FSEC Energy Research Center

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Metal and Flexible Duct Systems Impacts upon Cooling Energy and Performance

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Executive Summary

A research project was conducted with the primary goal to determine the central air space conditioning energy and performance impacts for a metal duct system and also for a flexible duct system. Testing and evaluation was completed at the FSEC Energy Research Center (FSEC) Flexible Residential Test Facility (FRTF) from early 2019 through January 2021. The FRTF consists of two separate single-family residential buildings built identically that are located next to each other with same layout and orientation. This permitted simultaneous testing of the metal and flex duct systems under the same environmental conditions. Null testing (houses with exact same duct and AC systems) prior to the duct tests indicated that each home and central air systems operated very similar. There was less than 1% space conditioning energy use difference between test homes and nearly identical interior temperatures were maintained during null testing. The daily average indoor temperature difference between houses was about 0.1°F with the maximum daily difference of only 0.2°F.

The metal duct system was installed in one home and had no modifications made during the testing period. A flex duct system was installed in the other home. Each duct system was installed in accordance with manufacturer and industry standards. House and duct tightness tests showed that both systems were tight and similar. The only difference in performance was in total external static pressure (TESP). The metal duct system TESP was 0.34 in WC and flex TESP was 0.44 at full capacity. A brief period of testing the "best practice" systems, referred to as Test 1, showed a modest increase in cooling energy of 1 kWh/day (5%) for a typical summer day (daily average of 75°F indoor and 80°F outdoor).

Test 2 was another brief test was conducted to examine the potential impact of a duct system with much more flex duct compression and extra length. This test was run with TESP of 1 in WC in the flex system and measured an increase in daily energy of 2.9 kWh (14%) in the flex system compared to metal system.

Test 3 was designed to represent what may be considered to be a "more typical" flex duct installation having significant compression that resulted in a TESP of 0.82 in WC while the metal flex duct TESP remained at 0.34 in WC. Using the same typical summer day conditions for Test 1 and Test 2 for comparison, Test 3 flex duct system used 1.9 kWh/day (9.3%) more than the metal duct system. Test 3 was conducted for almost a year to collect data with wide variation in environmental conditions. This allowed a simple model to be used to predict annual cooling energy impacts. There was inadequate heating data to compare heating energy impacts. The average results of three cities representing climate zones 1A and 2A predict the flex Test 3 duct to use 422 kWh per year (9%) more than the metal duct system. It is important to note that while the percentage impact difference of Test 3 was similar for Miami (9%), Orlando (8%), and Houston (9%), the annual cooling energy use in Miami (1A) had an annual energy use increase in flex that was 229 kWh (70%) more than Orlando (2A). This demonstrates the potential for more potential cooling energy savings for hotter climates as might be expected. Late in the project it was discovered that the insulation on the metal duct system had been over-compressed resulting in an R value of only about R2.5 instead of R6. If the metal duct was insulation performed at R6, the Test 3 flex duct may have used 17% more energy. The perils of overcompression is described in more detail later.

The cooling energy consisted of the outdoor condenser and the air handler unit (AHU). It was the increase in AHU fan motor energy that was responsible for most of the difference between flex and

metal systems. The fan motors were electronically commutated motors (ECM) that can adjust the fan rpm to variations in static pressure. This results in the designed airflow still being able to be reached within a range of varying static pressure. Therefore the increase in TESP of the flex systems tested resulted in large increases in AHU fan motor energy use. Test 3 flex AHU energy increased 1.1 kWh/day (72%). While this is a significant increase in fan motor energy, the daily motor energy use accounts for only about 12% of the total cooling energy use which explains why the total cooling energy percent difference is much smaller than the AHU energy percent difference.

The flex system condenser daily energy use was a little higher than metal. For example Test 3 flex system daily average condenser energy use was about 0.8 kWh more than metal system. The cause is not certain, but it is most likely due to the extra sensible load added to the flex system home from the higher motor energy use that would result in more sensible heat energy load.

The summer peak power impact was also evaluated and found that Test 3 flex had a peak cooling power increase of 0.233 kW (9%) compared to the metal system. Reductions in peak power are important as they help reduce the need for building future power plants and are an important part of improving grid reliability.

Condensation on the exterior insulation jacket on the cold air metal supply ducts was an unexpected event in this research project that did not become apparent until the second summer of monitoring. The installed fit and finish of the insulation wrap looked very good upon completion and attic duct inspections during the first summer of testing did not find any significant condensation, however in August 2020, a substantial amount of condensation was found around the lower portions of horizontally run ducts. By late September 2020, it was determined that there was also a substantial amount of water trapped between the metal duct and outer insulation jacket at the bottom.

Over-compression of the insulation wrap was a plausible cause since this would reduce R value and result in colder exterior surface temperatures. To investigate this, outside exterior insulation circumferences were carefully measured over the entire duct system. The results clearly demonstrated the insulation was over-compressed and the metal duct system did not have the equivalent of at least R6. Three representative samples were sent to an insulation manufacturer lab for testing and determined an R value estimate of R2 which is 67% lower than the expected R6. The area-weighted insulation circumference measurements indicated a higher estimate of about R3.5. As this method may have been prone to slight over-estimation we estimate the average R value of the ducts to be about R2.5.

Further investigations were conducted to evaluate possible causes for water inside the insulation jacket. An independent duct sealant representative inspected the taped and mastic insulation seams and did not find any cause related to sealing the outer jacket. Three samples of insulation were sent to an insulation manufacturer laboratory for testing and evaluation. The test findings conclude that severe duct condensation occurred from a combination of causes: 1) reduced R value from compression resulting in a colder external jacket temperature at or near ambient dewpoint, 2) increased moisture permeability likely due to over-stretched insulation wrap, 3) long cooling runtimes of the 2 stage cooling system that kept the supply ducts cold for several hours at a time, and 4) abundant ambient moisture in the vented attic providing the moisture source.

Installed insulation wrap compression is not something that can be determined visually. This highlights the need for installers to make insulation blanket compression measurements during installation.

An annual energy simulation was performed using EnergyGuage USA RESNET HERS version 7.0.00 to determine the potential impact of diminished R value around supply ducts in a vented attic in Florida climate. The results, assuming an effective R2.5 insulation, indicate an 8% increase in annual cooling energy compared to R6 insulation. If the metal insulation had performed at R6, then the metal duct annual cooling energy may have been about 8% lower than actually measured. If the metal duct energy use is decreased 8%, then the increase of the flex compared to metal may have been 811 kWh/y (flex duct energy increase of 17% instead of 9%). This adjustment was made by starting with the annual cooling energy of Test 3 found in Table 7 of this report. The metal duct energy of 4797 kWh/y (R2.5) was reduced by 8% to 4408 kWh/yr (R6). The flex duct system energy would then be 811 kWh/y (17%) greater than the metal after adjusting metal to R6.

Introduction

Residential energy codes and conservation programs increasingly seek home energy efficiency measures. The highest end-uses of heating, cooling and domestic hot water are at the top areas of consideration. Space heating and cooling use represents about 40%-50% of total annual energy and is usually the highest end use in homes. Therefore, matters impacting space conditioning may have significant impact on home energy use. Correct refrigerant charge, preventative maintenance, and air distribution duct location, design, airtightness and insulation integrity can have significant impacts on energy use. System static pressure and poor installation can also have significant impacts on performance. This research project was designed to investigate the space conditioning impacts of a metal duct system and a flexible duct system with each having the same general layout, heat pump, and house design. Both duct systems were reasonably airtight and insulated with R-6 rated insulation. Flexible ducts addressed in this project are manufactured with an inner plastic (polyethylene) membrane spiral wound and reinforced by wire fastened with an adhesive on overlapping membrane seams. The inner liner is covered by R6 fiberglass insulation with a class 1 moisture retarder on the outside circumference.

Metal ducts are very durable and have lower static pressure-related distribution losses due to the smoother interior surfaces and turning radii. However, currently the residential installed cost of metal ducts can be higher than other duct options. Flexible duct has a lower first cost, is easy to handle during installation, and can deliver intended airflow when properly designed and installed. Flex duct will have higher static losses even in a well-designed system, and there is also much greater potential for severe static losses associated with poor installation practice. Longevity of duct materials varies on quality of material and nature of environment. The wide range of environments (e.g. basement, crawlspace, attic) presents a challenge in determining an expected functional longevity. Warranty of residential low pressure flexible duct ranges from 5-20 years (Flexmaster U.S.A. type 9M 5 yr, Flexmaster other flex 20 years, Hart&Cooley 10 years). While the authors could not find specific warranty on metal ducts, properly installed metal duct should last at least as long as flexible duct materials.

The ACCA Manual D (ACCA 2016) "required standard of care for installing flexible wire helix duct" recommends a maximum of 4% compression along a straight line, no significant sag (2.5 inches sag per 5 feet of span, or less) or snaking (several bends on the same duct), the radius of a bend or turn shall not be less than the diameter of the duct, and no crimping or crushing at any point along a duct run. Any additional compression or sag results in excess pressure drop that must be accounted for during system design. Static pressure loss results in either reduced air flow, or increased energy use with compensating systems. Unfortunately, many flexible duct systems are designed following recommended guidance, yet installed outside of these tolerances by a wide margin. In review of 7 field tests that included a total of 245 homes, researchers found most residential duct systems are being undersized using arbitrary inputs for duct selection without regard for available static pressure, actual duct length, or fittings (Proctor 2000). While some work has been conducted to measure static pressure drop in flexible duct systems with varying amounts of compression (Abushakara 2002, Weaver 2006) no experimental work has been done to directly compare the space conditioning energy impact and factor in energy costs into lifecycle costing.

Contracted Scope of Work

The scope of work called for the FSEC Energy Research Center (FSEC) at the University of Central Florida (UCF) to test and collect energy and performance data on residential central heating and cooling system with different types of ducted air distribution systems. The primary goal of this research project was to compare the space conditioning impacts between a metal duct system and a flexible duct system with each having the same general layout, heat pump, and house design.

FSEC used its Flexible Residential Test Facility (FRTF) consisting of two identical, full scale, residential buildings located in central Florida. One building was operated with a well-designed metal duct system. The other building was operated with a flex duct system first tested with a design in accordance with industry specifications and then tested again with flex system having a more-typical installation that results in higher duct static pressure. Seasonal heating and cooling energy use consumed with the use of each duct system was measured and includes the effects of total external static pressure (TESP), duct heat gains and losses, and minimal duct leakage. Each duct system was made substantially airtight using manufacturer and code approved sealants and application methods at every connection. Airtightness testing verified reasonably tight duct systems. Laboratory results were used to develop a building cooling energy model to estimate associated impacts cooling dominated climate zones 1A and 2A.

Experimental Method

Lab Description

Experimental work was conducted in FSEC's Flexible Residential Test Facility (FRTF), which features two full scale, geometrically identical side-by-side residential energy research facilities as shown in Figure 1. General characteristics of the 1,536-ft^2 single-story buildings (volume = 14,285 ft^3) including details of the general instrumentation package are provided elsewhere (Parker 2014). Internal loads were established using guidance from a Building America report on internal residential loads (Hendron and Engebrecht 2010). Internal cooling loads were maintained consistently by keeping the building unoccupied and providing internal sensible and latent heat through controlled measures. Interior sensible loads were generated using heat lamps on a schedule that represents hourly variability throughout the day for an occupied building. Latent interior generation was produced using industrial-grade ultra-sonic humidifiers also on a daily schedule. The interior loads were monitored to verify they operated according to schedule and that they were the same in each lab.

Null testing of each house lab was conducted in summer of 2019 prior to the new duct installations and showed that each building had the same cooling and heating load when configured identically. Details from this testing can be found in Appendix A of this report.

Figure 1. Flexible residential test structures on FSEC campus. The house on right side is East of the left one.

The space conditioning system in each home is a two-stage central split-DX heat pump. During original design of the FRTF facility, an interior floor plan layout and corresponding duct design was developed (Figure 2). The majority of ductwork in both labs was constructed using flexible duct located in the vented attics, with short supply and return duct board plenums, and a few junction boxes. This duct layout had minimal sag, compression, and good turning radii. The layout on the right side of figure 2 was very similar to as-built with a few exceptions. Enlarging the right side of Figure 2 also shows each flex duct circumference. Two branch diameters were not shown in this figure. The flex branch to the left of the lower J-box was 8 "diameter and the branch to the right was 6". The air distribution systems were constructed to be very tight: tested at 13 cubic feet per minute of air leakage per minute at 25 pascals (CFM25)/100 ft^2 (Qn = 0.013) in each lab home. Null testing was completed using these identical duct systems.

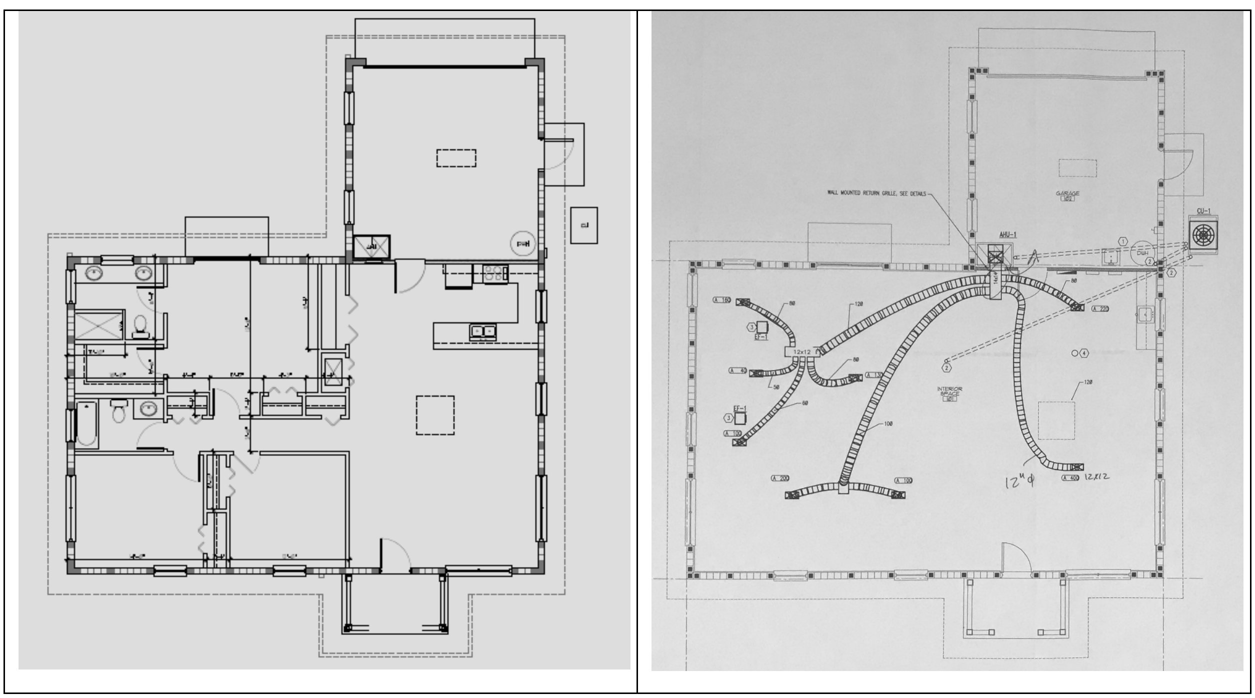

Figure 2. FRTF floor plan (at left) and pre-existing duct layout (at right) as designed. The interior walls were intentionally not installed.

To maintain a well-mixed, single zone, full height interior walls were never constructed. Building energy simulation models are typically single zone models, and this laboratory design feature enables experimentation for more accurate validation of such models. Instead of conventional wall construction, half-height, moveable wall modules were built and installed in order to simulate the thermal and moisture capacitance of a fully constructed building, while maintaining excellent air circulation throughout the space, thereby maintaining a single zone, and the reconfigurable nature of the laboratory. A takeoff was completed using the interior floor plan seen in Figure 2, and determined that a total of 1,120 linear feet of interior wall would need to be simulated. The module design to accomplish this involved constructing thirty-five 4’x8’ modules. To mimic interior walls as much as possible, 2’x4’ wood studs, 16” on center were used as a frame, along with a single top and bottom plate. Four feet by eight feet sheets of drywall were installed on each side, and were primed and painted. A painted wood baseboard was installed on one side of each module in contact with the concrete slab. Exposed faces of 2’x4’ framing members on top and sides of the modules were covered with foil tape so they would not be directly exposed to room air. A bracing system to support the walls was constructed out of metal so as not to affect moisture absorption. Figure 3 shows the interior of one of the labs with interior wall modules.

Figure 3. Interior of West FRTF Lab Building showing interior wall modules (identical to East lab).

Lab Space Conditioning Equipment

Each lab home was heated and cooled with a two-stage SEER 16 central heat pump with heating efficiency of 9.0 HSPF. The first stage was designed to provide 74% of full capacity (26.0 MBtuh) under rated test conditions and second stage provided 100% of rated capacity (35.0 MBtuh). The heat pumps were made by Daikin with outdoor unit model #DZ16TC0361 and indoor unit having model #DV49PTCD14. The air handlers have fans driven with electronically commutated motors (ECM) and are located in the garage on top of a return support platform. The ECM fans were designed to adjust to changes in TESP and were tested to verify they delivered designed airflow at each stage. Measured airflows at the single central return found a rate of about 800-851 cfm at first stage and 1200-1261 cfm at second stage. Later testing with at much higher static pressures determined that the target airflow rates were still achieved by the ECM fans.

Lab Sensors and Data Collection

All sensors for this project were verified to be in good working order. Temperature and relative humidity (RH) sensors measured indoor, attic, and outdoor conditions. Power meters measured internal loads and space conditioning energy. Interior latent loads were measured with flow meters on water supply lines to each humidifier. Refrigerant pressure sensors were used to measure each line at connection to outdoor unit. Thermocouples were used to measure the refrigerant temperatures on each line.

Latent heat removed from the building as condensate drained from evaporator coils was measured using tipping buckets calibrated at the expected rates of flow for each application. The basis of determining tipping bucket calibration was by supplying a drip rate of water to each bucket where the number of tips were measured for a given measured mass of water (pounds). Indoor and outdoor conditions were measured using Type T thermocouples and Vaisala HMP 60 temperature and relative humidity sensors. Temperature and RH were compared to a handheld Vaisala HM34 temperature and humidity sensor with NIST traceable calibration to verify that sensors were operating within manufacturer specifications.

A summary of manufacturer stated accuracy of meters and sensors can be found in Appendix A "Equipment Calibration and Testing".

Each FRTF lab home collected a total of 72 different channels of data. Data from sensors were collected using Campbell Scientific, Inc. CR1000 data loggers. FSEC's central computer terminal gathered data several times each day. Dataloggers read data sensors at 10 second intervals, then processed and stored at 15 minute intervals. Upon collection by the central computing terminal, the raw data from the data logger was screened for out of bound errors and then processed for terminal collection in the main project database account. Errors or missing scans were marked and noted within the main database. This is used to help avoid using any unsuitable data in analysis. Days during transition between test configurations or other interruptions to testing were also screened out from final analysis.

Lab Test Method

New Test Duct Description

The original flexible duct systems in both house labs were replaced with new test duct systems. The East FRTF house lab had a new metal duct system and the West FRTF house lab had a new flexible duct system installed. Design work for each duct system was completed by mid-April 2019, and drawings of each layout were created. Figure 4 shows the metal duct layout in the attic. Figure 5 shows the flexible duct design layout for installation that meets industry specifications and standards.

Both duct systems were installed by the same licensed contractor. Research staff were on site during installation to verify each system was correctly installed. Duct tightness of each system was tested while the contractor was present to ensure each system was reasonably air tight. Further details on tightness testing can be found in Appendix A Equipment Calibration and Testing.

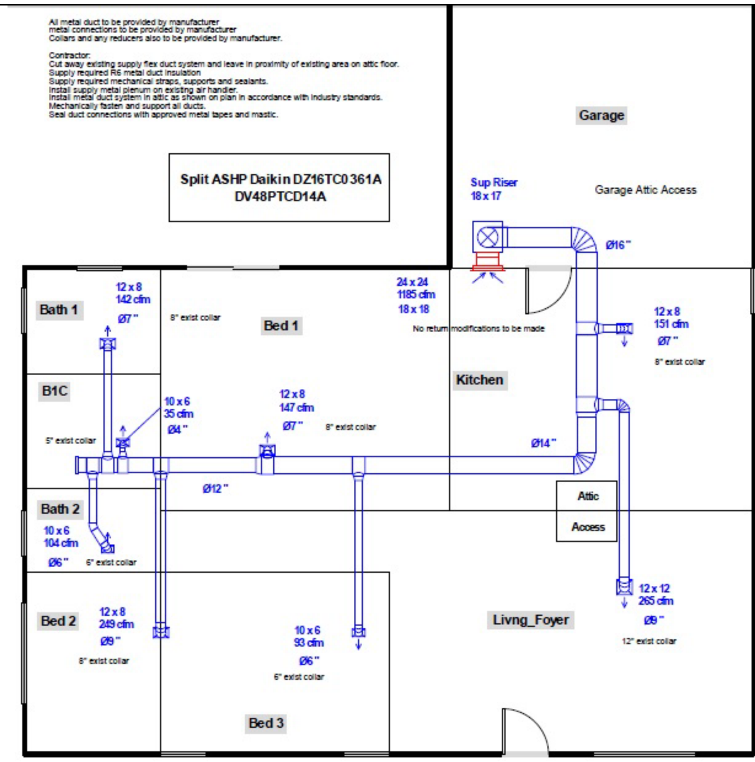

Figure 4. Metal supply duct layout prepared by Jonathan Jacobs, MechaniCalcs.com on 04/12/19.

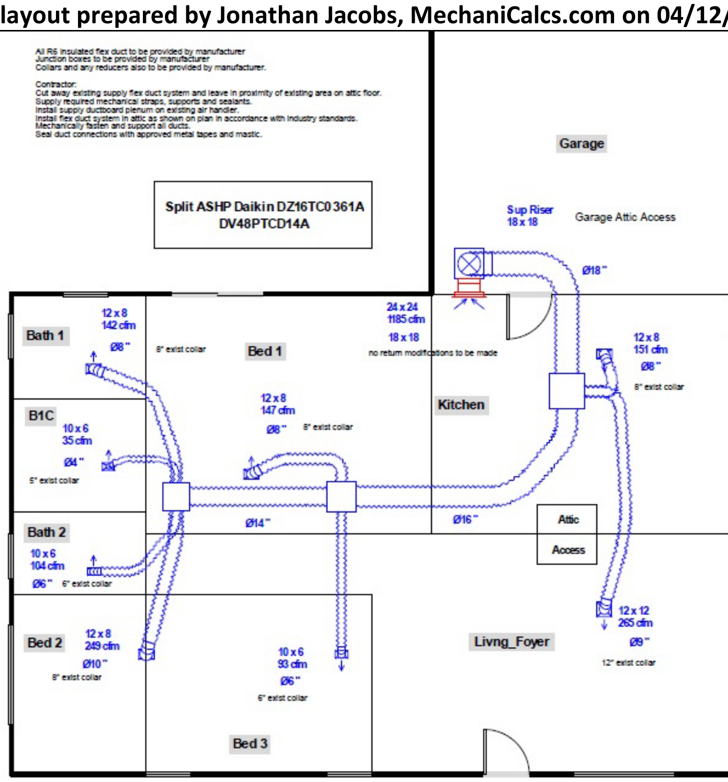

Figure 5. Flexible supply duct layout prepared by Jonathan Jacobs, MechaniCalcs.com on 03/06/19.

This study evaluated three different flex duct configurations. The metal duct system remained unchanged during all testing; however, one unplanned change occurred. In August 2020, it was discovered that the exterior jacket of the metal duct system had a significant amount of moisture on the sides and bottom of most of the main trunk lines and branch ducts. This wetness decreased the R-value of the cold air supply, which increased heat gain to cold-air supply that resulted in gradual increase in metal duct system energy use that became more obvious in the energy data after June 24, 2020. We believe the insulation wrap was compressed too much to result in at least R6 value. This would result in a colder exterior jacket surface that could be at or below attic dewpoint for significant periods of time during moist summer weather. The issue of the metal duct condensation became an unintended facet of this study, but the research team deemed the occurrence as an opportunity to gain more understanding on how to avoid this in other installations. Further details on observations, supplemental data collection and industry evaluation are provided in Appendix B "Metal Duct Insulation Condensation Evaluation".

A brief description of the planned test schedules is shown in Table 1. The first test (Test 1) was conducted with the best-practice design and installation of flexible duct having minimal sag and compression and proper turning radii. Test 2 was a brief exploratory test to get an idea on potential impacts when flex duct static pressure was increased to 1 in WC. Total static pressure for Test 2 was produced by installing a higher MERV rated filter at the filter-backed return grille and by partially blocking supply grille registers. Test 3 was conducted to represent a more-likely flex duct installation. A target TESP of 0.82 in WC was established based upon recent information from Rob Falke with the National Comfort Institute (Falke 2016, 2019). Older past published research studies indicated average TESP in the range of 0.41 in WC to 0.55 in WC (Blasnik et al. 1995, Proctor et al. 1995, Blasnik et al. 1996, Proctor et al. 1996, Parker et al. 1997). While the Test 3 target TESP was higher than older studies, the ducts of the older studies were much more likely to be leakier than newer residential construction today due to utility duct-tightness programs and more stringent building codes. Leakier ducts, air handlers, and furnaces would result in lower static pressure.

The flex duct system of Test 3 was configured by increasing the supply flex duct length such that there was 30% more length in the main trunk line and 50% more length on all branch flex ducts. This duct modification resulted in a TESP of 0.74 in WC with the 2 stage system at 2nd stage full capacity. To reach the 0.82 in WC target, some supply registers were partially closed.

Table 1. Project Schedule

Project Activity	Period
Planning, Calibration, Sensor Install, and Null Testing	February 15 – June 2, 2019
Duct Installation and Testing	June 3 –June 17, 2019
Test 1 Metal (@ 0.344 in WC) and Ideal Flex Duct @ 0.436 in WC TESP	June 18 – August 13, 2019
Test 2 Metal (no change) and Flex Duct @ 1 in WC TESP	August 14 – September 15, 2019
Installed Flex Duct With Added Compression for Test 3	September 16, 2019
Test 3 Metal (no change) and Flex Duct @ 0.82 In WC TESP	September 17, 2019 – September 7, 2020
Metal Duct Insulation Condensation Evaluation	August 11, - December 18, 2020
Final Analysis and Reporting	December 1, 2020 – January 31, 2021

Lab Test Results

Space Conditioning Energy

The total space conditioning energy use impacts of the different test configurations was evaluated. Total space conditioning includes energy used by the outdoor condensing unit and the air handling unit. The daily total energy use of the central cooling system was plotted against the daily average temperature difference between outdoors and indoors (dT=outdoor temperature - indoor temperature). The daily average temperature difference is also noted as delta temperature (dT) within this report. Use of dT enables the prediction of daily energy use at specific indoor and outdoor temperatures that may differ from actual test conditions. A least-squares best-fit regression analysis was completed and enabled an equation to be developed to predict energy use for each test. There was very limited space heating during testing due to mild winter conditions in east central Florida, therefore most of the space conditioning during testing was air conditioning. Due to limited data, comparisons between metal duct and flex duct Test 1 and Test 2 should be limited to warm weather.

Figure 6 shows daily data from all tests that includes the 24 days of heating. This shows that most of the difference between the tests occurred during the hottest and coldest weather.

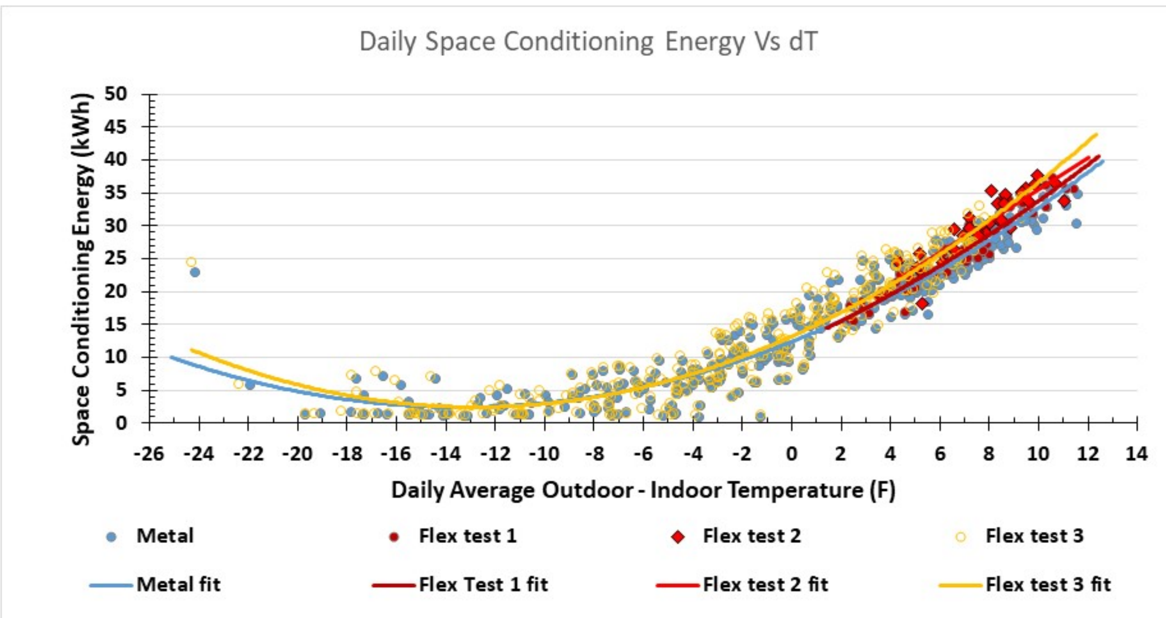

Figure 6. Daily space conditioning energy versus daily average dT for all tests including heating.

Figure 7 compares the energy use of the metal duct system to the flex duct Test 1 (ideal install) and Flex Test 2 (high TESP=1.0 in WC).

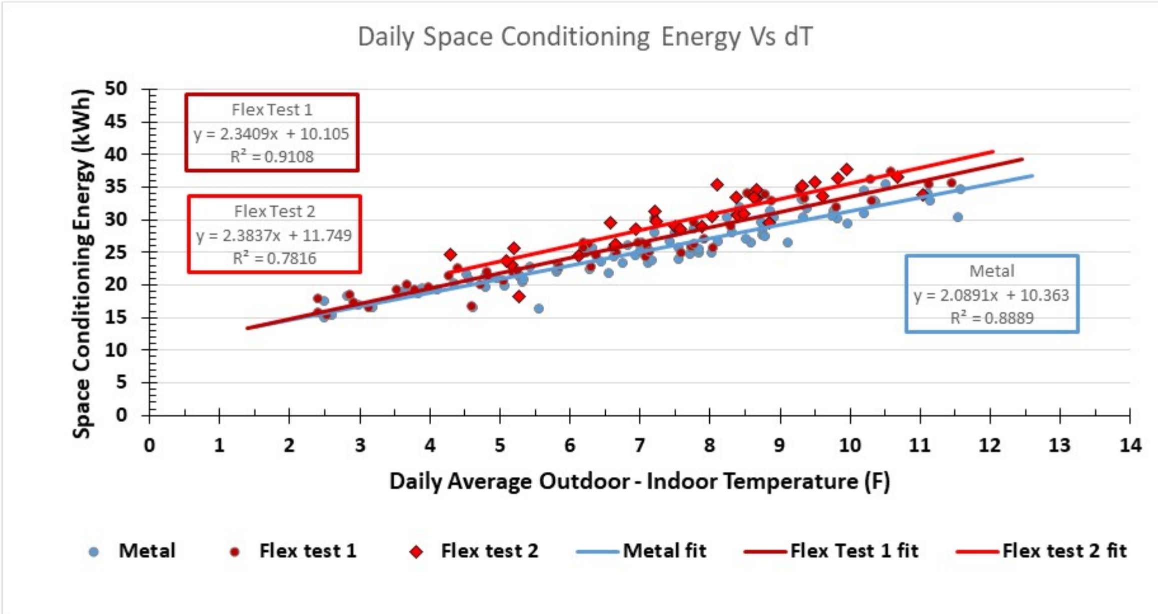

Figure 7. Daily energy vs dT for Metal and Flex Test 1 and Test 2.

Figure 8 compares the energy use of the metal duct system to the flex duct Test 3. Test 3 was designed to represent a more typical flex duct installation having TESP=0.82 in WC at full cooling capacity. The testing period for Flex Test 3 and Metal duct system was carried out for nearly 12 months spanning from September 16, 2019 through September 7, 2020.

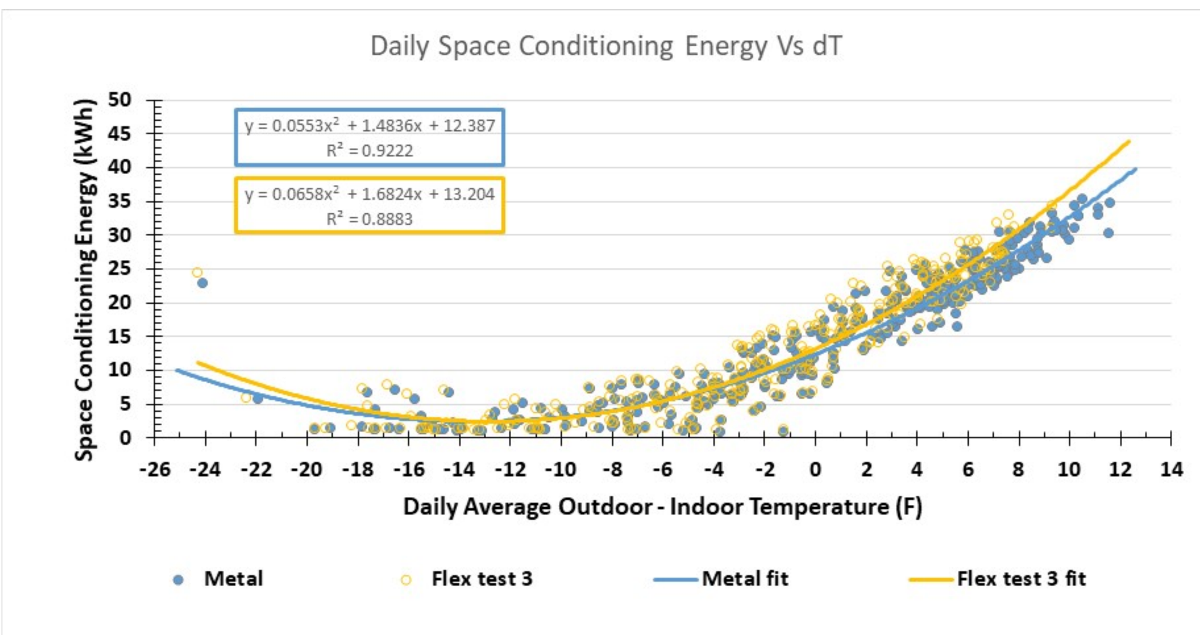

Figure 8. Daily energy vs dT for Metal and Flex Test 3.

Focusing on the energy used only by the air handler shows that most of the energy impact is due to fan power energy with greater relative increases in energy use of the flex duct tests compared to metal duct. Figure 9 shows the daily energy use of air handler fan for the metal duct system, Flex Test 1, and Flex Test 2.

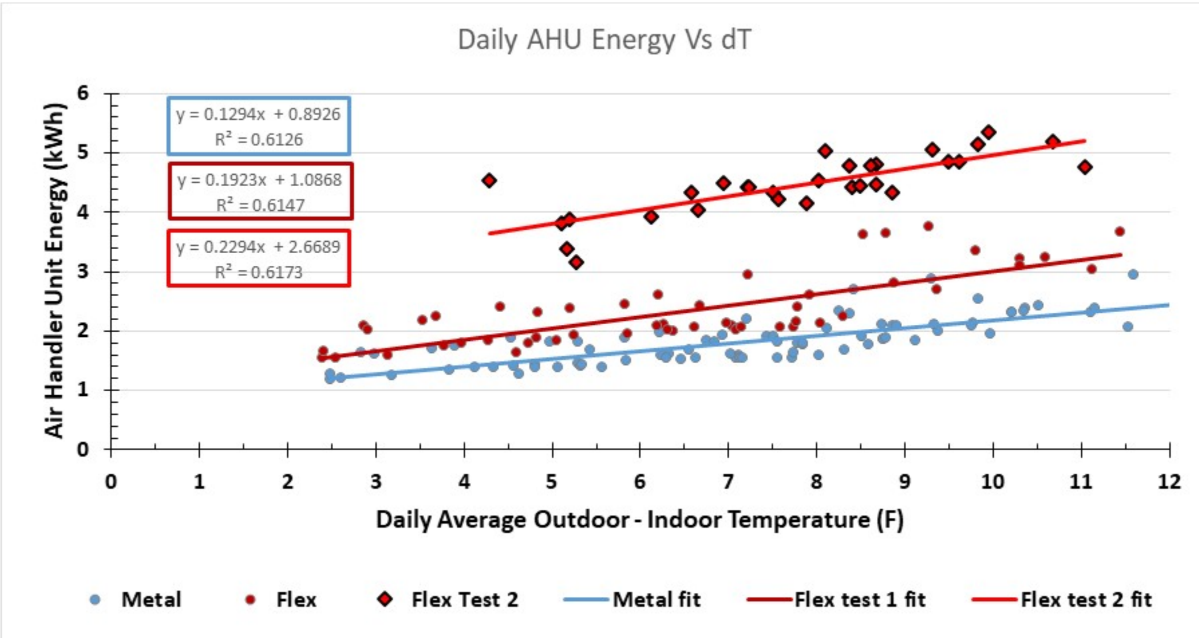

Figure 9. Daily air handler energy versus daily average dT shown for Metal duct, Flex Test 1 and Flex Test 2 configurations.

Figure 10 shows the daily air handler fan energy data for the metal duct system and Flex Test 3.

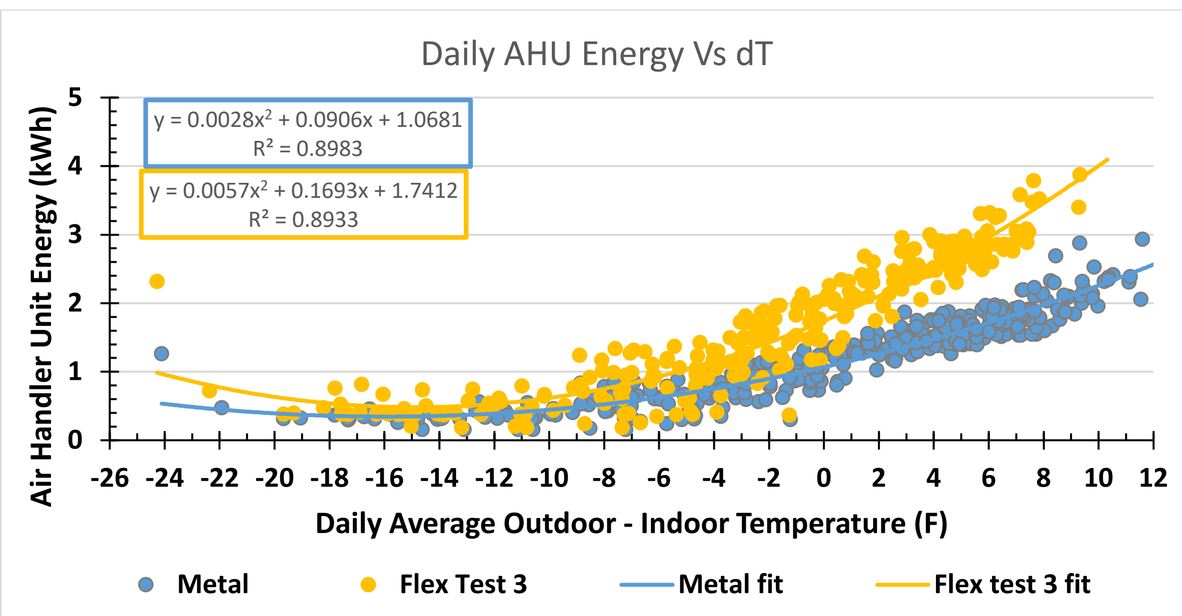

Figure 10. Daily air handler fan energy versus daily average dT shown for Metal duct and Flex Test 3.

Simple Energy use Comparison Of Metal Duct, Flex Test 1 and Flex Test 2 During a Warm Day

Test 1 and Test 2 were not conducted long enough to produce a reliable prediction for a whole year. However, a comparison can be made during warm weather conditions. The best-fit regression equations shown in Figure 7 were used to predict cooling energy for dT = 5°F. This could represent an indoor temperature of 75°F and outdoor temperature of 80°F. The results are shown in Table 2.

Table 2. Daily Cooling Energy Comparison of First Three Tests During Warm Summer Day

Test	Energy (kWh/day)	Flex Duct Increase from Metal (kWh/day)	Flex Duct % Increase Greater Than Metal
Metal Duct (0.34 in WC)*	20.805	---	---
Flex Test 1 (0.44 in WC)*	21.810	1.005	4.8%
Flex Test 2 (1.00 in WC)*	23.668	2.863	13.8%

* total external static pressure when cooling at full capacity 2nd stage

Since the Metal and Flex Test 3 testing was conducted over a wider range of outdoor temperatures with much more data, it was more appropriate to use a regression analysis of the metal duct system different from the linear regression used in comparing Test 1 and Test 2. The regression equations used to compare the metal duct to Flex Test 3 are shown in Figure 8.

Table 3. Daily Cooling Energy Comparison of Metal and Flex Test 3 During Warm Summer Day

Test	Energy (kWh/day)	Flex Duct Increase from Metal (kWh/day)	Flex Duct % Increase Greater Than Metal
Metal Duct (0.34 in WC)*	20.084	---	---
Flex Test 3 (0.82 in WC)*	21.945	1.862	9.3%

* total external static pressure when cooling at full capacity 2nd stage

The data analysis for Test 3 used data up through June 24, 2020. In August 2020, it was discovered that the exterior jacket of the metal duct system had a significant amount of moisture on the sides and bottom of most of the main trunk lines and branch ducts. This wetness decreased the R-value of the cold air supply, which increased heat gain to cold-air supply that resulted in gradual increase in metal duct system energy use that could be observed after June 24, 2020. Inspections were also made of the flex duct system and did not find any significant condensation. It is not known when the metal duct insulation jacket became so wet. Periodic inspections were completed during hot and humid weather in 2019 and did not find significant condensation of either duct system. Greater details on the metal duct condensation are provided in Appendix B "Metal Duct Condensation Evaluation".

As indicated earlier in Figures 9 and 10, most of the energy impact from increased static duct pressure resulted from substantial increases in air handler fan power. Table 4 shows the daily AHU energy use of Test 1 and Test 2 during warm summer day conditions (daily average 75°F indoor and 80°F out). The results show that a carefully designed and installed flex duct of Flex Test 1 will use 33% more daily AHU fan energy than the metal duct system. Increasing the TESP to 1 in WC for Flex Test 2 resulted in an AHU daily fan energy increases by 148%.

Table 4. Daily AHU Fan Energy Comparison of Metal and Flex Duct During Warm Summer Day

Test	Energy (kWh/day)	Flex Duct Increase from Metal (kWh/day)	Flex Duct % Increase Greater Than Metal
Metal Duct (data to 9/15/19)	1.540	---	---
Flex Test 1	2.052	0.512	33.2%
Flex Test 2	3.816	2.276	147.9%

The daily AHU energy use of the Flex Test 3 system was compared to the Metal duct and results are shown in Table 5. The Flex Test 3 duct system used 72% more energy than the metal duct system.

Table 5. Daily AHU Energy Comparison of Metal and Flex Test 3 During Warm Summer Day

Test	Energy (kWh/day)	Flex Duct Increase from Metal (kWh/day)	Flex Duct % Increase Greater Than Metal
Metal Duct (0.34 in WC)	1.591	---	---
Flex Test 3 (0.82 in WC)	2.730	1.139	71.6%

Predicted Annual Energy

The least-squares best-fit regression analysis shown in Figure 8 was used to characterize the cooling energy consumption over a full year to evaluate Flex Test 3. The daily cooling energy was calculated for the outdoor temperature minus the indoor temperature for each day of the year. The daily average outdoor temperature was based upon Typical Meteorological Year TMY3 data. The daily average indoor temperature was set at 75°F. Heating energy was not included due to inadequate heating weather during testing.

TMY3 data from Miami, Orlando, and Houston, were used to predict annual cooling energy for these three cities located within climate zones 1A & 2A. An assumed indoor temperature of 75°F was subtracted from the TMY3 outdoor temperature to calculate a daily temperature difference for each day of the year. Only days with temperature differences equal to or greater than -15°F were used to predict cooling energy. The dT of -15°F with indoor at 75°F would mean the outdoor daily average temperature would be 75-15= 60°F. While the balance point between heating and cooling is typically around 64°F, some cooling did occur on very sunny 60°F days. This limit was also used because there is still standby power used when unit does not cycle on. Heating would be expected at dT less than -15°F. The results for Flex Test 3 are shown in Table 6.

Table 7 shows the average of three cities. On average, Test 3 flex duct system used about 9% more energy than the metal duct system. The extra energy used by the flex duct represents approximately $51 per year in increased energy cost (422 kWh/yr x $0.12/kWh= $50.64).

The percent increase of the flex duct systems are about the same for the three chosen cities, however, the absolute increase in kWh per year is substantially greater for Miami in Climate Zone 1A compared to the other two cities in Climate Zone 2A. For example, Miami Test 3 flex used 229 kWh (70%) more annual cooling energy than Orlando (557 kWh/yr - 328 kWh/yr = 229 kWh/yr. The Test 3 flex duct system in Miami used 557 kWh more than the metal duct system. This would increase cooling energy costs by about $67 per year.

Table 6. Predicted Annual Central Cooling Energy of A Metal Duct System and Three Flex Duct Configurations for Three Cities Within Climate Zones 1A and 2A

Miami, FL (1A)					
	Metal Duct	Flex Test 1	Flex Test 2	Metal Duct	Flex Test 3
	Test 1 and 2			Test 3	
Annual kWh	4540	4793	5165	6061	6618
Delta kWH	0	253	625	0	557
Delta % from Metal Duct	0	5.6%	13.8%	0	9.2%
Orlando, FL (2A)					
	Metal Duct	Flex Test 1	Flex Test 2	Metal Duct	Flex Test 3
	Test 1 and 2			Test 3	
Annual kWh	2812	2942	3198	4139	4467
Delta kWH	0	129	386	0	328
Delta % from Metal Duct	0	4.6%	13.7%	0	7.9%
Houston, TX (2A)					
	Metal Duct	Flex Test 1	Flex Test 2	Metal Duct	Flex Test 3
	Test 1 and 2			Test 3	
Annual kWh	3146	3331	3580	4191	4573
Delta kWH	0	185	434	0	382
Delta % from Metal Duct	0	5.9%	13.8%	0	9.1%

Table 7. Predicted Annual Central Cooling Energy Average of Three Cities in Climate Zones 1A and 2A

Miami, Orlando, and Houston					
	Metal Duct	Flex Test 1	Flex Test 2	Metal Duct	Flex Test 3
	Test 1 and 2			Test 3	
Annual kWh	3499	3689	3981	4797	5219
Delta kWH	0	189	482	0	422
Delta % from Metal Duct	0	5.4%	13.8%	0	8.8%

Peak Cooling Power

The electric power demand is another important consideration as it has impacts on the amount of power the utility must provide to the grid. Utility demand and energy efficiency programs have been a successful way to minimize the number and size of new power plants needed. The power required for cooling was compared between the metal duct system and Flex Test 3. Since actual power consumed will vary according to cooling load, specific weather conditions must be chosen to represent the daily power use profile. Power data was compared using days having typical hot summer weather with no rain event. Figure 11 shows the daily cooling power use averaged at hourly intervals. The power usage can be seen increasing steadily from early morning until it peaks around 5-6 pm, then steadily declines as cooling load decreases. Metal and Flex "Total" indicated in Figure 11 refer to the combination of AHU and condenser cooling power.

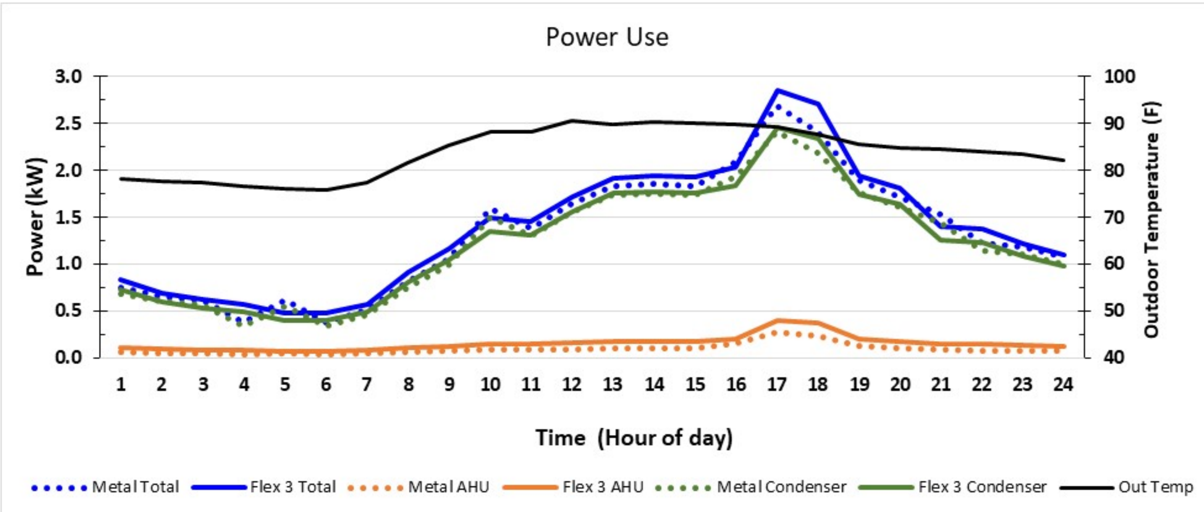

Figure 11. Cooling power profile over a 24 hour period for the metal and flex Test 3 configurations (7/31/20)

The average power during the peak usage from 4:00 PM – 6:00 PM was compared and results are shown in Table 8. The total cooling power of the flex duct was 0.233 kW (9%) greater than the metal duct. The flex AHU used 0.130 kW (51%) more than the metal AHU and accounted for nearly half of the difference in total power. This is significant since the AHU power only represents 14% of the total cooling power (0.386 kW/2.784 kW). The power consumption of the flex system AHU represented 56% of the increase in total peak power. The condenser power of the flex duct was 0.103 kW (5%) greater than the metal duct.

Table 8. Average Peak Power Use From 4 – 6 pm During a Hot Summer Day.

Test Configuration	Peak power use (kW)	Flex increase from Metal (kW)	Flex increase from Metal (%)
Metal AHU	0.257	---	---
Flex Test 3 AHU	0.386	0.130	50.5 %
Metal Condenser	2.295	---	---
Flex Test 3 Condenser	2.398	0.103	4.5 %
Metal Total	2.552	---	---
Flex Test 3 Total	2.784	0.233	9.1%
Daily Avg. temperatures	*Metal indoor 74.2°F*	*Flex Test 3 indoor 74.3°F*	*Out 84.0°F*

Refrigerant Line Pressure and Temperature

Pressure and temperature was monitored on each refrigerant line. The intent was to see if impacts imposed by a flex duct system would result in pressures high enough to impact compressor service life. Data was only recorded during cooling and heating. Refrigerant liquid and suction line pressure was measured at the service valves on the condensing unit using Setra model 209 transducers. The Setra pressure sensors were capable of measuring from 0 to 500 PSIG with an accuracy of +/- 0.25% at full scale (+/- 1.25 PSIG). Refrigerant temperatures were measured using Type T thermocouples with an accuracy of +/- 2.5 °F in the manor used. Accuracy between Type T thermocouples in air measured using the same datalogger typically have very good agreement within about 0.5°F. The refrigerant temperature was measured by placing the thermocouple on the outside of the copper pipe held in place by a strap and covered with pipe insulation. There can be more variability in this application than in direct air measurements.

Days with an average outdoor temperature around 82°F were selected to compare refrigerant pressure and temperatures. The results are shown in Table 9. The differences between refrigerant pressure are not likely significant enough to expect adverse impacts upon the condensing unit as the absolute differences are less than the increase in pressure caused by hotter weather. For instance, consider the liquid pressure is about 277 psig to 280 psig on average at about 82°F. When the outdoor average temperature is about 3 degrees warmer, the pressure increases to about 294 psig to 296 psig (an increase of about 6%). The suction pressure did show a trend of increasing pressure in the flex duct system compared to the metal duct system from 2% greater at the lowest flex static duct pressure of Test 1 increasing to 6%-7% in the higher static tests of Test 2 and Test 3.

The refrigerant temperatures showed no significant change between duct systems for liquid temperatures and some noticeable differences in the suction temperatures.

The lack of evidence of detrimental refrigerant pressure impacts seems reasonable for these cooling systems tested having ECM fans that delivered design airflow regardless of static pressure. With the correct design airflow through the evaporator coil and same entering air conditions, this is to be expected.

Table 9. Central AC Refrigerant Pressure and Temperature Summary During Warm Weather.

Test Condition	Liquid Pressure (PSIG)	Suction Pressure (PSIG)	Liquid T (°F)	Suction T (°F)	Outdoor T (°F)
Flex Test 1	280.2	141.1	89.0	55.7	81.6
Metal Duct Test 1	276.8	138.4	87.9	60.9	81.6
Flex % diff. from Metal	1.2%	2.0%	1.2%	-8.6%	
Flex Test 2	281.5	142.0	89.5	56.5	81.9
Metal Duct Test 2	278.9	134.3	88.3	60.9	81.9
Flex % diff. from Metal	0.9%	5.7%	1.3%	-7.2%	
Flex Test 3	279.4	144.3	89.2	57.5	81.6
Metal Duct Test 2	278.1	135.2	88.1	61.3	81.6
Flex % diff. from Metal	0.5%	6.7%	1.3%	-6.3%	

Energy Simulation Of Lower R Value Insulation on Ducts

Condensation on the exterior insulation wrap around the metal ducts prompted an investigation for the cause. Details of this evaluation are fully covered in “Appendix B Metal Duct Insulation Condensation Evaluation”. It was determined that the insulation wrap was compressed too much, which likely resulted in an R value around R2.5 instead of R6. The lower R value of the metal duct system would have imposed more heat gain than with R6, resulting in more cooling energy use of the tested metal system than would have been expected with R6. It is expected that the difference between metal and flex energy use would have been greater than measured, If the insulation performed as R6. Since repeating metal duct testing with R6 insulation was not able to be performed, an energy simulation was used to estimate the increase in metal duct system cooling energy.

An annual energy simulation was performed using EnergyGauge USA RESNET HERS version 6.1.00 to determine the potential impact of diminished R value around supply ducts in a vented attic in Florida climate. The results, assuming an effective R2.5 insulation, indicate an 8% increase in annual cooling energy compared to R6 insulation. If the metal insulation had performed at R6, then the metal duct annual cooling energy may have been about 8% lower than actually measured. If the metal duct energy use is decreased 8%, then the increase of the flex compared to metal may have been 811 kWh/y (flex duct energy increase of 17% instead of 9%). This adjustment was made by starting with the annual cooling energy of Test 3 found in Table 7 of this report. The metal duct energy of 4797 kWh/y (R2.5) was reduced by 8% to 4408 kWh/yr (R6). The flex duct system energy would then be 811 kWh/y (17%) greater than the metal after adjusting metal to R6. Since the R value of the metal duct became even lower as part of the insulation became saturated, a couple other R values were evaluated as well to establish an idea of the potential impact. Based on simulations, annual cooling energy increased 5%, 8%, 21%, 32% for R3.5, R2.5, R1, and R0.5 respectively compared to R6.

The significant decrease from R6 to R1 may explain why the daily energy difference began to diminish in late June 2020. It is expected that as the R2.5 duct became wetter through the summer, the R value decreased even more, heat load increased on metal system, and the system used more energy than before. This would erode the difference between the tested metal and duct systems late in summer of 2020.

Summary

This report covered an experimental study conducted in two brief phases and one longer phase to evaluate AC performance based upon the type of central AC system ducts. This research project was designed to investigate the space conditioning impacts of a metal duct system and a flexible duct system with each having the same general layout, heat pump, and house design. The research sought to determine if flex ducts used more energy and showed evidence of potential for diminished equipment life relative to a metal duct system. The metal duct system did not have any modifications made to it.

The flex duct system, best-case installation, was tested briefly first (Test 1). Another brief exploratory test was made using the flex duct system with the total external static pressure (TESP) manipulated to 1 in WC by partially closing supply registers and using a higher MERV filter at the return (Test 2). The final test evaluated what was estimated to be a typical flex duct system having TESP of 0.82 in WC (Test 3). The testing clearly demonstrated the trend for higher static pressure to cause increased space conditioning energy use with systems that had ECM fan motors. The longer phase testing of Test 3 found that the predicted annual cooling energy of the flex duct is about 422 kWh (9%) more than the metal duct. Peak power increased by 0.233 kW (9%) in the Test 3 flex duct.

Condensation was noticed on the exterior FRK insulation wrap of the metal ducts late into the second summer of testing. It was not noticed during the first summer. Seeking answers for the cause, an inspection of insulation seam seals was completed, insulation measurements were made, and samples of wet insulation were sent to an insulation manufacturer. Inspection by duct sealant representative did not find issues with the sealed insulation seams. Measurement and testing of the insulation jacket determined that the insulation was over-compressed. This resulted in diminished R value estimated to be about R2.5 instead of R6. The lower R value resulted in colder exterior insulation surfaces that approached the ambient dewpoint resulting in condensation. The long cooling runtimes of the two-stage cooling system resulted in prolonged periods of cold ducts that reduced the drying potential between cooling cycles.

This duct condensation issue highlights the importance of training and the need for installers to make insulation blanket compression measurements during installation.

The lower R value of the metal duct system imposed more heat gain than on the R6 flex duct system. An annual energy simulation was performed to determine the potential impact of diminished R value around supply ducts in a vented attic in Florida climate. The results, assuming an effective R2.5 insulation, indicate an 8% increase in annual cooling energy compared to R6 insulation. Had the metal insulation performed at R6 the annual cooling increase of the flex is likely to have been 811 kWh/yr (17% instead of 9%) compared to the R6 metal system.

Acknowledgments

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With the unexpected late development of condensation on the metal duct system, there was a need to determine the cause. We are especially grateful for input and assistance from several individuals among the air distribution industry. For insulation wrap evaluation by Owens Corning: David Burd, Victor Salvador, Agustin Hernandez, and Kathryn Smith. For site inspection of the taped and sealed insulation wrap: Gary Prine with Reeves Sales & Marketing and Tim Eorgan at Hardcast.

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Appendix A Equipment Calibration and Testing

This section summarizes the types of sensors and equipment used and results of different performance tests completed. The bullet list below states the types of sensors and equipment used along with accuracy.

- Vaisala Temperature and relative humidity HMP60 sensors were installed. These sensors have a manufacturer stated accuracy of +/- 3% RH of RH reading and +/- 0.9 °F for temperature. Type T Thermocouples were also used to measure temperatures. These have accuracy of +/- 0.2°F to 2.5°F depending upon application. The highest accuracy occurs with air measurements not in direct contact with solid surfaces.
- Periodic check of temperature and RH sensor readings was completed using a handheld Vaisala HM34 temperature and RH probe. This unit has an accuracy of +/- 2% RH and +/- 0.54°F .
- Continental Control Systems Wattnode power meters have a manufacturer stated accuracy of +/- 1% were installed to measure DHU energy, central AC system, and internal generated sensible loads.
- Condensate removal of AC system was measured by calibrated tipping bucket. Tipping buckets were calibrated by mass of water measurement collected along with the pulse output signal. Stated accuracy was 3% or better.
- Refrigerant temperatures were measured using Type T thermocouples with an expected accuracy of about +/- 2.5°F .
- Refrigerant pressures were measured with Setra Model 209 transducers designed for installation using existing field service valves. The accuracy is +/- 0.25% at full scale. Full scale was 500 PSIG so accuracy was +/- 1.25 PSIG.
- Air distribution duct TESP was measured using Energy Conservatory DG-2 digital manometers with analog output feature. The manometers were sent out for calibration prior to testing. Manufacturer accuracy is +/- 2% of reading or +/- 2 Pa (0.008 in WC) whichever is greater.

Null Testing Comparisons

Before changes were made to the duct systems of the two lab homes, testing was conducted to determine any bias in energy use or temperature control. Each lab home had identical flex duct systems and heat pumps. The identical flex duct systems had TESP 0.212 in WC at first stage and 0.438 in WC at second stage (full) capacity operation. This TESP was within 0.01 in WC of the TESP of the Flex Test 1 configuration. This testing occurred during distinct periods during the time between February 23 to May 7, 2019. Below is a summary of the findings.

- Indoor temperature setpoint was set at 74°F in both labs during the null testing period. This is one degree lower than setpoint during all other testing. This lower setpoint was chosen to help increase the cooling runtime during mild cooling weather.
- Indoor temperature comparison is very good, and RH comparisons are good. West interior room RH measured at about 3.5 % RH higher than East. A calibrated handheld Vaisala HM34 hygrometer found the difference to be due to the west RH sensor reading 3%-3.5% high. Indoor temperatures were maintained very close, often to less than 0.5°F on an hourly basis. The daily average temperature difference was not greater than 0.2°F from April 19 through May 5, 2019. April 19 is when East supply and return grilles were partially closed down to increase static dP to be closer to that of west static dP during the null testing period.

- There was very close agreement of daily cooling energy used during null testing. Figure A1 shows the east lab energy (x-axis) plotted with the west lab energy (y-axis). A least-squares best-fit regression over a range of weather conditions between February 23 - May 7, 2019 shows each house and cooling system operate very similar during the same weather conditions. There was less than 1% difference between energy use for days using at least 7 kWh. For days with low cooling load requiring around 5 kWh, there was about 0.07 kWh difference (1.4%). These differences are within the error of measurement and do not suggest any bias between the two different lab homes. This is further supported by the measured interior temperatures shown in Figure A2. The average difference was 0.07°F and maximum difference for any daily period was 0.2°F which shows excellent similarity in temperature control.

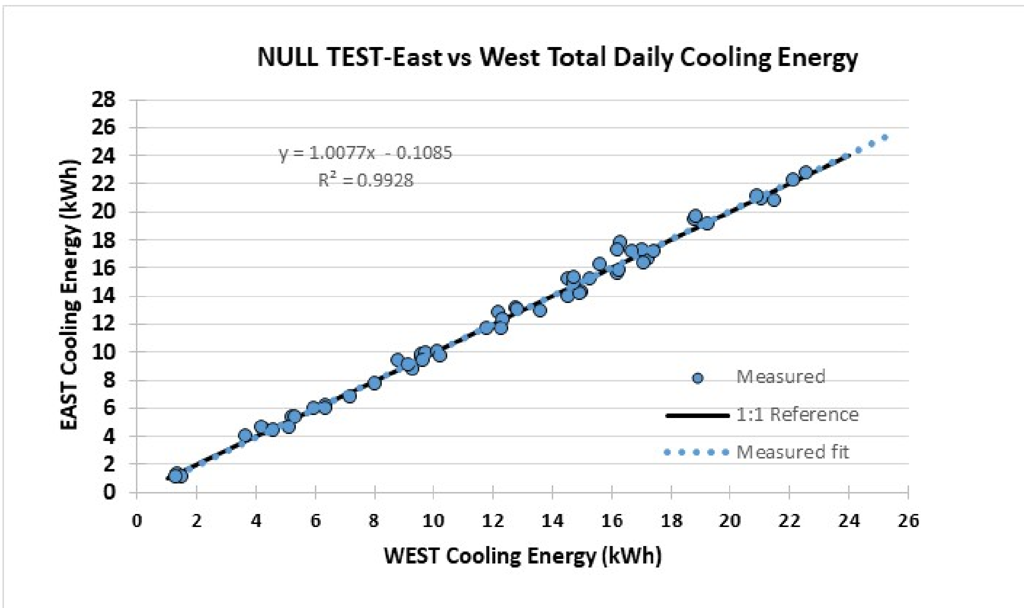


Figure A1. Null test of cooling energy use in two different lab homes shows very close agreement.

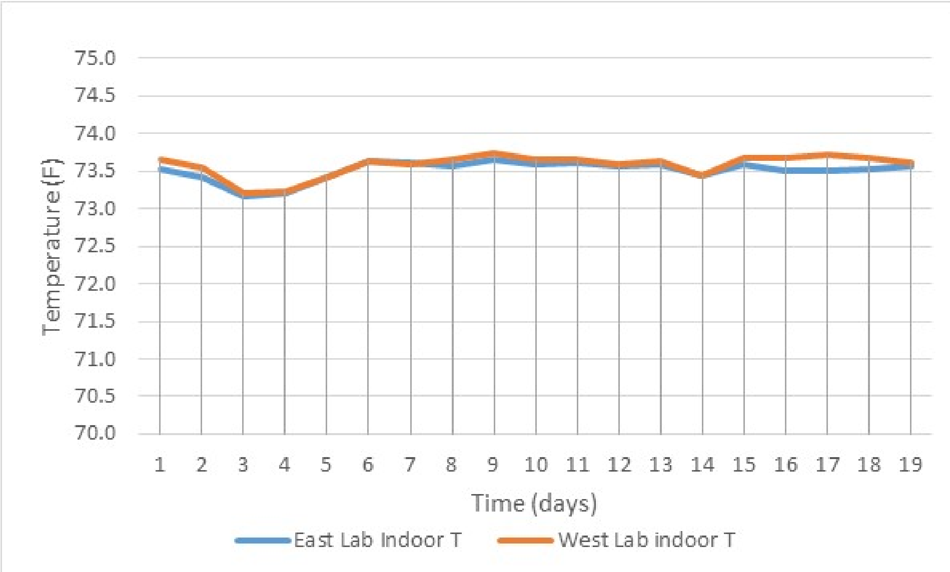


Figure A2. Null test period April 19- May 7, 2019 shows very little difference between the two labs.

House and Duct Tightness Testing

House and duct air tightness tests were completed in accordance with the **ANSI/RESNET/ICC 380 2016 Standard** in both Flexible Residential Test Facility (FRTF) lab homes. The East FRTF home had a new metal duct system installed and the West FRTF had a new flexible duct system installed. Both East and West lab homes were in their "tight" test configuration with no intentional air leakage pathways added. The new duct systems were installed by a licensed HVAC contractor under supervision and instruction of research project team. The test results are shown in Table A1 and found that house and duct systems were reasonably airtight. Further details on tightness testing follow.

Table A1. Summary of House and Duct Air Tightness Tests

Test Lab	House Tightness ACH50	Duct Total Tightness CFM25 per 100ft^2	Duct Leakage to Outside Conditioned Space CFM25 per 100ft^2
East (metal duct)	2.6 +/- 2.0%	2.86	2.44
West (flex duct)	2.7 +/- 1.3%	2.28	1.88

Proposed standard under public review, BSR/RESNET/ACCA Standard 310-201x "Standard for Grading the Installation of HVAC Systems", provides grades I, II, and III for duct tightness (Standard Table 1a). Grade I is the best grade given if the tested total duct tightness is "The greater of ≤ 8 per 100 ft^2 of CFA or ≤ 80" where CFA is the conditioned floor area.

Based upon this proposed standard, the tested duct tightness in both labs easily qualifies for the top Grade I duct tightness. The total duct tightness in each lab is tight enough that a difference of 0.58 CFM25total per 100 ft^2 is insignificant. The non-normalized leakages of 44 CFM25 total (East) and 35 CFM25 total (West) are also well below the "≤ 80 " CFM25 total requirement. While the proposed Standard 310 uses total duct leakage to grade the duct tightness, it is the duct leakage to outside that has an influence on space conditioning energy use. Again a difference of 0.56 CFM25out per 100 ft^2 is insignificant given that a tightness of 3 CFM25out per 100 ft^2 or less is considered reasonably airtight.

East Lab with Metal Duct System

Test completed by Eric Martin, Chuck Withers, and Dave Chasar June 6, 2019.

- Duct Tightness
    - Total leakage includes leakage to/from conditioned space tested at -25 Pa
    - Total leakage normalized by conditioned area (per 100 ft^2)= 44/15.36ft^2;
    - Total normalized leakage= 2.86
- Leakage to outdoors
    - CFM25out=38;
    - Duct leakage normalized by conditioned area (per 100 ft^2)= 37.5/15.36ft^2 ;
    - Total normalized leakage= 2.44
- House Tightness
    - House area is 1536 ft^2 with 9.3 ft height = 14,285 ft^3 volume
    - Tectite House Tightness Multipoint Results
    - 607 CFM50 +/-2.0%
    - 2.55 ACH50
    - C=33.4
    - n=0.741 +/- 0.060
    - r= 0.99498

West Lab with Flexible Duct System

Test completed by Eric Martin, Chuck Withers, and Dave Chasar June 5, 2019.

- Duct Tightness
    - Total leakage includes leakage to/from conditioned space
    - 35 cfm tested at -25 Pa. CFM25 total=35
    - Total leakage normalized by conditioned area (per 100 ft^2)= 35/15.36ft^2;
    - Total normalized leakage= 2.28
- Leakage to outdoors
    - CFM25out=29;
    - Duct leakage to out normalized by conditioned area (per 100 ft^2)= 29/15.36ft^2;
    - Total normalized leakage to out = 1.88
- House tightness
    - House area is 1536 ft^2 with 9.3 ft height = 14,285 ft^3 volume
    - Tectite House Tightness Multipoint Results
    - 637 CFM50 +/-1.3%
    - 2.68 ACH50
    - C=38.2
    - n=0.719 +/- 0.040
    - r= 0.99809

Outdoor Air Infiltration Tests

Using a Miran Saphire specific gas analyzer, we determined the outside air infiltration rates by injecting a specific concentration of sulfur hexafluoride (SF6) tracer gas into the conditioned space, and then measuring the decrease in tracer gas concentration over time. The SF6 gas concentration decreases over time as outdoor air, having no SF6 in it, dilutes the initial amount. This method is sometimes referred to as the tracer gas decay method. Tracking the change in SF6 concentration over time enabled the infiltration rate to be determined as air changes per hour (ACH). Infiltration was measured under three different central cooling system configurations. Infiltration was measured with central cooling off, next with the system maintained continually at first stage, and then with the system maintained at second stage. Samples were taken at 5 different locations within the building at 10 minute intervals over a period of about 75 minutes each. The test results are shown in Table A2 and indicate very low air exchange rates as is expected for tight house and duct construction.

Table A2. Summary of Test House Air Infiltration

Test Condition	Total test period	Air Changes per Hour (ACH)	Average Wind Speed and Maximum 15 Minute Average
East AHU off (natural)	01:35:00	0.010	3.63mph / max 4.9mph
East 1st stage	01:25:00	0.024	3.14 mph / max 6.5mph
East 2nd stage	00:55:00	0.072	4.34 mph / max 5.8mph
West Test 1 AHU off (natural)	00:55:00	0.008	4.2 mph / max 4.9mph
West 1st stage Test 1	01:30:00	0.111	3.71 mph / max 4.2mph
West 2nd stage Test 1	00:50:00	0.193	4.91 mph / max 5.1mph
West Test 2.2 AHU off (natural)	01:15:00	0.004	3.19 mph / max 4.2mph
West 1st stage Test 2.2	01:15:00	0.058	0.76 mph / max 1.1 mph
West 2nd stage Test 2.2	01:20:00	0.123	3.89 mph / max 5 mph

Since the houses were fairly tight, each test house was also operated for periods of time with continuous outdoor mechanical air supply at about 65 cubic feet per minute. This would provide the minimal ventilation rate according to ASHRAE 62.2 2019. Adding mechanical ventilation did not result in a change in difference between the flex duct and metal duct systems. This is reasonable as the primary impact is due to higher duct static pressure in the flex system.

Appendix B Metal Duct Insulation Condensation Evaluation

Overview

A new metal duct system wrapped in R6 FSK insulation was observed with significant condensation August 11, 2020. This new metal duct system was installed in the East FSEC Flexible Residential Test Facility by June 2019. House was cooled at a steady 75F maintained 24/7 with a 3 ton Daikin two stage heat pump. Periodic duct inspections were made around mid to late summer 2019 during humid weather conditions. Condensation was only noticed where mechanical support straps held the main supply trunk line. The condensation was only at a few very small areas and considered of negligible consequence. Condensation at the straps was due to compression of insulation resulting in a few square inches of cold exterior duct jacket temperature. By August 24, 2020, the bottom of most insulation wrap was so wet that water was dripping onto attic insulation below. Closer inspection found that the bottom insulation on Main trunk lines had water trapped inside the insulation between the insulation wrap and the metal duct exterior. There were some areas of corrosion on the metal ducts observed later when some samples of insulation jacket were removed.

The research team agreed upon the importance to try to determine the cause of the unexpected severe condensation. This appendix of the report provides detailed observations and some supplemental data used towards the evaluation. First a chronological log of observations and actions is shown, followed by more detailed descriptions of specific observations. The information herein shows that insulation wrap compression would have reduced the duct insulation to an estimated R2 instead of R6. This could be part of the cause for condensation. The water trapped inside the bottom of insulation may have occurred due to long-term wetness on the bottom of duct that slowly wicked up into the insulation.

Brief Site Notes During Condensation Evaluation Period

8/11/2020 significant condensation noted during an attic inspection
8/28/20 *Brief test*: AC on 1st stage from 10:45-11:41 am, then on to 2nd stage 11:43am-12:03pm and again from 12:15pm-1pm. Setpoint returned to 75F at 1pm.
9/2 TSTAT setpoint left at 78F from 12pm until Sept.3 9:15 am.
9/3 Setpoint returned to 75F at 9:15am.
9/4 *Brief test* infiltration rate tests. AHU off 9-10:30am, cool 1st stage 10:30a-12p, cool 2nd stage 12p-1:40p.
9/10 light rain 1am and 10pm
9/11 TG AHU off 8:30-11:45a. Tstat set at 75F after testing.; Rain traces at 8am and 3pm
9/12 Saturday rainy day into next morning
9/16 rain at 11am on/off short showers
9/18 attic duct moisture inspection; measured exterior jacket circumference at several main trunk locations. No duct or sensor modifications made. Installed additional attic air strata T&RH.
9/19 5p- 9/20 5pm Outdoor Tdp steady at 77F or greater (very moist!). Very windy and rain began afternoon 9/19.
9/19 is a good day for duct sweat potential as Tdp high, cloudy but warm and rain.
9/20 cool front begins and out Tdp begins steady drop to 65F by 9/21 12 noon. Still Very windy, rainy morning and early afternoon.
9/21 dry air coming in from NE wind front. Cloudy and windy.
9/22 inspected East ducts and found still wet, but slightly less visible water. Still wet on bottom of main trunk all the way to end. Top side dry. Windy mostly cloudy but drier air.

11/12 9a-10a Gary Prine, Reeves Sales representative, met Chuck Withers at East test house to inspect insulation jacket. No evidence of poor tape application at seams. Gary also thought the jacket looked to be in good condition with no significant rips or tears.
Jacket was very wet at bottom on most all main trunk, water inside bottom of jacket on much of E-W run of main trunk. Light condensation noticed on top of jacket today (usually dry). Likely due to several days of very cloudy rainy weather as tropical storm impacted south and west FL. Emailed summary to Chris VanRite, Tim Eorgan, Eric Martin and Gary Prine.

11/25 9a-12pm measured metal duct circumference on all main trunk and branch ducts. Three different FSK jacket samples from T2, T3, and B1 ducts were also removed and replaced with new FSK jacket. All jacket samples were cut across top center and circumference cuts made 12" apart creating a strip 12" wide and the length = jacket circumference.
T2 sample was taken near the attic hatch from one of the most-wet areas. The T2 metal duct diameter was 14". This main trunk T2 location was on the East-West oriented line 39" downstream from the trunk turn from south towards west. The measured existing jacket circumference was 51" before cutting out. The replacement section jacket had a circumference of 53". If duct was R6 insulated, circumference would be expected to be 54.2". Omnisense#5013F sensors were placed between the metal duct and new section of jacket. Channel 1 was placed on the S. side and Channel 2 was placed near the bottom of duct. The pre-existing jacket sections adjacent remained soaking wet at bottom of jacket and will have influence upon the new jacket section.
T3 sample began 16" downstream from the T2 to T3 transition. The T3 metal duct diameter was 12". The measured existing jacket circumference was 44-3/4" before cutting out. The replacement section jacket had a circumference of 47-3/4". If duct was R6 insulated, circumference would be expected to be 47.9".
B1 sample began 8" downstream from the T1 to B1 transition. The B1 metal duct diameter was 7?". The measured existing jacket circumference was 28.5" before cutting out. The replacement section jacket had a circumference of 29.5". If duct was R6 insulated, circumference would be expected to be 32.2".

12/4 Shipped three insulation wrap samples to Owens Corning lab for testing and evaluation. Detailed document on sample location, duct size, and some performance data had also been emailed.

12/11 Very cool weather since December 1 has resulted in little to no cooling or heating. *Brief test:* Ran east and west labs in heating set at 82F from 1:50pm- 2:47 pm. Can use this 45 minute period to see how heating impacts moisture trapped inside insulation.

12/16 cool and dry weather still prevailed. *Brief test:* Short cooling test run from 11:30a-12:30 p. Forced cooling to 2nd stage in metal and flex duct systems. Attic dewpoint air from 55F early am up to 72F during warmest time of day. Inside jacket RH at bottom side is > 80% most hours of day and cooling increased RH up to about 93% RH. Inside jacket RH on S. side runs a little lower than bottom side which is much wetter.
The hour period during continuous cooling shows temperature and RH within the jacket reach the same temperature as expected with very high RH. These inside jacket measurements were made on the replacement sections of insulation wrap and would not be as wet as the existing insulation.

1/14/2021 waiting for results from Owens Corning testing and evaluation of the three samples of insulation and data sent early December. Results anticipated end of this month.

Observations, Monitoring and Measurement Results

Figure B1 below shows the trunk (T) and branch (B) section identification on the metal duct layout that will be referred to in this section of the report.

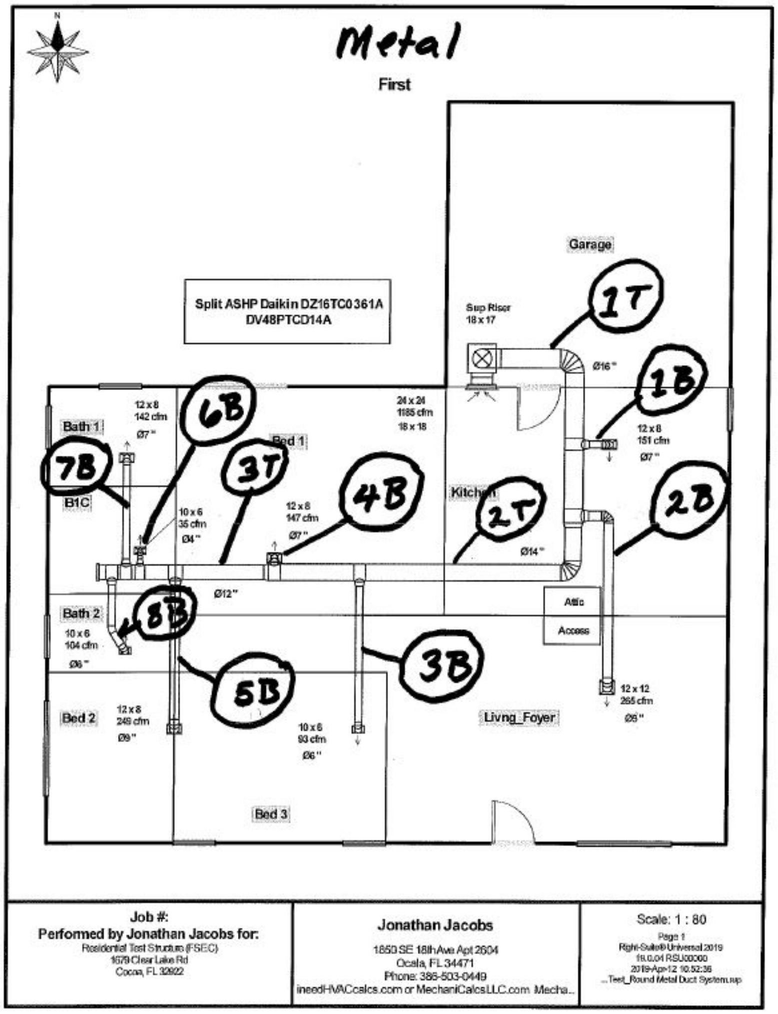


Figure B1. Metal duct layout with trunk and branch identification numbers.

August 24, 2020

A follow-up inspection at 1:15-1:45PM on August 24, 2020 found condensation isolated to the lower third of main supply trunk (T2), on the first branch duct (B1) after supply plenum, and minor amounts on two other branch ducts (B3 and B5) with some compressed insulation.

Condensation was worst at the first branch (B1) duct serving kitchen area. Water condensation drained down the approximately 3 foot vertical section over the boot. Water soaked the top of boot and east side of ceiling. Drywall was wet along east side of grille, but not soft. Ceiling paint had bubbled in this area due to water dripping.

Condensation on the main trunk (T2) was more pronounced along the first half. Light condensation was noticed on lower sides and large water droplets formed at bottom center. The top exterior surfaces were dry.

August 28, 2020
The same condensation pattern was noticed as 4 days prior. The cooling system was turned off from about 9:30-10:30 am to allow supply duct to warm up some. The exterior duct surface was toweled dry and 6 mil plastic sheet strips were placed under main trunk line to protect insulation and ceiling. Four temperature and RH sensors were placed around circumference of exterior main trunk (T2) jacket in attic.

September 18, 2020
Inspected East lab attic ducts 9am- 9:35am. Main trunk (T1) directly off of supply plenum had some moisture on all sides, but mostly wet at bottom. Top and sides had very light fog. Top moisture not very visible, but shows up and can be felt by a slight finger wipe. Taped seams with compressed insulation had more moisture on main trunk near plenum. Some very wet spots and drip line on bottom of the main trunk (T1) that runs north to south. Main trunk line (T2) running east to west had similar moisture as seen August 24. Protective plastic sheet under duct is protecting insulation and ceiling from water. Observed a little more moisture along the bottom main trunk (T3) and downward than previous inspection.
Exterior duct circumference measurements were made on a small sample of main trunk lines that indicate insulation wrap may be compressed such that insulation value is less than R6.

The West flex duct main trunk near plenum was also inspected. Only one small area inside a fold on bottom lying on top of attic floor wood platform. This was not bad enough to wet wood. Exterior duct surface was dry otherwise.

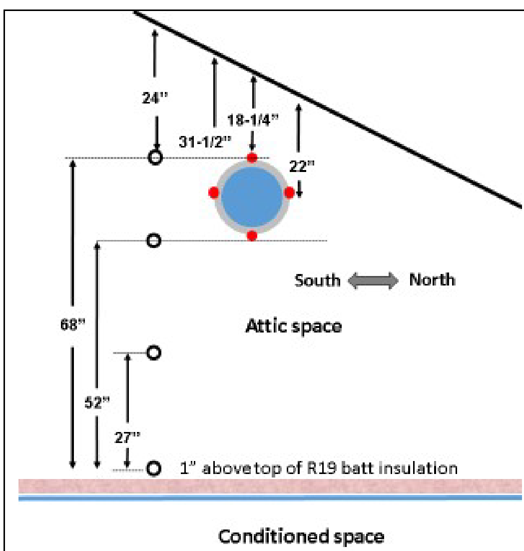
Temperature and RH Monitoring on Metal Duct

Omnisense T&RH sensors were added around the perimeter of main trunk (T2) exterior jacket August 28 after the exterior surface was toweled dry. The location was representative of the typical condensation. Figure B2 shows an example of one of the sensor loggers. Sensors were placed at top, bottom, and each side of the duct.
Logger#140 CH 1= top of main trunk (at 12 O'clock)
CH2= on south side of main trunk (looking downstream flow at 9 O'clock)
Logger#01DB CH 1= on north side of main trunk (3 O'clock)
CH2= bottom of main trunk (at 6 O'clock)

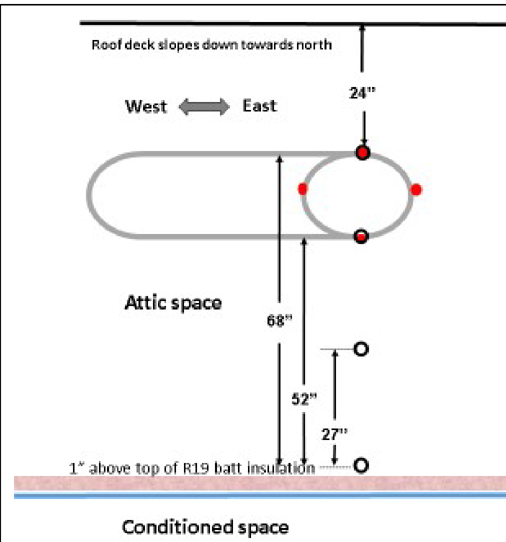
Figure B2. Temperature and RH sensor logger used on and around ducts in attic.

Attic strata temperature and RH sensors (Ominsense) were added on September 3. These are shown on Figure B3 as black circles. The red solid circles indicate the location of sensors on the duct exterior surface.

Logger#0262 CH 1= highest level at same ht. as top of main trunk (68" above top of insulation)
CH2= next level down at same ht. as bottom of main trunk (52" above top of insulation)
Logger#015D CH 1= 3rd level down from top sensor (27" above top of insulation)
CH2= lowest level 1" above top of insulation



View looking towards West also towards main trunk (T2) downstream flow



View looking towards North

Figure B3. Metal T2 exterior surface measurements with reference to proximity to roof deck and attic insulation.

Temperature and RH Monitoring on Flex Duct

Omnisense T&RH sensors were added around the perimeter of main trunk exterior jacket on October 12. Sensors were placed at bottom, and south side of the duct at mid diameter height.

Logger#0395 CH 1= bottom of main trunk (at 6 O'clock)

CH2= on south side of main trunk

Logger 03EA CH1=attic air 52" above insulation top (at same height as bottom of duct main).

CH2= attic air 68" above insulation top (same height as side duct main).

While some brief periods of warm moist weather show outside jacket T& Tdp approach similar values, it was not enough to develop notable condensation.

Duct Surface Temperature and RH Results

Measurements made on the exterior insulation surface show some potential for condensation on both metal and flex ducts, however, the period of condensation potential appears to be a little longer for this metal duct system. The flex duct exterior surfaces were noticeably warmer which would also reduce flex duct condensation potential and more quickly dry any small early morning condensation that may form temporarily. The attic conditions were nearly identical and were not a factor.

Figure B4 shows data for both the metal and flex duct systems. The areas where the temperature and dewpoint temperature are nearly the same are when condensation potential is greatest. The first 11 hours of the flex duct system are notably different since the sensors were in conditioned space until installed on attic ducts around noon October 13. The bottom surface temperatures were always lower than the side or top temperatures. This is most obvious during sunny periods when the roof deck radiation is greatest and contributes to heating exposed surfaces.

The solid green and blue temperature lines are warmer than the metal temperature (solid red and brown). The warmer exterior flex temperature is very likely due to better effective R value. The metal duct wrap appears to have less than R6 insulation due to compression during installation. More supporting information on this follows within this section covering circumference measurements.

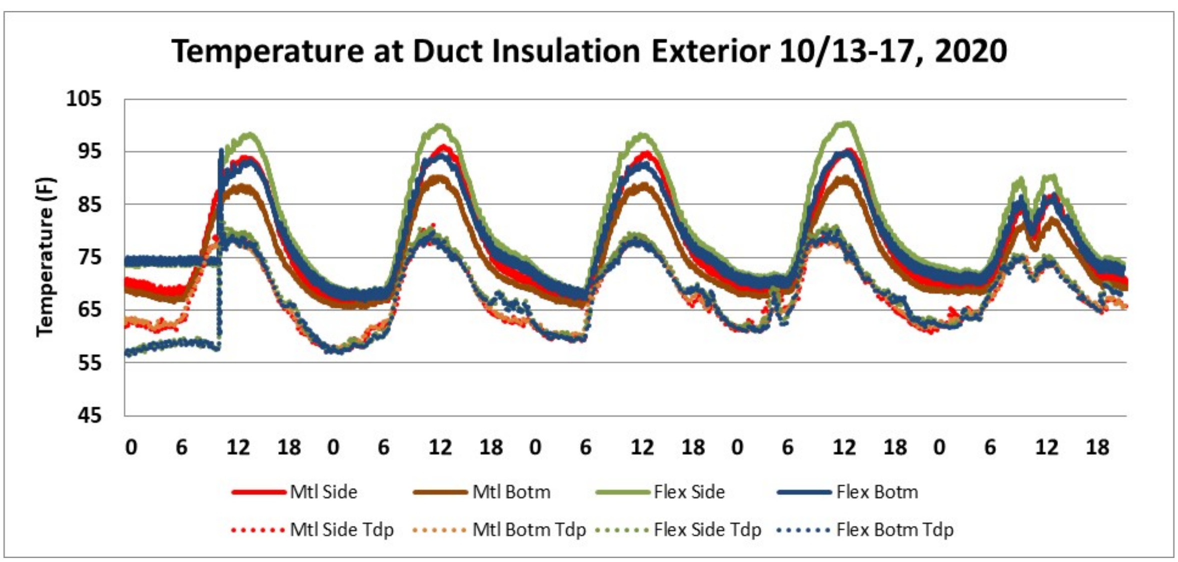


Figure B4. Exterior surface temperatures of metal and flex ducts over a five day period.

Figures B5 and B6 show a five day period in October of the metal and flex duct systems respectively. Separating the two makes it a little easier to observe the periods when surface temperature is close to the dewpoint. The flex bottom surface (Figure B6) was about 5°F warmer during peak temperatures and the flex side surface was about 3°F warmer than metal (Figure B5). These have been highlighted with a blue rectangle. The differences in condensation potential are noticeable around the 6 am periods of each day. The dotted dewpoint temperatures of the metal duct hug closely to the drybulb temperature more often and for a longer period than exhibited in the flex duct data. The first two days of data illustrate this better than the following days as highlighted by blue ovals.

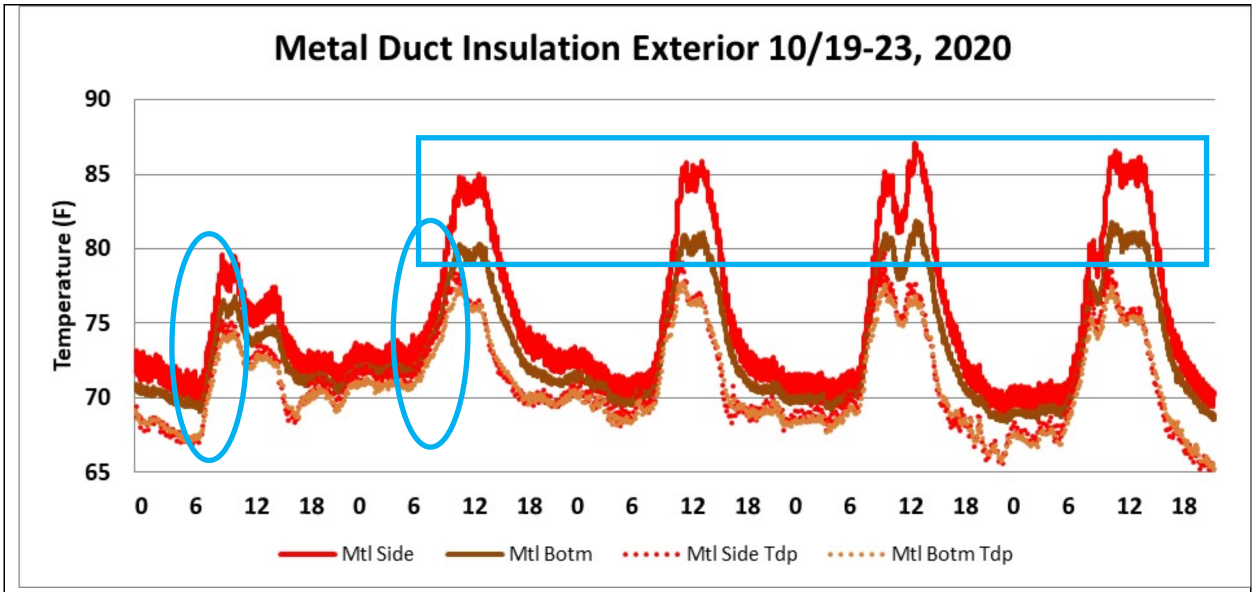


Figure B5. Metal duct insulation temperatures over a five day period towards late October.

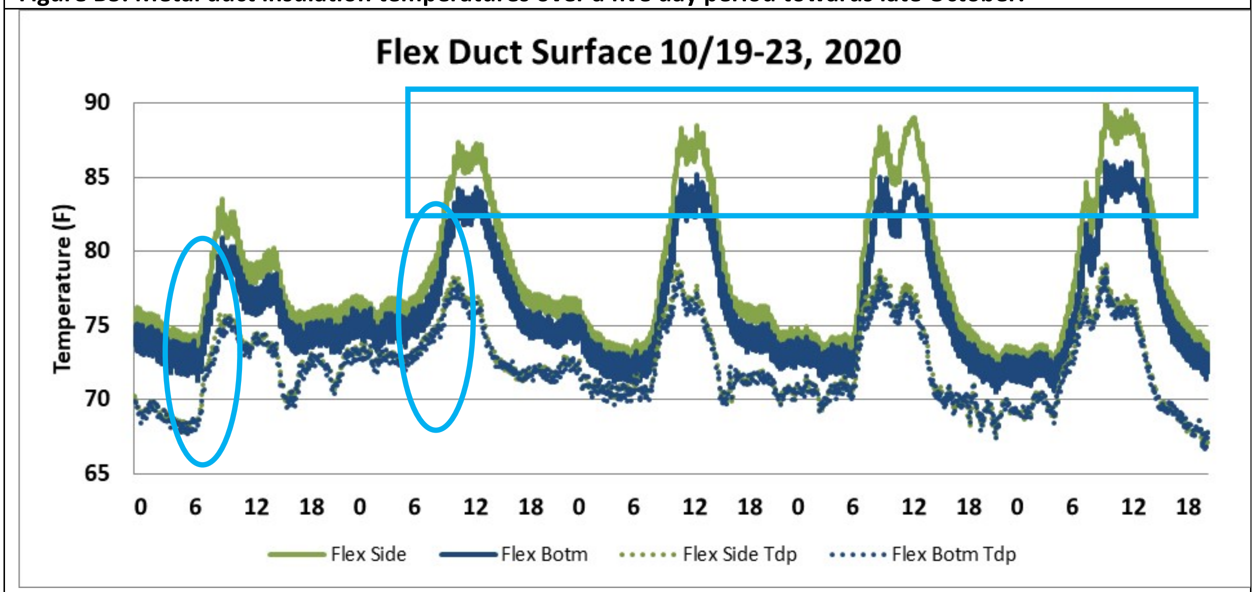


Figure B6. Flex duct insulation temperatures over a five day period towards late October.

Some early September data was collected on the metal duct before sensors were available to be placed on the flex duct. Similar patterns are seen as in the previous plots, however the last day shows that there are some days when the potential is for a much longer period from about midnight to 10 am. Figure B7 shows this five day period highlighted with a red circle. This type of incidence most likely occurs when previous days had cloudy but moist weather that limits the attic dry-out period during mid-day. This would support observations of this author where there is an increase in calls from homeowner complaints of duct condensation during late summer/ early fall when big thunderstorms and tropical storms are more prevalent.

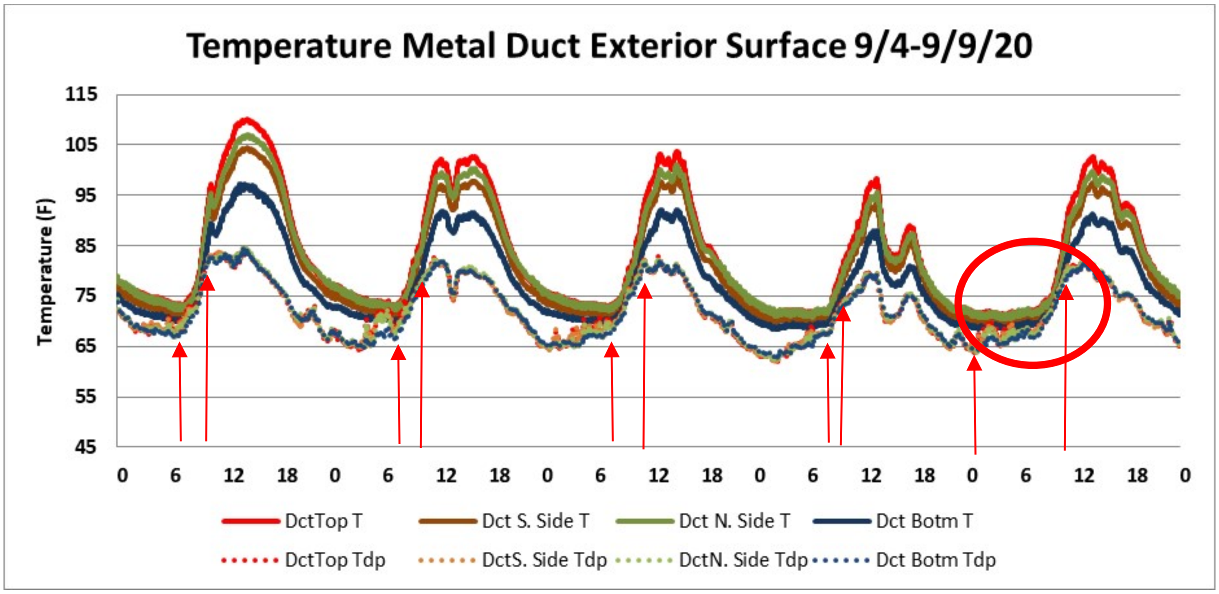


Figure B7. Temperatures on the metal duct during early September show some variability when condensation potential is highest.

Duct Circumference Measurements

The exterior duct insulation circumference was measured throughout the whole metal duct system to determine potential for over-compression that may have contributed to diminished R value. Insulation compression results in colder exterior insulation temperatures during cooling and it increases the potential for condensation. Table B1 shows the measured circumference, sectional area and an estimate of the duct insulation wrap R-value. The circumference was used to determine total external surface diameter including insulation thickness. The insulation thickness as installed was calculated subtracting the duct diameter from the calculated total diameter. The insulation manufacturer stated an R value with 1.63 inches of thickness. This was used as the basis for R value estimation. It is acknowledged here, that measurement of duct circumference offered a manageable approximation of the average FRK wrap thickness with associated minor measurement errors. This method may be prone to over-estimate insulation thickness than to under-estimate, but was used as a relatively simple means to estimate approximate R value of the installed insulation without destructive disassembly. The measurements were carefully taken such that the flexible tape measure was not drawn too tightly around to avoid added compression. However, a loose wrap around the jacket may not account for small depressions of the outer jacket resulting in higher estimated thickness.

The results clearly demonstrate the metal duct system did not have the equivalent of at least R6. The area weighted R value estimate of 3.5 is 58% lower than the expected R6. This result indicates a higher R value than the R2 estimate from the insulation manufacturer. The possible reason for the circumference method indicating a higher R value was previously discussed. The R2 estimate was based upon more limited samples that may have had more compression than much of the remaining insulation. Given that the circumference method may overestimate some and the manufacturer thinks it would not be more than about R2.8, we settle on an average overall duct R value of R2.5.

The installed fit and finish of the insulation wrap looked very good upon completion, however insulation compression is not something that can be easily measured or determined visually. This highlights the need for installers to make insulation blanket compression measurements during installation.

An annual energy simulation was performed using EnergyGuage USA RESNET HERS version 7.0.00 to determine the potential impact of R value less than R6 around supply ducts in a vented attic in central Florida climate. The results indicate increased annual cooling energy of 5%, 8%, 21%, and 32% for R 3.5, R2.5, R1, and R 0.5 respectively compared to R6. The insulation installed on the metal may have performed between R 3.5 to R2 and could have diminished savings compared to flex duct tested by about 5% to 8%.

Table B1. Measured Duct Insulation Exterior Circumference, Area and Estimated R value

Metal Duct Supply Section ID	Duct Diameter (in)	Measured Avg. Exterior Insulation Circumference (in)	Estimated R value *	Duct Section area (ft^2)
T1	16	57.25	4.1	83.09
T2	14	50.50	3.8	101.00
T3	12	46.33	5.1	36.68
B1	7	28.50	3.8	7.72
B2	9	33.00	2.8	51.33
B3	6	25.17	3.7	30.06
B4	7	33.00	6.5	11.00
B5	9	34.25	3.5	40.91
B6	4	17.00	2.6	6.97
B7	7	27.00	2.9	21.56
B8	6	24.25	3.2	26.94
Average R value			3.8	
Total Attic Duct Insulation Exterior Surface Area (ft2)				417.27

* based upon manufacturer rated R6 at 1.63 inch thickness (R3.6/inch)

The measurements and location of circumference measurements are also located in Figure B8. The first value within text boxes is the circumference in inches followed by the trunk or branch section, then the incremental sample number further downstream.

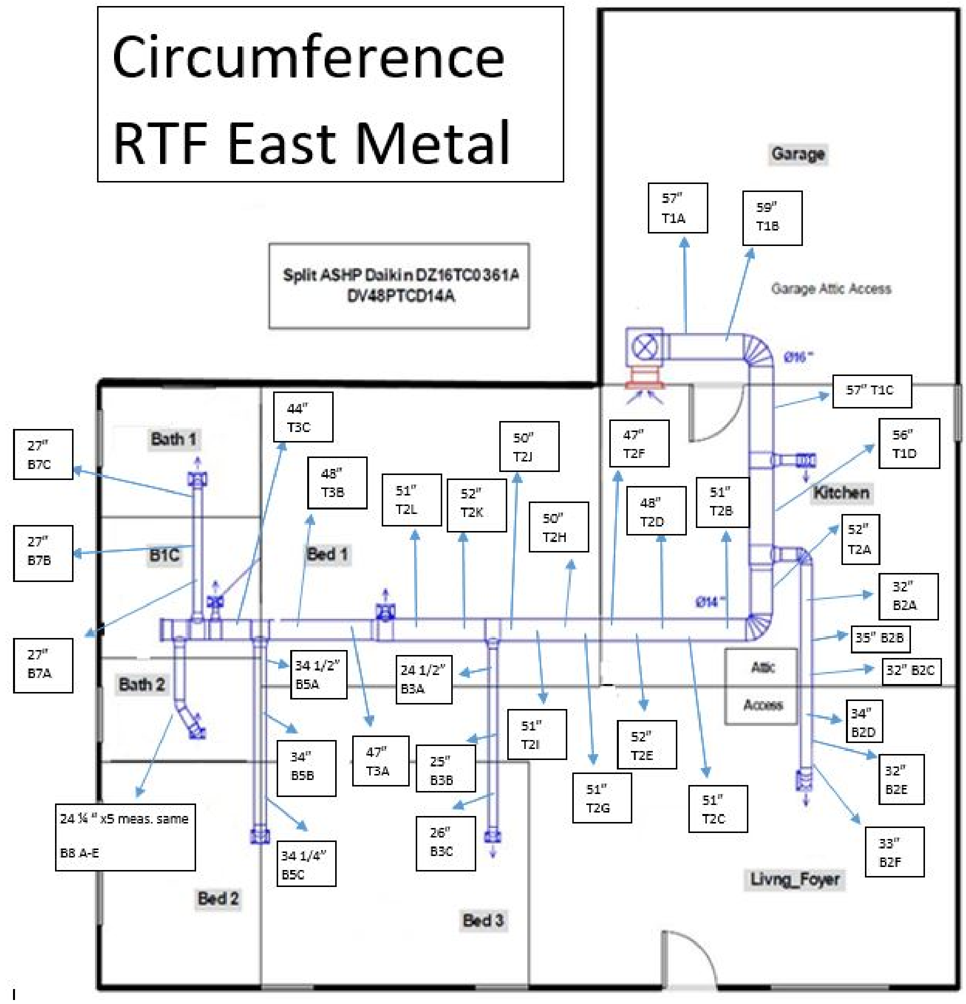


Figure B8. Metal duct layout shown with exterior insulation surface circumference measurements.

Detailed Observations and Measurements of Three Duct Insulation Wrap Samples

Insulation blanket compression offered a plausible explanation for the exterior condensation, but the question remained, “How did bulk water build up between the exterior metal duct and insulation wrap?”. Inspection of the insulation seam tape and mastic seals by an industry representative and did not find anything that should have allowed water vapor migration into the insulation. Charles Withers of the research team hypothesized that perhaps prolonged bulk water on the surface may have been slowly wicked through the class 1 vapor retarder, but this had not been tested.

Following a phone conference between the research team and Owens Corning, Owens Corning graciously agreed to take a look at some insulation samples and environmental data. Three samples of insulation wrap were taken by FSEC and sent to Owens Corning to evaluate with the goal of possibly offering an explanation for the water saturation trapped inside the insulation.

A document describing the nature of condensation and observations made during sample collection was developed and sent to Owens Corning prior to their assessment of the samples. This document, beginning on the next page, shows evidence of advanced corrosion on some parts of the metal duct after 2 years of service due to the moisture migration between the insulation and outer metal duct surface.

FSEC Energy Research Center

UNIVERSITY OF CENTRAL FLORIDA

Information About Three Samples of FSK Jacket Insulation Taken from a Wrapped Metal Duct System with Significant Condensation

Description and photos herein provided by Charles Withers, Sr. Research Scientist, FSEC Energy Research Center (FSEC), chuck@fsec.ucf.edu .

12/09/2020

Background

A cold air supply metal duct system located in the FSEC Residential Test Facility has had severe condensation on the outside of insulation jacket, which was first noticed in August 2020. The duct system was only about 14 months old by August 2020. A few attic duct inspections were made during summer of 2019 and only found a very small amount of condensation located on the bottom of some metal mechanical support bands of trunk lines where insulation was severely compressed. Condensation on metal support bands alone were considered to be of minor consequence due to very small duct area impacted.

In August 2020, condensation on the exterior insulation jacket was noticed on most of the main trunks and on most branches. It was most noticeable on the bottom where larger drops formed. Figure 1 shows a photo taken August 24, 2020 at a main trunk section about mid-way down the main trunk line.

Figure 1. Significant water condensation on exterior insulation jacket wrapped around an airtight metal duct supply system in a vented attic August 24, 2020.

It was thought that water may have also been trapped inside the jacket, but was not confirmed until later. Trapped water was very obvious within the jacket at the bottom of jacket on horizontally run ducts by October 7, 2020 when a small hole was poked into the insulation jacket.

Figure 2 shows the a two-dimensional layout. It does not show vertical orientation. The main trunk line was run horizontally at about 53 inches above the attic floor. Three samples of insulation were taken from locations that had exhibited substantial condensation from August- November 2020. Figure 2 shows the locations of each FSK insulation sample.

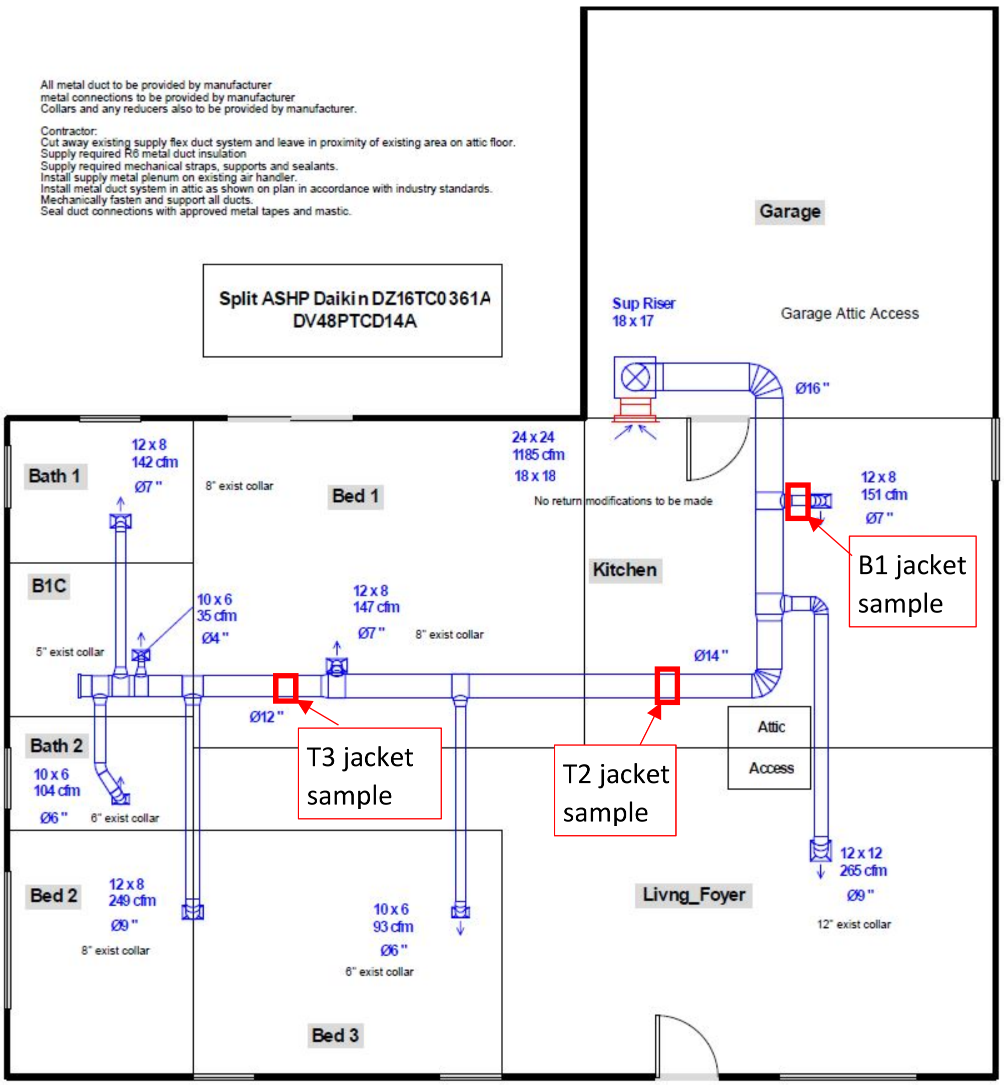


Figure 2. Metal supply air layout in vented attic shown with locations of three insulation jacket samples.

Before any insulation was disturbed, the duct system jacket tape seams were inspected to see if poor sealed seams could help explain how water got trapped between the metal duct and jacket. A representative of Hardicast came to inspect the jacket taped seams on November 12, 2020 and stated the jacket seams appeared to have had tapes adequately applied.

Insulation Samples

Insulation Sample B1

The first sample was marked as “B1” and was taken from around a 7 inch diameter metal duct. The top side of sample was taken from 8 inches below the trunk to branch transition and width of cut was 12 inches. This branch duct is the first supply drop from the system and is 100% vertically oriented. There was a lot of condensation on the outside of jacket, however there was no obvious collection of water trapped inside the insulation jacket. This is likely due to the vertical nature where any water inside jacket had drained down the vertical branch onto the top of the supply boot box and then ran down through ceiling. The circumference of existing jacket as found before cutting out was measured at 28.5 inches. If the insulation has an R-value of R6 at about 1.6 inches thick, then the jacket circumference should have been about 32.2 inches. This indicates significant compression and less than R6 insulation.

Figure 3. A shiny new duct branch “B1” is shown here during installation in June 2019.

Figure 4. “B1” sample taken November 25, 2020 is looking much duller.

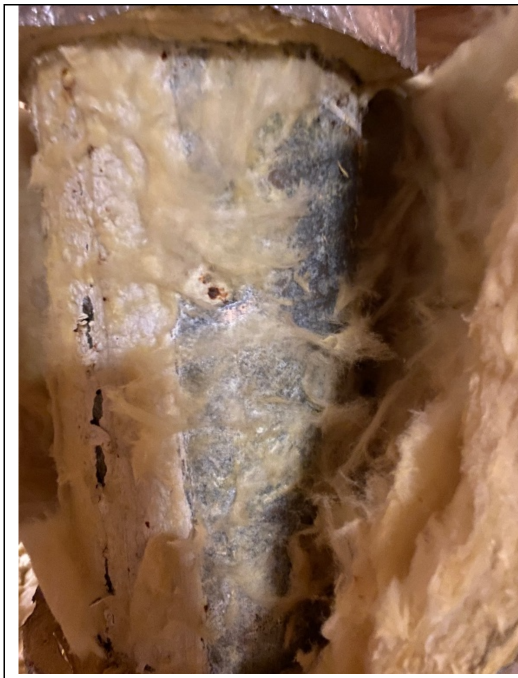


Figure 5. B1 metal duct shows signs of some water marking and corrosion. Except for corrosion, the mastic seal was in good condition.

Figure 6. B1 metal duct with insulation pulled away showed thickness of about 1”-1 ¼” . The rips in mastic seam occurred during sample retrieval.

Insulation Sample T2

The second sample was marked as “T2” and was around a 14 inch diameter metal duct. The right side of this sample was taken 39 inches downstream of a 90 degree turn from south to east direction. The width of cut was 12 inches. This trunk duct section was horizontally oriented. There was a lot of condensation on the outside of jacket and substantial collection of water inside jacket. The circumference of existing jacket as found before cutting out was measured at 51.0 inches. If R6 insulation is at about 1.6 inches thick, then the jacket circumference should be about 54.2 inches. This indicates significant compression and less than R6 insulation. The thickness of insulation jacket was measured immediately after sample cut-out. It varied from about 1/2 inch at bottom to 1-1/8 inch thick with an average of about 1 inch thick. The much thinner thickness at bottom is likely due to long-term saturation of water trapped inside at bottom. Observations of insulation before insulation was observed to be wet found the bottom to be thicker than 1/2 inch.

Figure 7. Main trunk section “T2” sample section with right side (upstream) sample cut visible.

Figure 8. Topside of “T2” with corrosion spot found at left side (downstream) of sample.

Figure 9. At top of T2 trunk line on right side of sample.

Figure 10. At bottom of T2 trunk line where water was found trapped between duct and insulation.

 **Figure 11**. Topside insulation (left side of sample) was about ¾" thick near the corrosion spot.	 **Figure 12**. Another close-up view of corrosion spot at T2.

Figure 13. Water droplets observed on metal duct T2 immediately after pulling away insulation sample.

Insulation Sample T3

The third sample was marked as "T3" and was around a 12 inch diameter metal duct. The right side of this sample was taken 16 inches downstream of the transition from T2 trunk line to T3 trunk line. The width of cut was 12 inches. This trunk duct section was horizontally oriented. There was a lot of condensation on the outside of jacket and some collection of water inside jacket. The circumference of existing jacket as found before cutting out was measured at 44.75 inches. If R6 insulation is at about 1.6 inches thick, then the jacket circumference should be about 47.9 inches. This indicates significant compression and less than R6 insulation.

Figure 14. Sample "T3" before pulling it out.

Figure 15. Close inspection at the T3 sample found water droplets near top and on bottom of the metal duct. Corrosion can be seen at the mastic duct seam on metal duct.

Additional Photos

Figure 16. supply grille on duct branch B1 has visible water on grille and staining and paint damage on right side. The integrity of the drywall was still good. Photo taken September 18, 2020.

Figure 17. Main trunk section T1 shows light condensation on bottom and some sides (red circles). Heavier condensation and water marking is on the bottom of T1 after bend on left side of photo circles by red rectangle. Photo taken September 18, 2020.

Figure 18. Close view of finger swipe on jacket surface shows light condensation on section within the largest circle shown in Figure 17 (9/18/20).

Figure 19. Photo of wet bottom on section T1 shown within the rectangle in Figure 17. Large water droplets and light grey water marking can be seen. The duct branch drop B1 is the vertical duct in the background (9/18/20).

Figure 20. Example photo of jacket circumference measurement made on main trunk T2. Light condensation was on sides and larger water droplets on bottom of jacket (9/18/20).

Figure 21. Condensation and water drops on bottom of main trunk T3 (9/18/20.

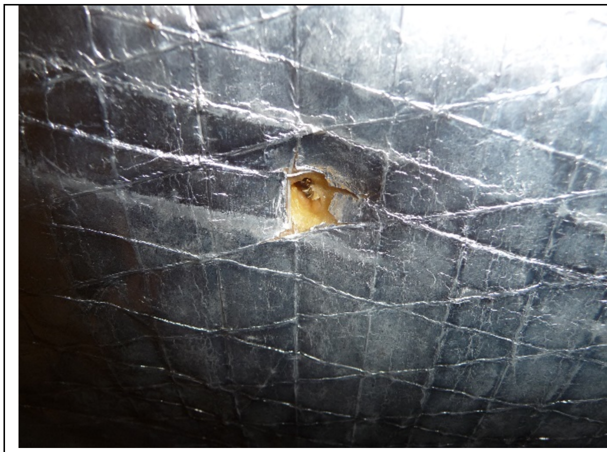


Figure 22. A small hole was poked into the bottom of jacket near T2 sample on October 7 to verify if water was also between the jacket and metal duct. Bottom of jacket was filled with water that did not readily pour out until pressure was applied to jacket.

Figure 23. A steady stream of water can be seen coming out of the inspection hole in jacket while applying pressure on jacket. Water was trapped inside jacket throughout the main trunks.

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Insulation Wrap Testing and Evaluation by Owens Corning Laboratory

A video conference call was held on January 25, 2021 where the manufacturer lab staff presented findings from testing FRK insulation samples sent from the FSEC lab ducts. An analysis of monitored cooling performance data from the system with duct condensation was also evaluated. The following summarizes FSEC's understanding of the lab test findings and group discussion:

- FRK insulation compression was evident in the samples sent.
- Understanding this event occurred because of under-insulated duct due to over-compression of the fiberglass insulation. Water in the form of condensation will occur on the duct itself if the temperature of the duct reaches dew point. The point of effectively insulated duct is to not let the warm ambient air reach the cold surface of the duct. If the duct is not sufficiently insulated the warm air will contact the cold duct surface and condense the moisture at dew point in the air surrounding the duct and will not dissipate if not able to escape or dry through normal air handling cycling.
- Job-site handling, cutting on a floor with debris, and over-stretching can result in micro-fissures in foil vapor barrier and result in higher moisture perm.
- Not unusual for perm of installed FRK to be about 1 perm.
- Perm testing of samples was from 6.2 to 6.6 perms in sections T2 and T3. This is about 6 times what might be expected and would not be effective as a vapor barrier. Sample B1 was 11.7 perms.
- The long runtimes of the two-speed air conditioner keep duct colder longer and don't allow intervals of warming back up and drying off.
- Discussions highlighted the importance of this condensation event as good learning opportunity for the building industry.
- Also discussed was that climate zone 2 prescriptive code requires R8, however R6 is allowed under the performance method of compliance. This illuminates important Florida code considerations of condensation potential that should be considered. R6 insulation is most commonly used in Florida.