Measured Cooling Performance and Potential for Buried Duct Condensation in a 1991 Central Florida Retrofit Home

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NOTICE

Measured Cooling Performance and Potential for Buried Duct Condensation in a 1991 Central Florida Retrofit Home

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Definitions

A/C	Air conditioning
ACH_{50}	Air changes per hour at 50 Pascals
AHU	Air handler unit
BA-PIRC	Building America Partnership for Improved Residential Construction
cfm_{25}	Cubic feet per minute at 25 Pascals
FSEC	Florida Solar Energy Center
kW	Kilowatt
kWh	Kilowatt-hour
mV	Millivolt
Pa	Pascal
Qn	Normalized duct leakage to outside (cfm 25), out/ft^2
R	A measure of resistance to the flow of heat through a given thickness of a material (as insulation) with higher numbers indicating better insulating properties
RH	Relative humidity
RTD	Resistance temperature device
SEER	Seasonal energy efficiency ratio
T	Temperature
U	A measure of the flow of heat through an insulating or building material
V	Volt
Wh	Watt-hour
ZEH	Zero energy home

Executive Summary

This research analyzed measured energy savings from a moderate retrofit by comparing post-retrofit performance with measured pre-retrofit monitored data. The test home, occupied by a Florida Solar Energy Center researcher and five family members, was fully instrumented to yield detailed energy, temperature, and humidity measurements. Two years of pre-retrofit data were available to characterize improvements in cooling energy and electric demand savings from an upgraded heat pump (seasonal energy efficiency ratio [SEER] 10 to SEER 16) and increased attic insulation (R-19 to R-38). Additional efforts investigated condensation on supply duct surfaces during periods of high dew point temperatures. This potential side effect, specific to the hot-humid climates, is a known consequence of flex ducts being buried in cellulose insulation.

Cooling energy savings of 30% were measured during the summer of 2011 (June to September) and compared to the previous two summers (2009 and 2010) using a least squares linear regression that accounts for differences in indoor and outdoor temperatures. Directly comparing the daily average total building and cooling energy use, unadjusted for weather differences, showed a 26% total building energy reduction and 37% less cooling energy use after retrofit measures were in place. Summer electricity peak demand was reduced by 37% on a whole-building basis and 46% for the submetered air-conditioning system. The whole-building peak demand was reduced to essentially the same level once required by the old SEER 10 air conditioning alone, 2.82 kW.

The presence of condensation on attic ducts buried in blown insulation was investigated with moisture-sensing strips mounted to exterior duct surfaces. Four distinct ranges—from a dry surface to a fully wetted, condensing condition—were identified to indicate the presence of moisture. Pre-retrofit measurements showed very low condensation potential, although these were limited to a relatively short 3-week period and moderate dew point temperatures. Data recorded after the ducts were buried showed strong signs of condensation during periods of high dew point (mid-summer), but it was reduced during the fall when dew point temperatures dropped. Visual inspection of the ducts showed no evidence of damage from accumulated moisture. The relatively high set point temperature (79°F) of the study home, however, might indicate that greater potential for damage could exist at lower thermostat set points.

1 Introduction

The Florida Solar Energy Center (FSEC) conducted energy performance monitoring of two existing residences in Central Florida that were undergoing various retrofits. These homes were occupied by FSEC researchers and were fully instrumented to yield detailed energy, temperature, and humidity measurements. The data gave feedback about the performance of two levels of retrofit in two types of homes in a hot-humid climate. This report covers a moderate-level retrofit and includes 2 years of pre-retrofit data to characterize the impact of improvements. The other home, covered in a separate report (Parker and Sherwin 2012), is a deep energy retrofit that has performed at near zero energy with a photovoltaic system and extensive envelope improvements.

2 Background

The 2,200-ft^2, four-bedroom wood frame home discussed in this report was built in 1991 and is located in Cocoa, Florida (Figure 1). It is occupied by a family of six. It has a 12-year-old flat plate solar water heater and a 6-year-old white metal roof but has otherwise had no energy-related improvements. During roof replacement, attic venting was eliminated. Measured cooling savings from the replacement of dark shingles with a white metal roof amounted to 19% and are documented in an FSEC report (Chasar, Moyer, and Martin 2006).

Figure 1. Wood frame retrofit home located in Cocoa, Florida

The most recent retrofit measures were completed in May and June 2011. The 20-year-old seasonal energy efficiency ratio (SEER) 10, split heat pump was replaced with a SEER 16, 2-speed heat pump. In addition, blown-in cellulose insulation (R-19) was added over existing R-19 ceiling batts, which brought the total ceiling insulation level to R-38. Flex duct runouts buried in the cellulose were monitored for condensation.

These two measures have been part of many retrofits documented by FSEC over the past few years. They typically represent a significant portion of the 30%–50% total energy reduction goal sought by the Building America Program and might be broadly applicable to many hot-humid climate homes built from the 1980s to the early 1990s. Burying attic flex ducts in blown insulation is a common practice where replacement of existing ductwork is not required. Although ducts buried in insulation are expected to benefit from reduced heat gains and losses, there remain unresolved durability and air quality implications with this practice when implemented in hot-humid climates. Buried ducts have an increased potential for condensation on exterior surfaces of ducts, especially in humid climates, that could result in moisture damage or mold growth. A method of determining the presence of condensation was employed in several key locations to provide feedback about this phenomenon.

Table 1 lists home construction and equipment details. Building and duct airtightness tests were performed before and after the retrofit measures were implemented. An evaluation of the original R-6 ductwork showed only limited degradation of the duct board trunk and flex duct runouts. Repairs were performed at flex duct collar connections, reducing duct leakage from 77 to 55

cfm$_{25}$ to out, as shown in Table 1. During each test for duct leakage to outside with the house held at –25 Pa (with respect to out), the pressure in the house was recorded at –20.5 Pa with respect to the attic. This measurement gives an indication of the reduction in attic venting because in a home with a fully vented attic, it would typically be –25 Pa (same as to out). Even though the natural attic venting in the study home was eliminated, then, the attic was by no means sealed and maintained some connection with the outside.

Table 1. Construction and Equipment Details

Component	Pre-Retrofit	Post-Retrofit
Construction Date	1991	
Construction Type	Wood frame	
Floor Type/Area (ft^2)	Slab-on-grade/2,200	
Attic/Roof Type	Unvented /white metal	
Window Type	Single-pane, clear glass, aluminum frame	
Glass/Floor Area	11%	
Insulation Attic/Wall/Floor	R-19/R-11/R-0	R-38/R-11/R-0
Exterior Wall Cladding	Natural cedar (medium-dark)	
Space Conditioning	3-ton, SEER 10, heat pump, 20 years old	3-ton, SEER 16, 2-speed heat pump
Thermostat	Standard	
Ventilation	None	
Water Heater	Active direct solar, 80-gal electric backup	
ENERGY STAR Appliances	H-axis clothes washer and second refrigerator	
Other Appliances	Refrigerator, dishwasher, clothes dryer	
Fluorescent Lighting	70%	
Occupancy	6, (2 adults, 2 teens, 2 adolescents)	
Infiltration (ACH$_{50}$)	4.7	4.8
Duct Leakage (cfm$_{25}$)	173 (total)/77 (out)	158 (total)/55 (out)
Duct Leakage (Qn)	0.035	0.025

3   Monitoring Equipment and Measurements

Energy use, temperature, and relative humidity (RH) conditions were recorded with a Campbell Scientific data logger both pre- and post-retrofit. Energy use measurements included whole-house and indoor and outdoor components of the split heat pump. The difference between interior and exterior temperature measurements was useful in characterizing cooling energy performance and isolating the influence of thermostat set points.

Various other measurements were used to examine additional impacts from the retrofit measures, including attic and interior temperatures as well as RH and supply air temperature. The ducts were fitted on the outer surface with thermocouples and condensate-sensing, resistive strips before being buried within the R-19 cellulose that was blown over the existing fiberglass batts. The photos in Figure 2 show the placement of instrumentation on the duct and the extent of duct coverage by the cellulose insulation. These readings, along with attic air conditions, were evaluated for potential and frequency of condensation. The ducts were also visually inspected for any noticeable physical effects.

Figure 2. Photos of buried duct (left) and exposed moisture sensing strip (highlighted, right)

A Campbell Scientific data logger had been in place at this home for several years. It has been used for various experiments including a baseline cooling performance compared to high performance homes (Chasar et al. 2006) and the before and after effects of replacing dark asphalt shingles with white metal roofing (Chasar, Moyer, and Martin 2006).

The data logging system was upgraded in 2010 to a new model CR1000 logger and WattNode energy meters. Current data channels include energy use measurements as well as indoor, outdoor, and attic conditions (Table 2). The logger operates at a 30-s scan rate and stores data in 15-min time steps.

Table 2. Sensors and Data Logger

Measurement	Equipment Used
Indoor and Attic T/RH	Vaisala RTD/thin-film probe
Outdoor T/RH	Vaisala RTD/thin-film probe
Other Temps (duct surface T)	Type-T thermocouple
Duct Condensation	Resistive surface strips
Whole House and HVAC Energy Use	WattNode electric energy meters
Data Collection and Storage	Campbell Scientific data logger

Note: T, temperature; RTD, resistance temperature device

4 Analysis

4.1 Cooling Energy Performance Comparison

To normalize results for weather and occupant thermostat settings, best-fit linear regressions were used to characterize cooling energy use versus temperature difference (T_outdoor minus T_indoor). These methods are well established to estimate combined HVAC equipment and building efficiencies (Kissock, Haberl, and Claridge 2003). Uncertainties in the method have been documented by Cummings, Parker, and Sutherland (2010). Figure 3 shows the pre- and post-retrofit results. It includes reference to two other Central Florida homes built in 1998 where cooling performance was similarly measured from 1998 to 2002. Located in Lakeland, Florida, these reference homes were monitored by FSEC to show the impact of extensive envelope and equipment improvements between homes with otherwise identical building style, layout, and orientation (Parker et al. 1998). The Lakeland Control Home provides an upper boundary for cooling energy use in a typical, code-minimum, mid-90s home with a SEER 10 heat pump. Cooling energy use in the Lakeland Zero Energy Home (ZEH) provides a lower boundary for comparison purposes. Data from this home (the first to use the ZEH label) continue to compare favorably with more recent ZEHs. The home even outperforms many Building America prototype homes with cooling efficiencies that are higher than its SEER 14 system (Chasar et al. 2006).
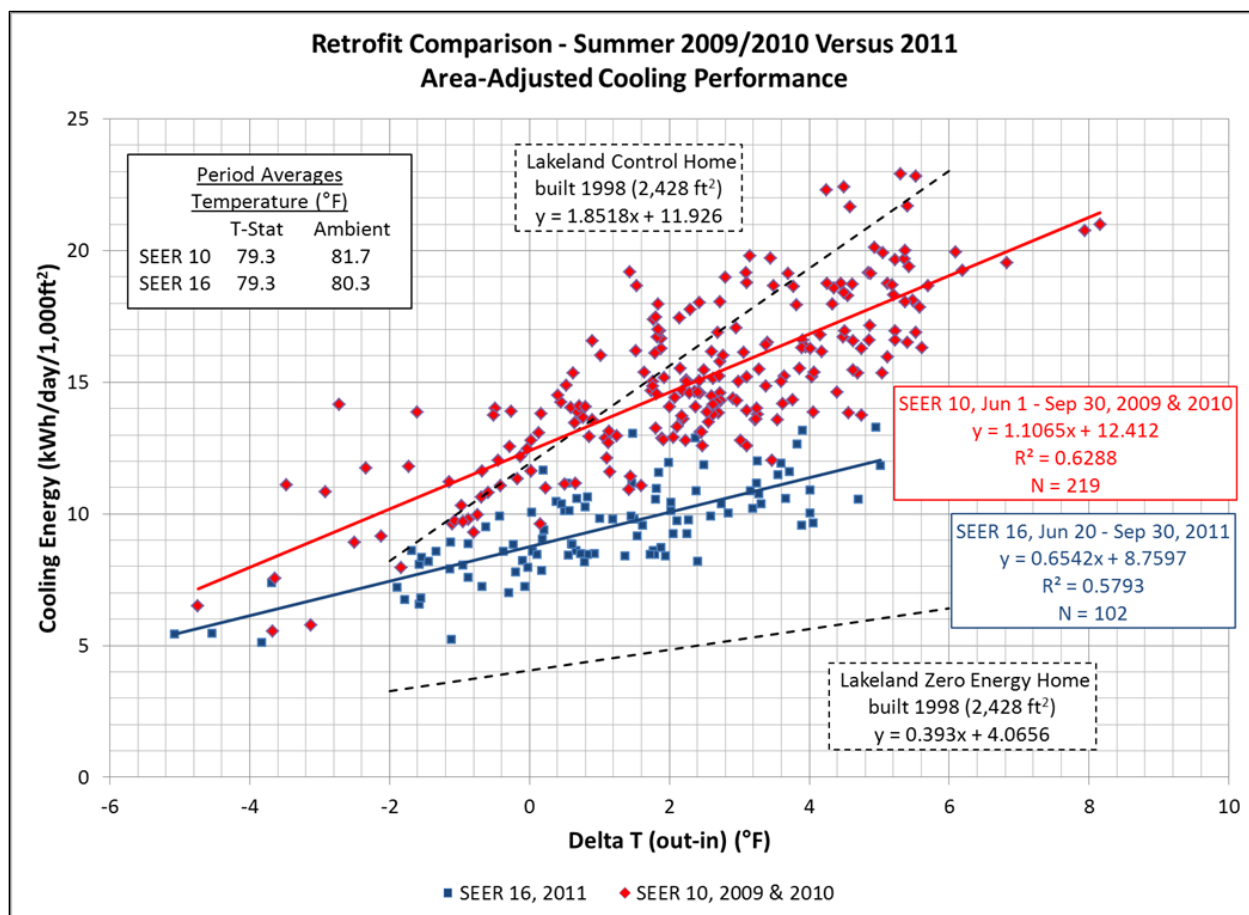

Figure 3. Pre- and post-retrofit cooling performance comparison

The pre-retrofit regression results in Figure 3 (red data) are composed of a data set from the two summers before improvements (2009 and 2010) and include a total of 219 data points. Each point represents the total cooling energy use (air handler unit [AHU] + condenser unit) for 1 day (y-axis) with respect to the outdoor minus indoor average temperature difference for the same day (x-axis). The resulting regression line has a similar y-intercept (12.4 versus 11.9) to that of the Lakeland Control Home; however, it has a noticeably lower slope (1.1 versus 1.9). This may reflect similar equipment efficiencies (both were SEER 10), but enhanced levels of building envelope performance. A similar effect was found with data taken from this residence in 2004 and 2005 that documented the impact of replacing dark shingles with a white metal roof (Chasar, Moyer, and Martin 2006).

Data from 2011, after retrofit implementation (blue data), includes 102 data points. It shows the relative performance improvements from both envelope and equipment retrofits (SEER 16, additional R-19 attic insulation and slightly tighter ducts). Twenty-six days were removed from the data sets over the three summers because of data logger downtime and known occupant influences such as vacation periods and major cooking or party events. Otherwise, all collected data were included in the analysis. An average savings of 30% was derived by applying the measured daily delta Ts for the 2011 summer period from June through September to each best-fit equation. The magnitude of this savings in the study home would amount to 1,072 kWh (or 8.9 kWh/day) for this 4-month summer period.

Table 3 directly compares average daily energy use and temperatures from the two pre-retrofit years (2009 and 2010) with post-retrofit data (2011). These values were unadjusted for weather differences between years but were taken from equivalent periods from June 20 to September 30. The results show a 27% total building energy reduction and 39% less cooling energy use after retrofit measures were in place. Average daily outdoor temperatures were 1°F to 2°F higher during the pre-retrofit years than during the post-retrofit period. Indoor temperatures were maintained at a stable 79.1°F to 79.5°F over the full study period with a relatively constant thermostat setting. Table 3 and Figure 4 also show how the variable-speed AHU effectively used about one-half the energy of the single-speed unit it replaced. Condenser unit energy was reduced by about one-third.

Table 3. Average Daily Data, Summer Results Comparison

Year	Average Site Energy (kWh/day)				Average Daily Temperature (°F)	
	Total Building	**AHU**	**Condenser Unit**	**Total A/C**	**Indoor**	**Outdoor**
2009	56.5	4.2	27.9	32.1	79.1	81.5
2010	57.7	5.0	30.4	35.4	79.5	82.3
2011	41.7	2.3	18.5	20.7	79.3	80.3
Savings Over Previous Years (%)						
2009	26	46	34	35		
2010	28	55	39	41		
Combined	27	51	37	39		

Note: A/C, air conditioning

Average Daily Summer Energy Comparison

Measured data from Jun 20 - Sep 30
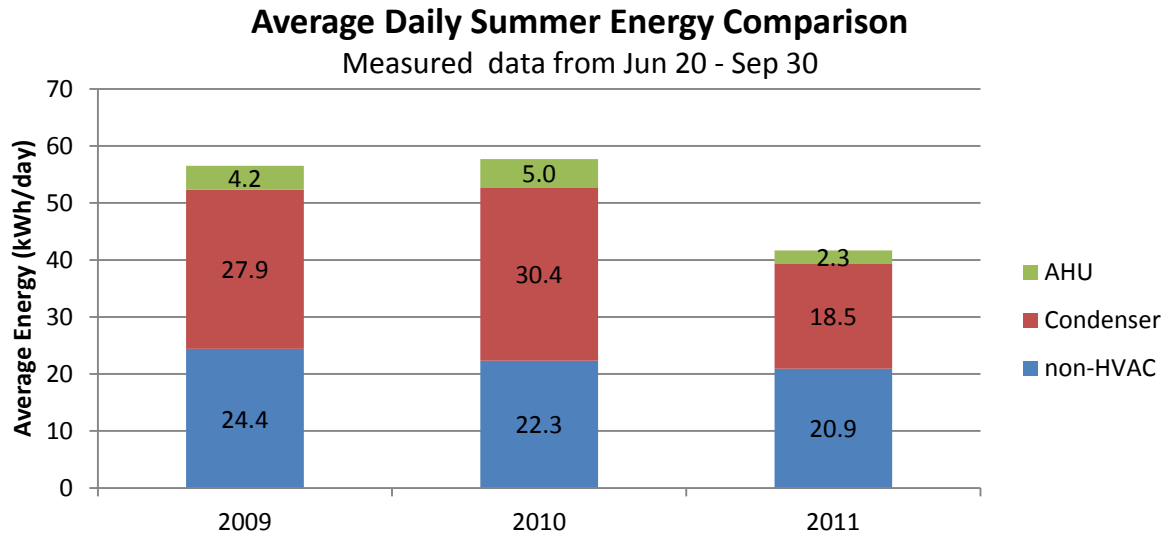
Figure 4. Unadjusted average daily cooling performance comparison

Electric demand was also analyzed over the same summer periods. An average daily demand profile was created (Figure 5) by averaging 15-min power draws and plotting the pre- and post-retrofit values. The figure shows what an average 24-h day would look like before and after energy improvements took place. Average 15-min peak demand was reduced by 37% on a whole-building basis; submetered A/C peak demand (combined AHU and condenser unit energy) was reduced by 46%. The peak summer demand window for utilities is typically from hours 14 to 16 (2 p.m. to 4 p.m.), and reductions during this period were slightly reduced at 34% for whole-building demand and 45% for A/C peak demand.

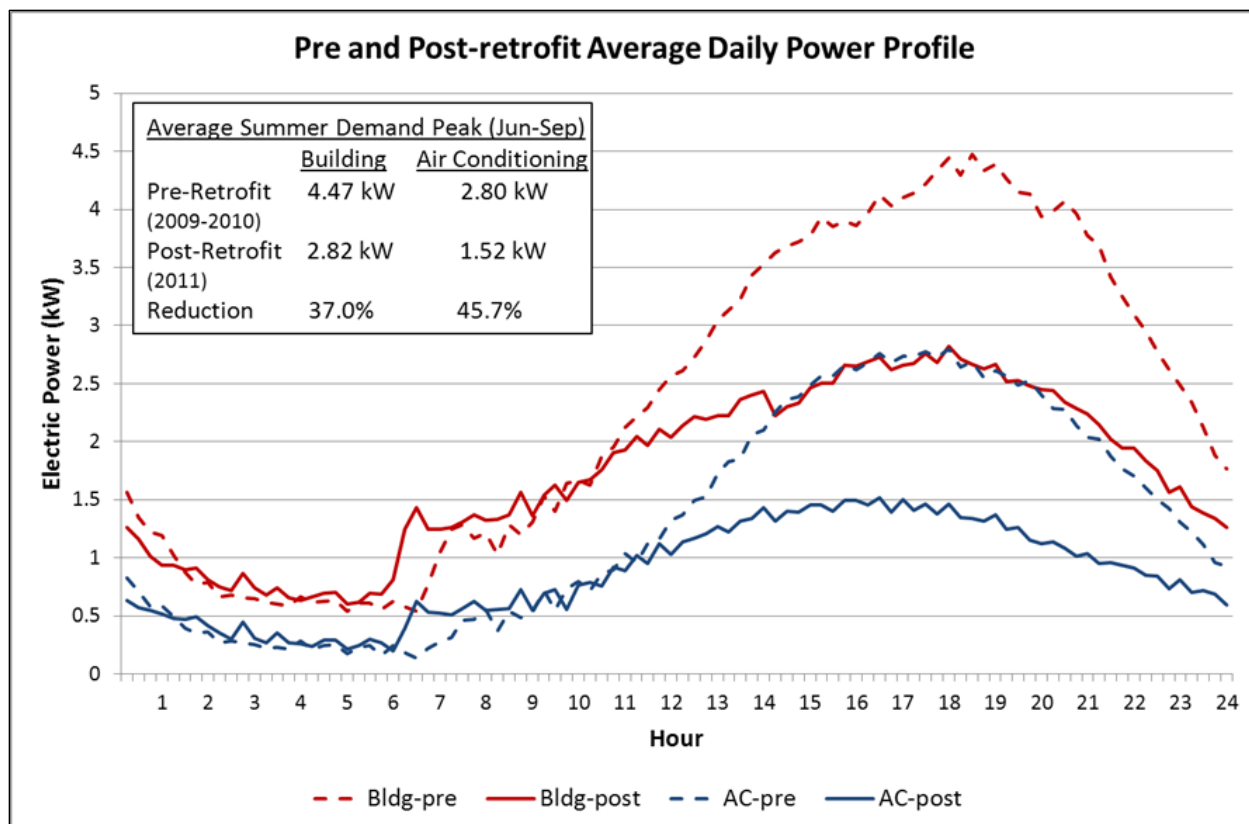**Figure 5. Pre- and post-retrofit average daily electric demand**

4.2 Buried-Duct Condensation Analysis

Increasing the level of attic insulation is a common retrofit measure and can be highly cost effective in poorly insulated attics. Where flex duct systems are used for air distribution, these can often be found lying directly on top of existing insulation. This was the case for all the flex duct runouts in the study home, which were attached to a flex and ductboard trunk line elevated above the attic insulation and connected to the AHU, which was mounted in the conditioned space.

Labor expense is reduced by reusing existing flex ducts and simply applying blown attic insulation on top of the old ductwork. This effectively adds insulation to the duct system, which can deliver efficiency gains of its own but also reduces the exterior surface temperature, raising the probability of surface condensation during high dew point periods.

Covering supply ducts in attics with blown insulation results in colder external supply duct surfaces, which increases the potential for condensation during summer cooling periods. Condensation on duct exterior surfaces is primarily a building degradation concern. In a worst-case scenario, long cooling cycles would keep the duct surface cold, causing moisture to accumulate long enough that it builds up and runs off of the duct and onto other building materials. Wood, drywall, and some insulation materials could stay damp enough to support mold growth and eventually rot if substantial drying cycles do not occur.

Exterior duct condensation is not expected to cause an increase in cooling energy use, unless significant perforations in the outer duct jacket permit water to run into the insulation. Water would not dry out readily and would tend to accumulate over time, resulting in wet insulation that would drastically diminish the effective R-value. Although this is possible, it is not likely in most cases. Water most likely will accumulate on the exterior duct surface and then eventually run off the jacket if the surface is cold for long enough.

A simple and relatively inexpensive monitoring method was desired that would be able to differentiate a wet duct surface from dry and determine the amount of time the duct was wet. The estimated duct surface moisture was a relative evaluation simply classified as dry, surface humidity >90%, surface condensation, and surface saturated. This phenomenon was investigated by evaluating attic air conditions as well as duct surface and supply air temperatures. In addition, duct surface moisture levels were estimated by measuring the voltage drop across two metallic strips imbedded onto a thin porous fabric substrate that was adhered to the duct surface. Voltage varied with the change in resistance on the strip as a function of the moisture level with the maximum occurring when the strip was fully wetted from condensation. This same principle is commonly used in moisture meters (James 1988). Resistive strips were attached to the exterior surface of a 5-in.-diameter R-6 flex duct in two locations (side and bottom). The side location would be at the 3 or 9 o'clock position if looking down the duct in direction of air flow. The bottom would be at the 6 o'clock position and represents the most likely location for condensation because it would have a colder surface temperature than the sides or top of duct covered by less insulation. The side location allows the bottom to be compared to a lower potential condensation area. The flex duct chosen for this investigation was the one nearest the cooling coil, meaning that the moisture-sensing strips were within 5 ft of the cooling coil. This represented the worst-case condensation potential with the coldest supply air passing through the duct.

The moisture sensor tape was calibrated in a laboratory before field installation. The moisture sensor was applied to a duct foil jacket surface taken from a flexible duct. The duct jacket was then placed in direct contact around a container of water. The sensor had a 2.5-V excitation applied every 30 s, and the differential voltage was read across the sensor after each excitation. The wetter the surface, the greater the measured voltage across the sensor. Visual observations of the duct jacket surface were made for moisture indications of dry, light condensation (fog), small droplets of water, and running drops of water. The sensor voltage was noted during these observations. Ice was gradually added to water inside the container to create moisture at the duct jacket surface. Type T thermocouples were placed on the jacket surface and inside the ice water mixture. The temperature and RH of the surrounding air was also measured to determine the dew point of the air environment around the sensor at the test surface.

The sensor was also tested with placement in unconditioned space during periods of high outdoor RH without an ice water mixture inside the container. This allowed the characterization of lower boundary sensor voltage for RH > 90%, but without visible signs of condensation.

In the field installation, a 2.5-V, direct-current potential was applied to the sensor, and the measured voltage across the sensor was recorded at 30-s intervals. Voltage readings varied from a low of a few hundred millivolts under dry conditions to 2,300 mV or more for fully wetted, condensing conditions. Initial laboratory experiments found two other significant threshold

levels: (1) when the surface is still dry but ambient RH is elevated to near 90% RH (800 mV) and (2) when the surface initially begins to show condensation (1,600 mV), as shown in Table 4. Although rigorous experiments have yet to be conducted with these strips, these thresholds form a basic framework to evaluate readings in this particular research project.

Table 4. Moisture Strip Readings Derived from Initial Laboratory Observations

Measured Output (mV)	Observed Conditions
400 or Less	Dry conditions (ambient below 60% RH)
800	Dry conditions (ambient approximately 90% RH)
1,600	Beginning of surface condensation
2,300 or More	Fully wetted surface (condensation)

Figure 6 illustrates relative duct moisture levels using the Table 4 thresholds during pre- and post-retrofit periods. Three periods chosen from the data set (one pre-retrofit and two post-retrofit) show the impact on moisture readings under various circumstances. Data points in Figure 6 were plotted by taking the daily average duct surface moisture (mV) against daily average outdoor dew point (°F). Duct moisture data logging began in late May 2011 just 3 weeks before the blown insulation was added, as reflected in the relatively small number of blue data points clustered near the 500-mV level. Although this data set is small and was taken at moderate dew point temperatures, it illustrates the relatively low potential for condensation before burying the ducts in insulation.
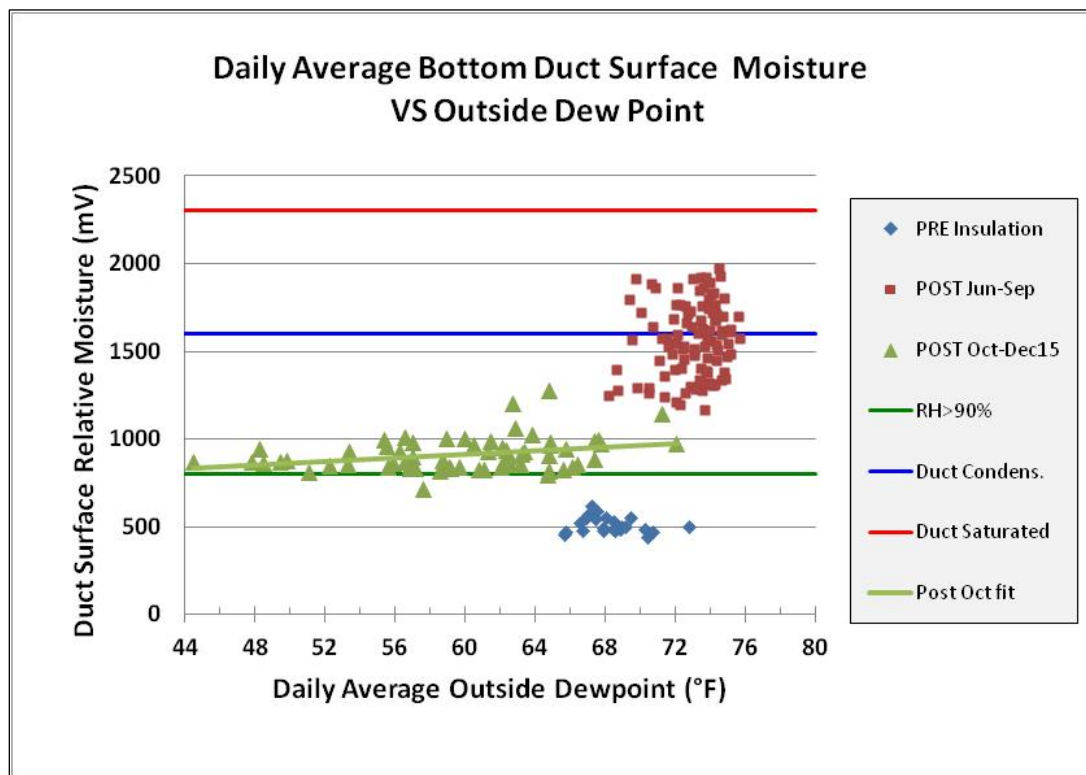

Figure 6. Relative duct moisture levels during one pre-retrofit and two post-retrofit periods

A larger data set was collected after the blown attic insulation was applied. These data were separated into two groups by level of daily average outdoor dew point, which tended to be higher from June through September (red data points) than from October through December (green data points). Condensation potential is elevated during the summer months when dew points are generally 65°F or higher and reduced in the dryer fall and winter months. Interior conditions were maintained at a nearly constant 79°F during this study, suggesting that lower thermostat settings would create greater potential for duct surface condensation because the ducts would be cooled for longer periods and possibly reach lower surface temperatures.

Additional data need to be collected during hot and humid weather to determine how well the moisture tape performs as a moisture sensor over long-term periods. It still needs to be determined if the conduction will change over time as the sensor material ages. Controlled laboratory experiments did find that the absolute measure of voltage varied by the length of sensor used and the type of material to which it was adhered. In this monitoring experiment, the sensor was evaluated for the type of flex duct surface to which it was attached. It is important to remember that the sensor is only intended to indicate a relative amount of moisture so that adequate warning can be provided to prompt an inspection before building material can become damaged.

Data were selected for 2 days that had similar outdoor dew points representative of common summer conditions. Data for the selected days are shown in Figures 7 through 9, one before and the other after adding blown insulation to illustrate the impact of burying the ducts. Figure 7 shows the similarity of outdoor and attic dew points between periods. Pre- and post-retrofit outdoor dew points were quite similar in each case, remaining at or above 70°F during the entire period. Attic dew point temperatures were also quite similar but varied over the period, with each data set experiencing a peak between 3 p.m. and 4 p.m. before declining steadily until approximately 7 a.m. the next morning. This is a common characteristic in summertime attics where moisture desorbs from wood building materials during solar heating, adding moisture into the attic air and resulting in elevated dew points that can exceed the ambient dew point. As the attic begins cooling down overnight, the dry attic wood begins to adsorb moisture from the air, and the attic air dew point drops (Cleary 1985; Fairey, Swami, and Beal 1988).
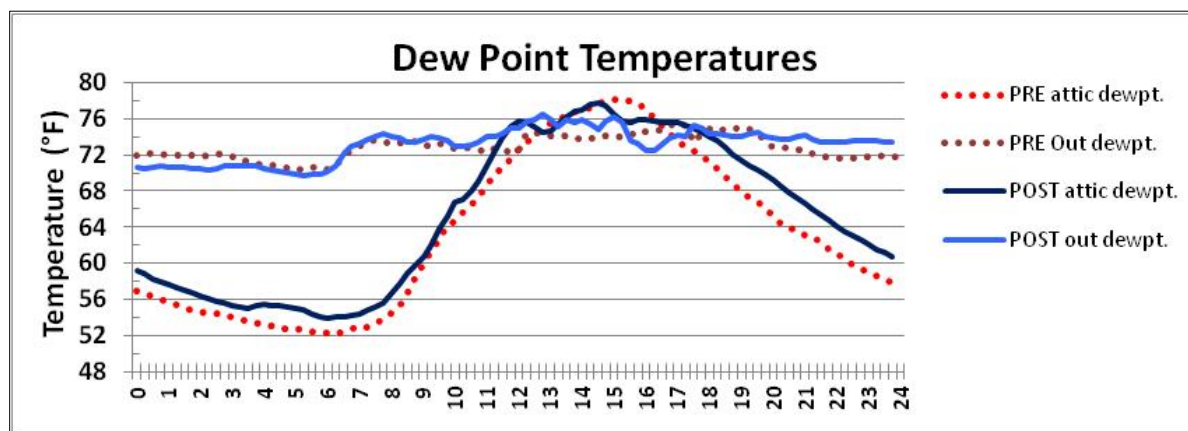

Figure 7. Outdoor and attic dew point temperatures

Figure 8 compares duct surface temperatures over a daily period. This graph clearly shows how duct surface temperature is reduced after being buried in insulation. Dotted lines represent the pre-retrofit condition, which shows higher surface temperatures than the post condition, as would be expected. The bottom surface of the duct showed an 8°F drop in temperature during peak temperatures, and the side surface location showed a 12°F decrease.
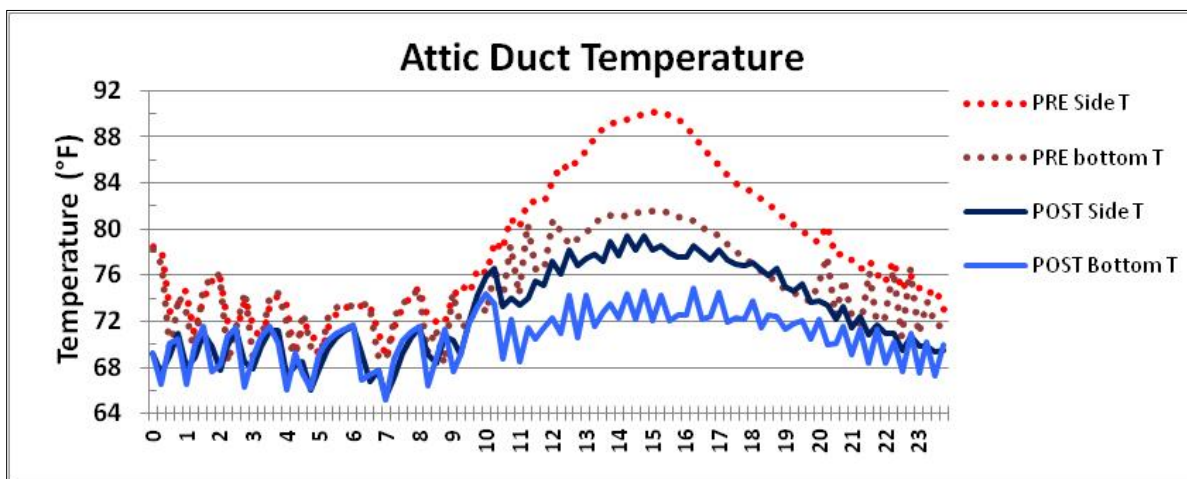

Figure 8. Pre- and post-retrofit attic duct dry bulb temperatures during similar outdoor conditions

Figure 9 shows duct surface moisture levels. Two solid horizontal lines are shown as a reference to the degree of wetness. The solid red line at the top indicates a saturated surface dripping with water. The solid blue line indicates a lesser degree of moisture with condensation present on the surface, but not dripping wet. A clear impact can be seen where adding insulation over the ducts results in greater surface moisture levels. The bottom area is coolest and shows the highest moisture levels. Gaps in the post-retrofit measured data (dashed lines) can be seen in the graph and are unexplained at the time this writing. These gaps occurred only during the post-retrofit period when moisture levels were elevated. Further research in the use of moisture-sensing strips will help establish the long-term reliability of moisture sensing tapes.
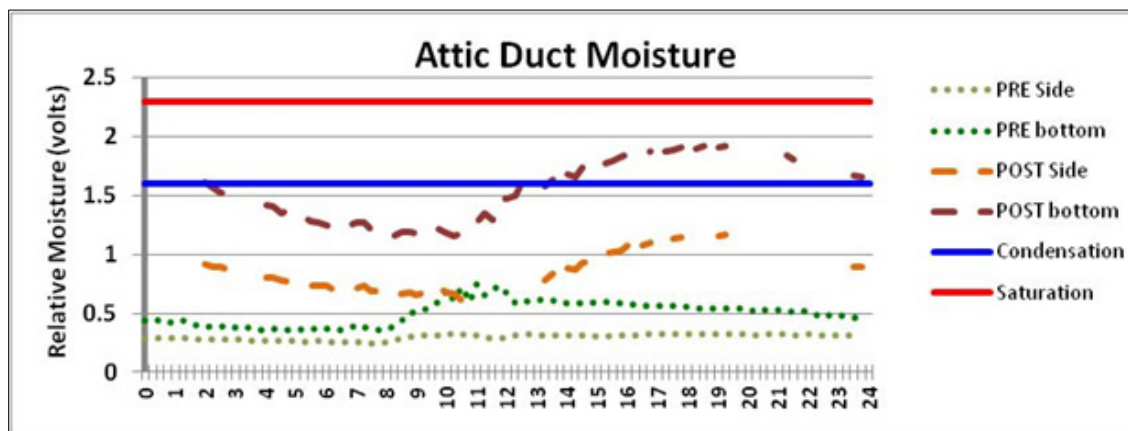

Figure 9. Pre- and post-retrofit attic duct surface moisture levels during similar outdoor conditions

Figure 10 is a 24-h plot of post-retrofit duct, attic, and outdoor conditions when dew point temperatures and A/C runtime were at their highest. This would represent a higher potential for attic duct condensation. As seen in Figure 9, the moisture sensor on the bottom duct location showed the highest potential for condensation. The daily average reading of the bottom duct location in Figure 10 is 1,929 mV. This is high enough to indicate some condensation, but not high enough to be considered saturated. A visual inspection of the ducts conducted in late fall showed no obvious signs of physical damage from accumulated moisture. Therefore, even though the moisture sensors indicate significant periods of elevated moisture during hot and humid weather, it was not enough to create any visually observable impact such as material damage or mold and mildew. As a caution, however, even though no moisture damage was observed, it might still be possible under different circumstances. As mentioned previously, a colder thermostat cooling set point will cause long runtime and colder duct surfaces. It is possible that such operation in this home could still result in enough moisture accumulation to cause moisture-related damage. Conditions will continue to be observed during the next hot and humid period.
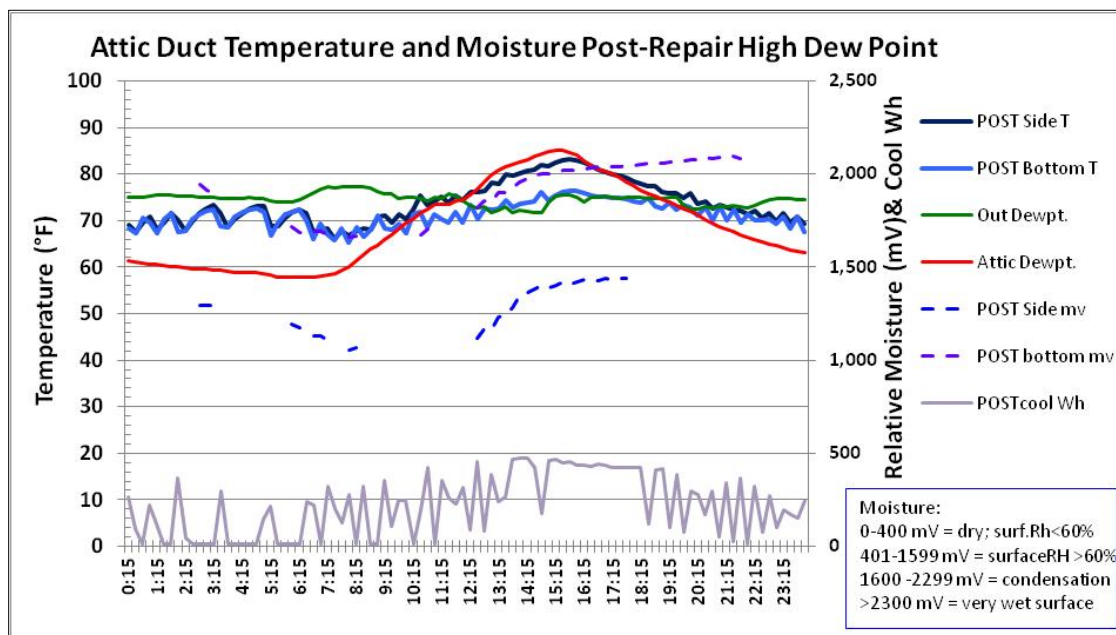

Figure 10. Post-retrofit duct conditions during worst-case dew point temperatures

5 Conclusions

This research provides a measured example of energy savings from a moderate residential retrofit in a hot-humid climate with relatively high occupancy (six persons). The retrofit measures employed are common and often cost-effective choices for older homes in need of A/C replacement and with relatively low attic insulation levels. Although homeowners can expect to benefit from reduced cooling energy costs (30% in this case), electric utilities will value the substantially reduced peak summer demand, which in this case averaged 46% for cooling only and 37% on a whole-home basis. Demand reductions during the typical utility summer window (2 p.m. to 4 p.m.) were slightly reduced at 34% for whole-building demand and 45% for A/C peak demand.

Moisture damage from condensation on attic ducts buried in blown insulation was found to be a real possibility, but the consequences from one cooling season appear to be minimal. The duct surface moisture levels increased from dry during the uncovered duct period to periods of condensation after covering the ducts with insulation from late June through September. About 45% of these days had sensor indications of duct surface condensation. After September, the outdoor dew points dropped enough to result in dry duct surfaces during air conditioning.

Although this study home did not exhibit physical evidence of moisture damage, concerns about covering attic ducts with blown insulation over the long term remain. Further study is needed to investigate how the potential moisture damage increases with vented attic and lower cooling set points. This should include additional data on duct surface condensation in the standard (unburied) condition, especially at higher dew point temperatures that were limited in this investigation. Investigation of this phenomenon at lower thermostat set point temperatures than the temperature of the study home (79°F) might reveal greater potential for damage. The study home's unvented attic may also have reduced the chance of condensation by limiting infiltration of summertime, higher dew point outside air. Additional laboratory work under controlled conditions would also yield a clearer interpretation of readings from the moisture-sensing strips, which were limited in this study to four distinct ranges.

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