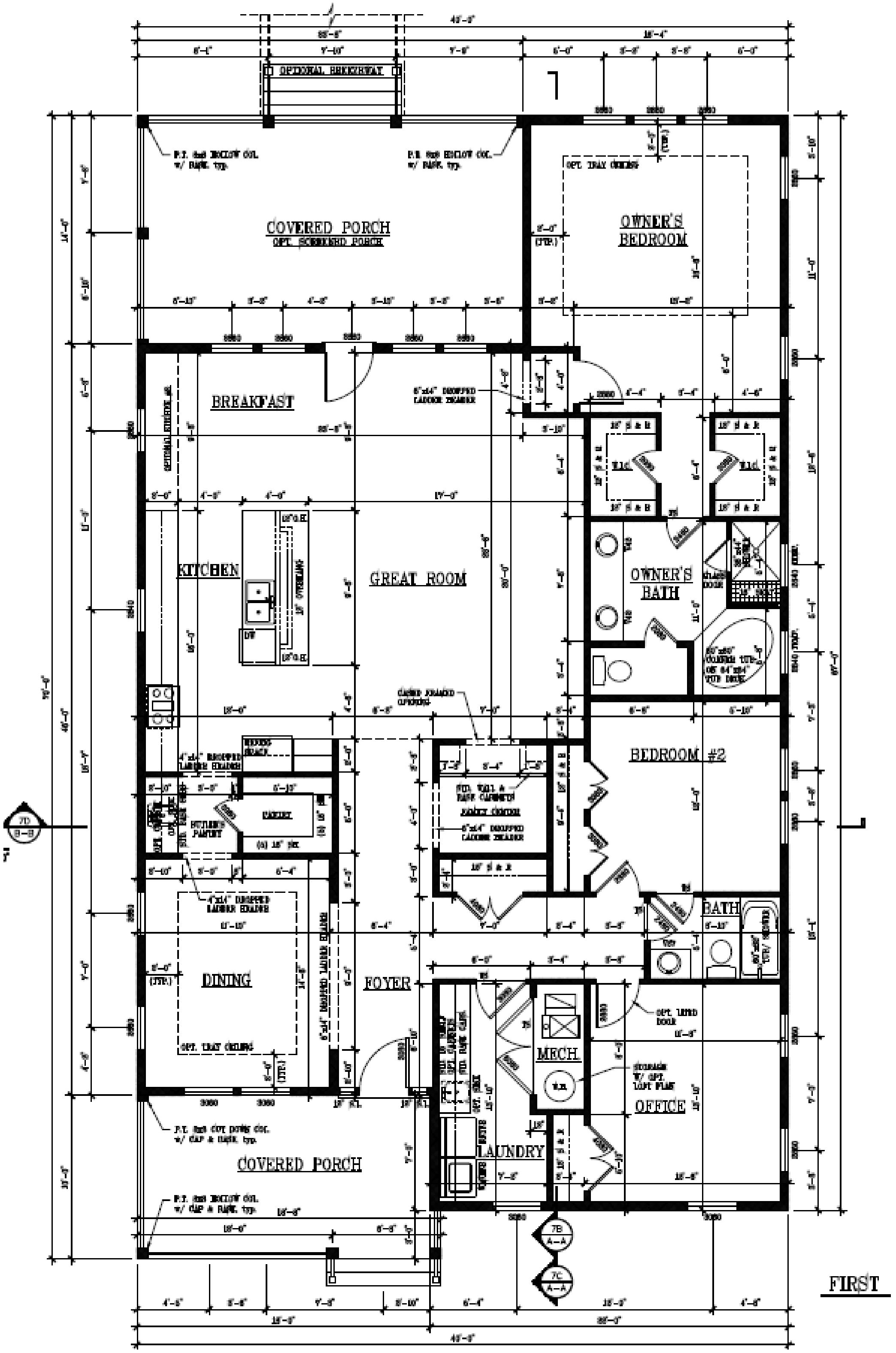
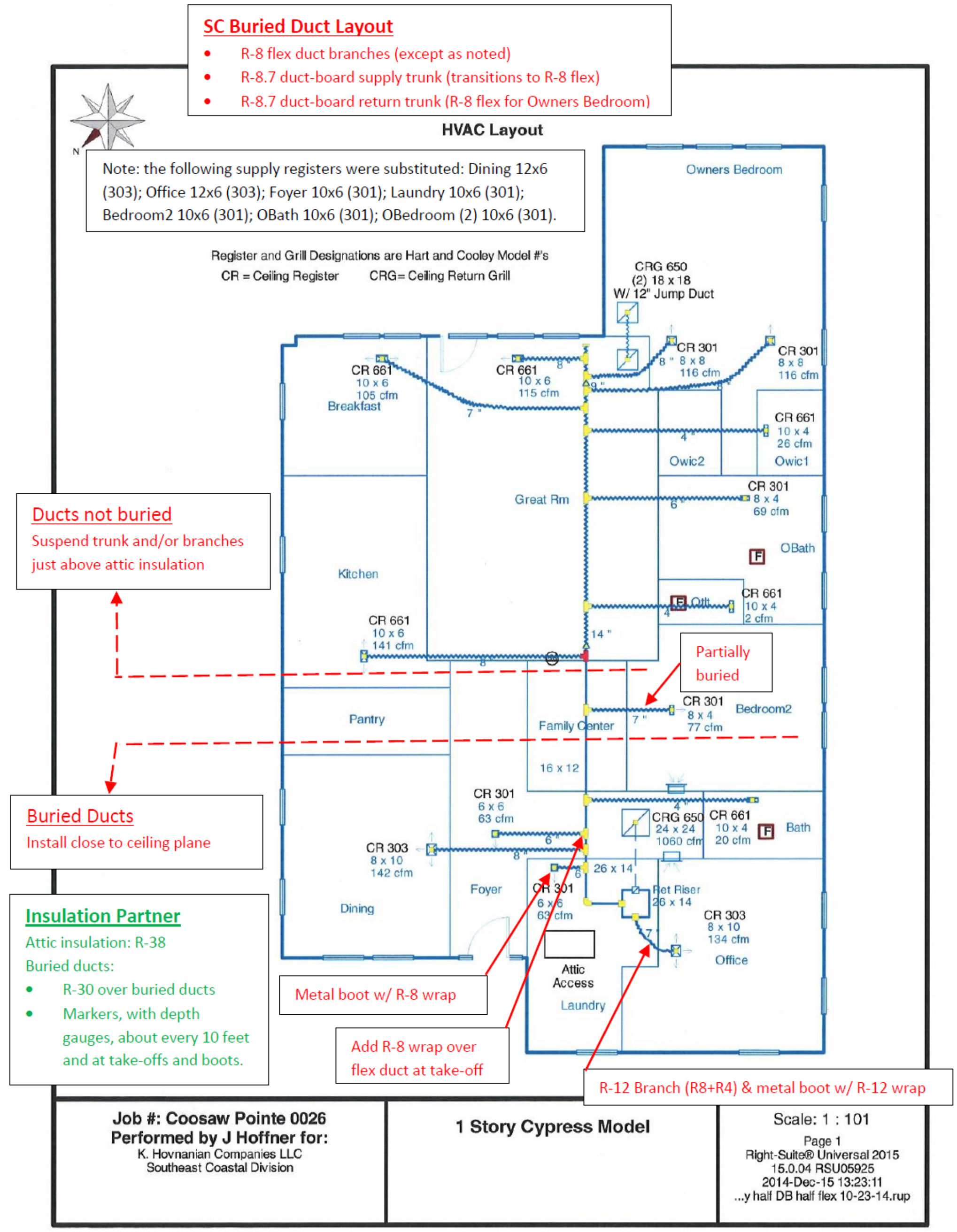
Appendix C:
South Carolina Test House Floor Plan



Appendix D:
South Carolina Test House Duct Layout



SC Buried Duct Layout

- R-8 flex duct branches (except as noted)
- R-8.7 duct-board supply trunk (transitions to R-8 flex)
- R-8.7 duct-board return trunk (R-8 flex for Owners Bedroom)

Note: the following supply registers were substituted: Dining 12x6 (303); Office 12x6 (303); Foyer 10x6 (301); Laundry 10x6 (301); Bedroom2 10x6 (301); OBath 10x6 (301); OBedroom (2) 10x6 (301).

Ducts not buried

Suspend trunk and/or branches just above attic insulation

Partially buried

Buried Ducts

Install close to ceiling plane

Insulation Partner

Attic insulation: R-38

Buried ducts:

- R-30 over buried ducts
- Markers, with depth gauges, about every 10 feet and at take-offs and boots.

Metal boot w/ R-8 wrap

Add R-8 wrap over flex duct at take-off

R-12 Branch (R8+R4) & metal boot w/ R-12 wrap

Duct Leakage Test Targets:

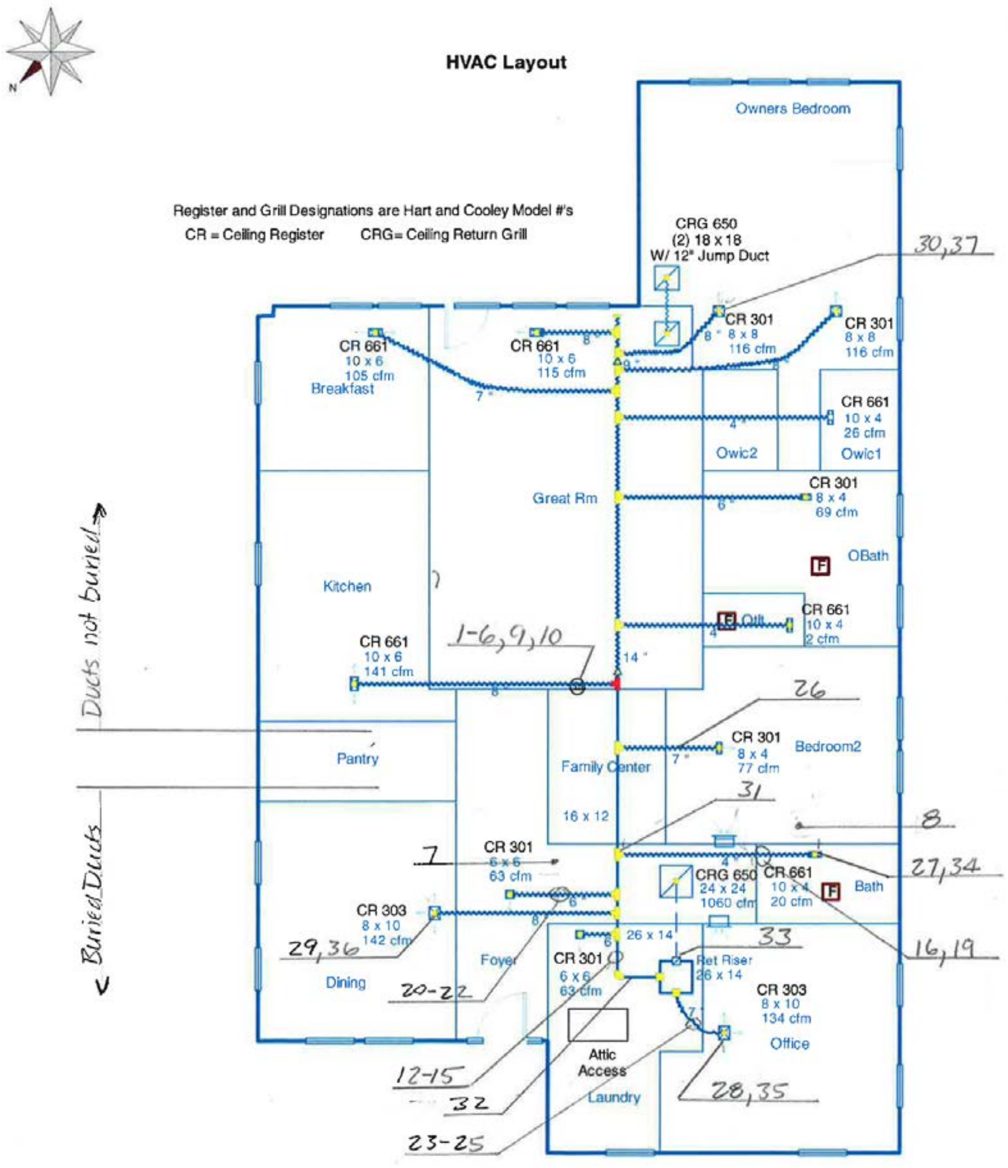
Rough-in test 1 (without air handler, before drywall): 1 CFM25/100SFcfa including returns (23 CFM25, about 2% of air flow).

Rough-in test 2, if possible (without air handler, after sealing boots at drywall, before attic insulation): same.

Final test: 3 CFM25/100SFcfa (69 CFM25).

Appendix E:
South Carolina Test House Sensor Locations

Sensor Key			
ID	**Tag**	**Details**	**Sensor**
		Conditions (MC indicates also measures moisture content)	
1	tree 1"	1" above ceiling, on PVC tree	OD1202E7
2	tree 3.5"	3.5"	OD1201CE
3	tree 6"	6"	OD120189
4	tree 8.5"	8.5"	OD120177
5	tree 36"	36"	OD1202C9
6	attic1 63" MC	63" above tree, at truss (MC)	OA3E0966
7	attic2 63" MC	63" same bay as foyer (MC)	OD1202F6
8	deck 63" MC	63" above BR2 near bath wall (MC)	OD1202AA
9	indoor at tstat	At thermostat	OD120061
10	indoor ceiling	At ceiling above thermostat, below tree	OD12012D
11	outdoors		OA3E0E43
		Condensing surfaces (buried unless noted)	
12	trunk top	top - R-8.7 ductboard trunk	OD120150
13	trunk sideL	side, left	OD120148
14	trunk sideR	side, right	OD120265
15	trunk bottom	bottom	OD12025C
16	bath duct top	top - 4" branch R-8 (Bath)	OD120039
17	bath duct sideR	side, rear	OD120201
18	bath duct sideF	side, front	OD120136
19	bath duct bot	bottom	OD1202B0
20	foyer duct top	top - 6" branch R-8 (Foyer)	OD120169
21	foyer duct side	side	OA3EOBE9
22	foyer duct bot	bottom	OA3E08D0
23	office R-12 top	top - 7" branch R-12 (Office)	OD12029C
24	office R-12 side	side	OD1201E6
25	office R-12 bot	bottom	OA3E0DE7
26	BR2 part. Duct	bottom 7" branch R-8 (BR2) (partially buried)	OD12006A
27	bath boot	Boot, R-8 wrap (Bath)	OD120105
28	office R-12 boot	Boot, R-12 wrap (Office)	OD120176
29	dining boot	Boot, R-8 wrap (Dining)	OD12029E
30	owner boot	Boot, R-8 prefab (Owner bedroom)	OA3E06F1
31	bath takeoff	Takeoff (bath)	OD12004C
		Airstream	
32	supply air	Supply plenum	1E70012D
33	return air	Return plenum	OA3E0366
34	bath air	bath - within register boots	OD120049
35	office air	office -	OD1200F3
36	dining air	dining -	OA3E0F95
37	owner air	owner -	OA3E074B



HVAC Layout

N
Register and Grill Designations are Hart and Cooley Model #'s
CR = Ceiling Register
CRG= Ceiling Return Grill
Owners Bedroom
CRG 650
(2) 18 x 18
W/ 12" Jump Duct
30,37
CR 301
8 x 8
116 cfm
CR 301
8 x 8
116 cfm
CR 661
10 x 6
105 cfm
Breakfast
CR 661
10 x 6
115 cfm
8"
7"
9"
4"
CR 661
10 x 4
26 cfm
Owic2
Owic1
Great Rm
CR 301
8 x 4
69 cfm
6"
OBath
F
Kitchen
Otlt
CR 661
10 x 4
2 cfm
CR 661
10 x 6
141 cfm
1-6,9,10
14"
26
Ducts not buried
Buried Ducts
Pantry
CR 301
8 x 4
77 cfm
Bedroom2
Family Center
16 x 12
31
8
7
CR 301
6 x 6
63 cfm
27,34
CRG 650
24 x 24
1060 cfm
CR 661
10 x 4
20 cfm
Bath
CR 303
8 x 10
142 cfm
29,36
26 x 14
33
16,19
Foyer
CR 301
6 x 6
63 cfm
Ret Riser
26 x 14
Dining
20-22
CR 303
8 x 10
134 cfm
Office
Attic Access
Laundry
12-15
32
28,35
23-25

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