FLORIDA SOLAR ENERGY CENTER®

Final Report

Residential Attic Performance Comparison Research

DBPR Project #B3EB11
UCF/FSEC #2012-7111

June 1, 2019

Submitted to:

Mo Madani
Florida Department of Business and Professional Regulation
2601 Blair Stone Road
Tallahassee, Florida 32399

Submitted by:
Charles R. Withers, Jr.
Karen Fenaughty
Jeff Sonne

1679 Clearlake Road, Cocoa, FL 32922-5703 • Phone: 321-638-1000 • Fax: 321-638-1010
www.fsec.ucf.edu

A Research Institute of the University of Central Florida

Disclaimer

Executive Summary

The primary focus of this research was to evaluate energy and moisture-related impacts between conventional attic venting and sealed attic vents in a lab home located in central Florida. All tests had R30 insulation on the ceiling and the roof deck uninsulated. Currently the attic vent sealed test configurations are not permitted by the Florida Building Code. A total of four different test configurations were tested. The four tested configurations were:

- Attic Vented with Attic Ducts (AVAD)
- Attic Vents Sealed with Attic Ducts (AVSAD)
- Attic Vented with Indoor Ducts (AVID)
- Attic Vents Sealed with Indoor Ducts (AVSID)

On average the impact from sealing attic vents will increase annual cooling energy use between 5%-10% and equate to an increased annual energy cost of approximately $25 to $54 (@$0.12/kWh). The increased cooling energy associated with the attic vents sealed was due to the attic becoming hotter primarily during the period of time with greatest amount of solar insolation upon the roof deck. This increased peak attic air temperature, and heat transfer from the attic into the conditioned space.

The potential for moisture-related concerns was evaluated through extensive measurements of temperature, RH, dewpoint temperature, as well as ceiling and roof deck moisture content. No moisture-related issues such as condensation, mold or wood rot occurred during the full course of testing of all configurations. Interior and attic ceiling surfaces were at reasonable levels of moisture, RH and dewpoint temperature under all test configurations. Attic roof deck surface conditions were much more dynamic and showed the highest levels and range of RH, and moisture content.

Building material moisture levels under all test configurations measured at hourly intervals remained under 20% wood moisture equivalent (WME), and only nearly approached this level of moisture on a few occasions for short durations. However, trends did emerge to raise caution about the potential for moisture issues to occur with sealed attic vents under colder weather conditions than experienced during the lab house test periods.

Comparisons between attic vented and attic vents sealed at different comparable weather conditions showed a clear trend of higher moisture content in roof deck and higher roof deck surface RH in attic vents sealed from warmer to cooler weather. The greatest differences between vented and sealed attic vents were observed during the coolest weather. Sealing attic vents resulted in roof deck surface RH to increase from 68% RH to 82% RH. The roof deck moisture increased from 11.5% WME up to 13% WME. These were not the highest occurring WME. These were values during comparable weather conditions to enable a fair comparison to be made. The highest hourly WME around 17% occurred during the coldest hourly temperatures. Occurrences of these happened during vented and sealed attic tests.

This research evaluation was conducted over a relatively mild central Florida winter. Given the observed trends of increased potential moisture issues at colder temperatures, further research conducted under cooler outdoor temperatures is warranted to develop a fuller expectation of potential moisture issues for the sealed vent configuration described in this report before accepting this particular sealed attic vent into Florida Building Code. The primary moisture concern is for central and north Florida. South Florida homes with R30 insulation could expect a modest increase in energy, but low likelihood of moisture issues with sealed attic vents given the warmer winter weather there.

Table of Contents

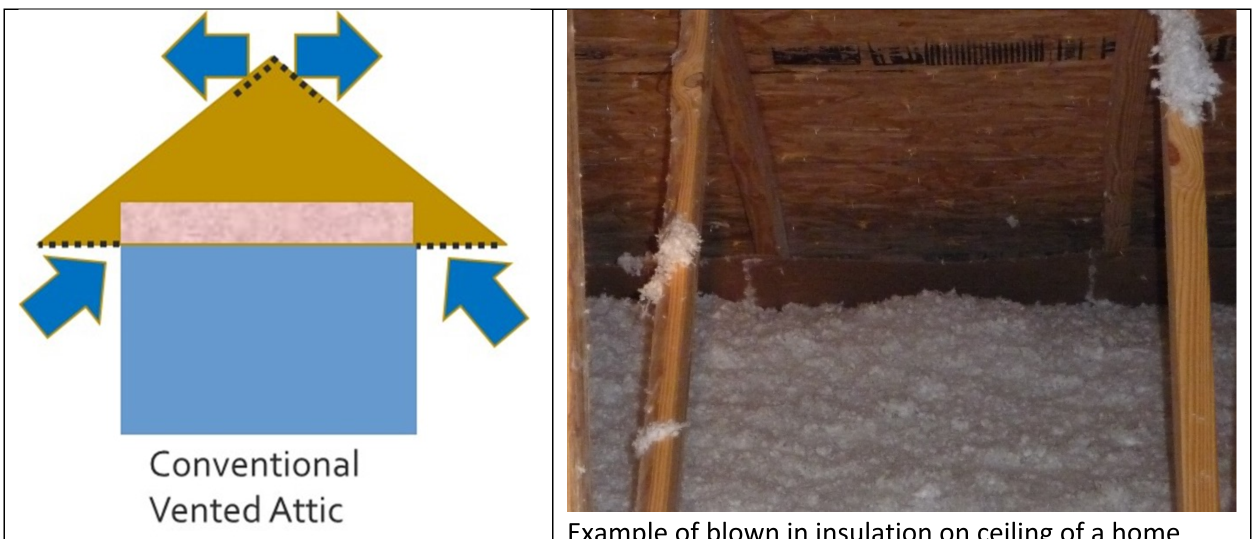
Introduction

The primary goal of this research was to determine if measureable energy savings would occur from simply eliminating attic venting in a research lab home with insulation on the ceiling plane and having no insulation applied on the roof deck. This specific practice is not acceptable in the current Florida building code. Anecdotal claims from individual homeowners taking it upon themselves to seal attic vents have claimed significant energy savings and even lower indoor humidity. One such homeowner served on the Florida Building Code Mechanical Technical Advisory Committee for years.

Another goal of this research was to determine if there were any potential beneficial or detrimental moisture issues associated with eliminating attic venting when R30 insulation remained on the ceiling and the roof deck remained uninsulated.

Building Science Digest- 102, (Lstiburek 2006) points out that attic ventilation helps keep the attic colder so that ice dams don't form from melted snow and it also helps vent moisture that comes into the attic from the conditioned space. Increased moisture in an attic increases the potential for mold or mildew on a cold roof deck. While ice dams are not a concern in Florida, north Florida does experience some prolonged periods of cold weather when attic moisture buildup may be a concern. Ventilating attics during warmer weather has been promoted to reduce attic temperature and shingle temperatures believed to help prolong shingle life, however the color and material of a roof shingle can have much more impact on the shingle temperature than venting or sealing an attic (Rose 1991), (Parker and Sherwin 1998), (Lstiburek 2006).

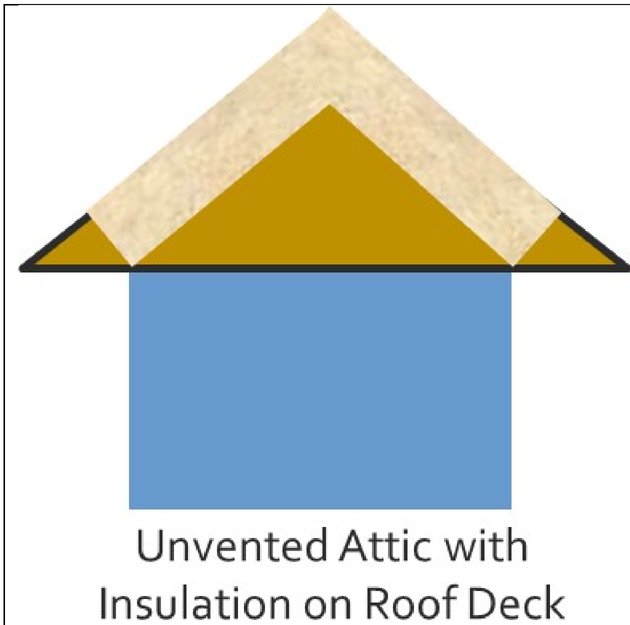
Most Florida homes have vented attics with insulation on the topside of ceiling and kneewalls. The attic is typically vented with soffit vents and ridge or off-ridge vents. Figure 1 illustrates this common attic.



Example of blown in insulation on ceiling of a home with a vented attic.

Figure 1. Illustration of vented attic concept with photo of inside attic with blown-in insulation on ceiling.

Residential Florida Building Code R806.5 currently only allows an unvented attic space that "is completely within the building thermal envelope." A common method of unvented attic compliance in homes is use a spray foam applied over the underside of roof decks continuously downward to the upper top edge of ceiling at exterior walls. An example is shown in Figure 2. This method is preferred by some since it is more likely to result in a tighter home and it minimizes the energy penalties associated with having central ducts in an attic. Properly installed, this type of unvented attic works in cold and warm climates.



Example of an off-site home with spray foam insulation on the roof deck in an unvented attic.

Figure 2. Illustration of the unvented attic concept with photo of low density spray foam application in an attic.

The Florida Department of Business and Professional Regulation (DBPR) has established a contract with the Florida Solar Energy Center (FSEC) to perform a comparative study of attic performance between a lab home with a vented attic and same home with sealed attic vents.

The contracted scope of work is summarized below in the following items:

1. FSEC shall monitor attic and space conditions of four attic/duct configurations shown in Figure 3.
2. Testing shall be completed using the FSEC Manufactured Housing Lab (MHLab). The MHLab shall be tested with existing insulation on the ceiling, with attic ducts, and with indoor ducts. Interior sensible and latent loads will be programmed on daily schedules. A central ducted SEER 13 heat pump will be used for space conditioning.
3. In the MHLab, data shall be collected by rotating the configuration of the sealing or venting of the attic and alternating the central duct location (see Figure 3). The four test configurations are:

   - Vented attic with central ducts in attic.
   - Unvented attic with central ducts in attic.
   - Vented attic with central ducts in conditioned space.
   - Unvented attic with central ducts in conditioned space.

4. Monitoring shall include:

- Space conditioning energy use.
- Interior, attic, and outdoor temperature and relative humidity.
- Ceiling heat flux measurement by thermocouple.
- Supply plenum and supply register air temperature to assess attic duct heat gain.
- Moisture content measurement in roof deck and ceiling.

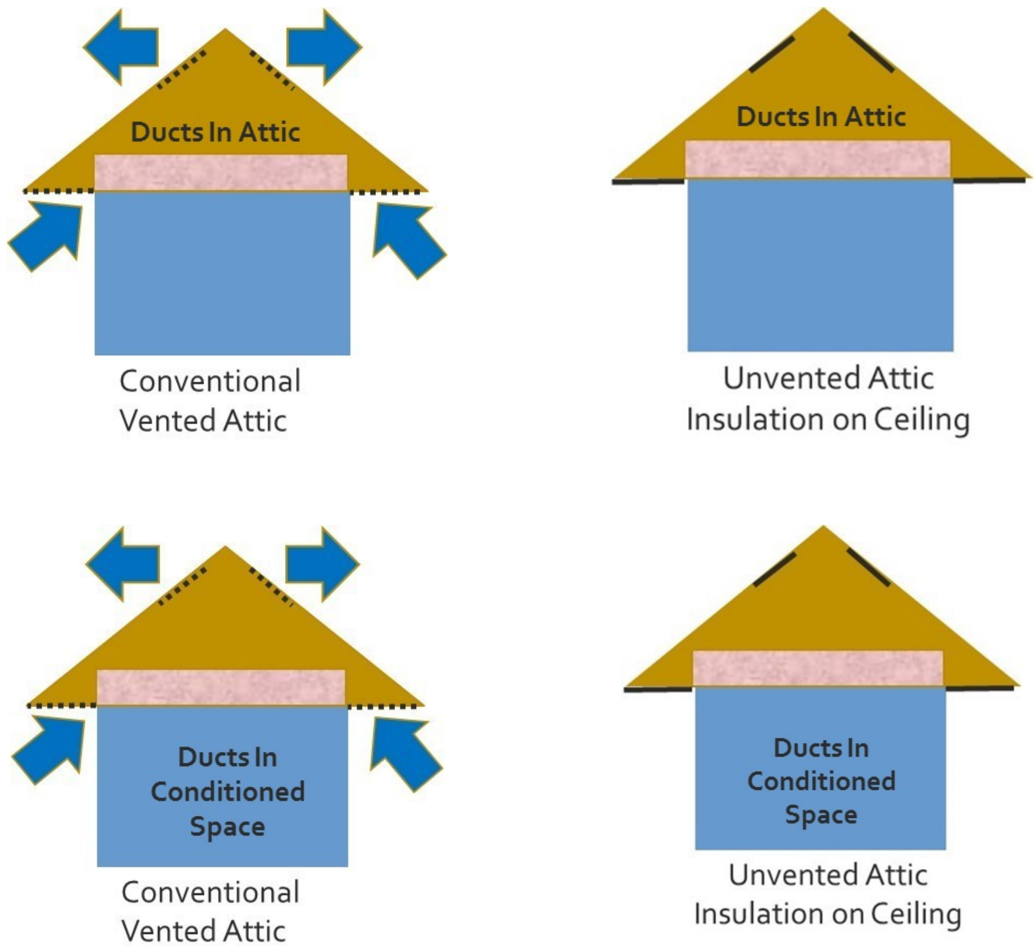


Figure 3. Illustrations showing the four test configurations to be tested in the MHLab.

This final report discusses the experimental method and preliminary results of this research project.

Experimental Method

Lab Description

This section discusses details about the test building, equipment details, and data collection procedures. All test configurations were conducted within the MHLab building located on the Florida Solar Energy Center campus. The MHLab is a 1620-ft^2 double-wide manufactured home with an unvented crawl space, R19 floor insulation, vented attic with R30 insulation on the ceiling, wood frame wall construction with R19 insulation, double-pane low-e windows, three bedrooms, and two bathrooms. The floor plan is shown in Figure 4.

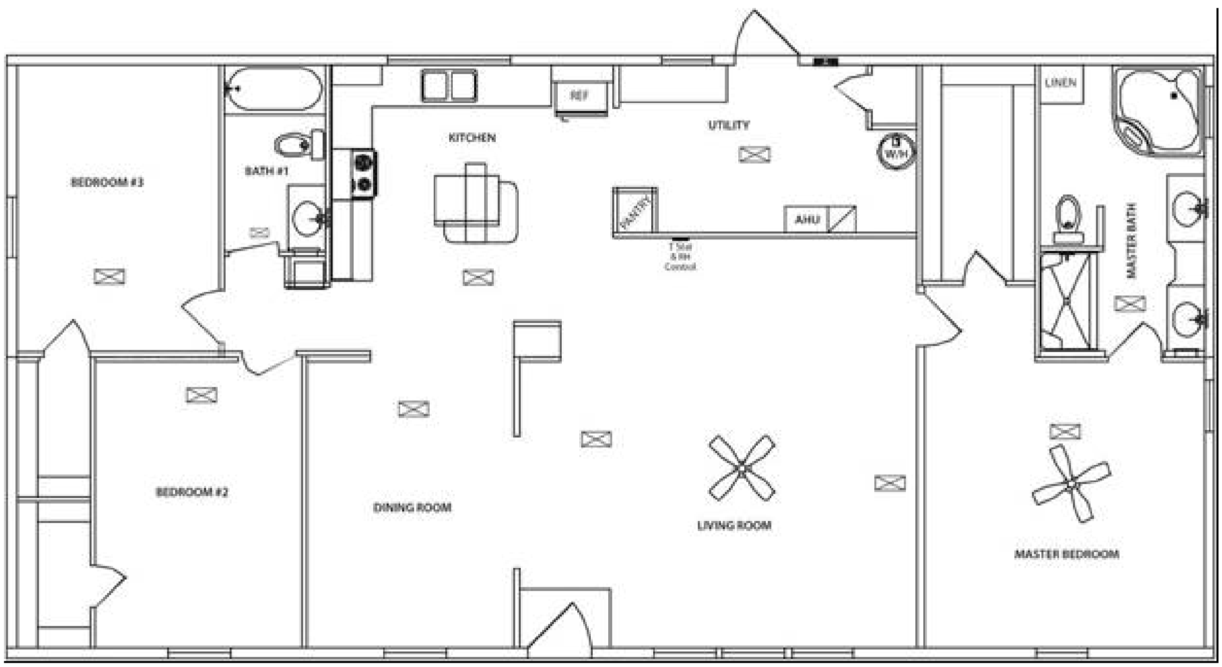


Figure 4 MHLab floorplan.

Building airtightness was tested using a blower door with the Delta Q method and measured a normalized air leakage rate of 5.4 ACH50. House tightness testing with attic venting was repeated after the attic vents were sealed and yielded no significant change. This helped verify that the ceiling plane of the lab home was reasonably tight having no significant air pathways from the conditioned space into the attic.

There was no return duct leakage. The attic supply duct leakage to outdoors was indicated to be 26 cfm with duct at 25 pascals of pressurization (CFM25out= 26). This indicates a normalized leakage (Qn) of only 0.016 cfm25 / ft^2 conditioned space, which is reasonably tight and would have negligible energy impacts.

Attic Vent Description

The MHLab attic had venting that meets 1ft^2 venting per 150 ft^2 of attic area (1:150). This venting is provided by continuous soffit vents that run around the entire roof perimeter. Five additional off-ridge vents were equally distributed on the roof deck. Polyisocyanurate board Foil-faced on both sides was used to seal soffit vents. The soffit seals were carefully installed to fit tightly against the vented surface and tightly between the exterior wall and fascia board. Vent seal boards were mechanically secured using screws and large fender washers. Each board was numbered so that they could be placed back in the exact location each time vents were re-sealed. Foil tape was also used to seal some vent areas as needed. Heavy 6 mil plastic bags and tie-straps were used to seal the upper off-ridge vents.

Figure 5. Attic soffit vented through perforations.

Figure 6. Attic soffit vents sealed.

Figure 7. Attic off-ridge vent caps sealed.

Space Conditioning Loads

Manual J8 load calculation on the tested building calculated a summer 99% design total cooling load of 1.8 tons with supply ducts in the attic. The central ducted system was a SEER13 heat pump with a nominal rated cooling output of 2.0 tons. The heat pump system was controlled by a thermostat located on an interior wall in the large open central living room area. The centrally ducted system located in the attic was primarily flex duct with an effective insulation R-value of 11.6 based upon previous testing and analysis. While this is greater than typical R6 duct insulation, the impact of this increased R value was previously determined to result in about 6% decrease in typical summer cooling energy (Withers, Cummings, and Nigusse 2014). The central ducted system located within the conditioned space had R6 insulation.

Internal loads were established using some guidance from a Building America report on internal residential loads (Fang et al. 2011), (Hendron and Engebrecht 2010). Internal cooling loads were maintained consistently throughout all experiments by keeping the building unoccupied and providing internal sensible and latent heat through controlled measures. Sensible heat was added primarily through interior heat lamps, and an oven. The interior sensible loads were monitored using power meters to ensure consistency was maintained for each experiment. The average interior sensible load target delivered per day was at a rate of about 3,398 Btu/h.

Interior latent loads were scheduled throughout the day with a daily total target of about 9 pounds per day (average rate of 619 Btu/h). Most of the latent load was produced by evaporating water from a pan in the oven. The delivered latent load was monitored throughout the project by means of tipping bucket that provided a pulse output proportional to the volume of water passing through the latent delivery assembly. Three scheduled hot showers provided additional latent each day. Shower water volume and heating energy were measured to assure consistent shower operation.

Lab Test Sensors and Data Collection

All sensors for this project were installed and verified to be in good working order. Temperature sensors measured indoor, attic as well as the inner roof deck and outer roof deck surface conditions. Humidity sensors measured outdoor, indoor and attic conditions. Power meters measured internal loads and space conditioning energy. Omnisense loggers were used to measure roof deck and ceiling moisture content as well as temperatures and RH strata. A total of six vertical profile locations were measured from the attic roof deck downward to the conditioned space.

A summary of manufacturer stated accuracy of meters and sensors are below:

- 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.
- Continental Control Systems Wattnode power meters have a manufacturer stated accuracy of +/- 1% were installed to measure 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.
- Outdoor air temperature and humidity were measured by Vaisala sensors.
- Omnisense loggers had a stated accuracy of +/- 0.5 °F, +/- 2.0% RH.

In all, 117 channels of data from sensors were collected using Campbell Scientific, Inc. CR10 dataloggers. Data was gathered several times each day from FSEC's central computer terminal. Data from sensors were sampled at 10 second intervals, then processed and stored at 15 minute intervals. Upon collection by the central computing terminal, the raw data from the datalogger 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. Ominsense logger data used for the attic to indoor vertical profile of temperature, RH, and moisture content was uploaded to an off-site data base collection system of the sensor manufacture. This data was then manually collected, screened by analysts and then stored in secured on-site data files.

Lab Test Method

Four test configuration experiments were conducted to evaluate the energy and moisture management impacts of each test configuration. Conceptual illustrations of these lab test configurations were shown previously in Figure 3. The testing configurations were as follows with an acronym sometimes used in this report:

- Attic Vented with Attic Ducts (AVAD)
- Attic Vents Sealed with Attic Ducts (AVSAD)
- Attic Vented with Indoor Ducts (AVID)
- Attic Vents Sealed with Indoor Ducts (AVSID)

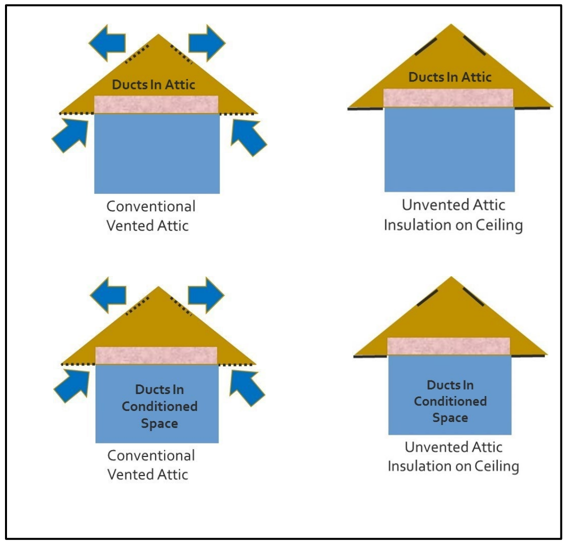


Figure 3 repeated

Testing began September 20, 2018 with vented attic and attic ducts and continued through May 27, 2019. The test configurations were rotated over time in an effort to acquire as much variation in weather conditions for each test as possible. Winter conditions were very mild during the testing periods resulting in inadequate heating season data to enable measured heating season energy impacts.

Test Results

Space Conditioning Energy

The space conditioning energy use impacts of the four different test configurations were evaluated. The evaluation covered data collected from September 20, 2018 through May 27, 2019. The measured daily total cooling energy use was plotted against the daily average temperature difference (dT) between outdoors and indoors. Days during transition from one test to another or from other test interruptions such as equipment calibration or repair were screened out of the analysis data set. Using dT enabled the ability to predict energy use at specific indoor and outdoor temperatures other than what had occurred during test conditions, such as with a Typical Meteorological Year (TMY3) weather data set.

Data from all four test configurations are shown together in Figure 8. Attic duct configurations use square markers, indoor ducts use circles. Vented attic configuration data is marked using open markers and unvented attic data uses filled in markers. Figure 8 includes days with cooling and heating energy use. Cooling energy ceased with daily average dT at about - 15°F (average outside temperature about 61°F). The data shows that there was too little heating data to be able to evaluate heating energy. This was due to very mild winter weather conditions that occurred during the testing periods.

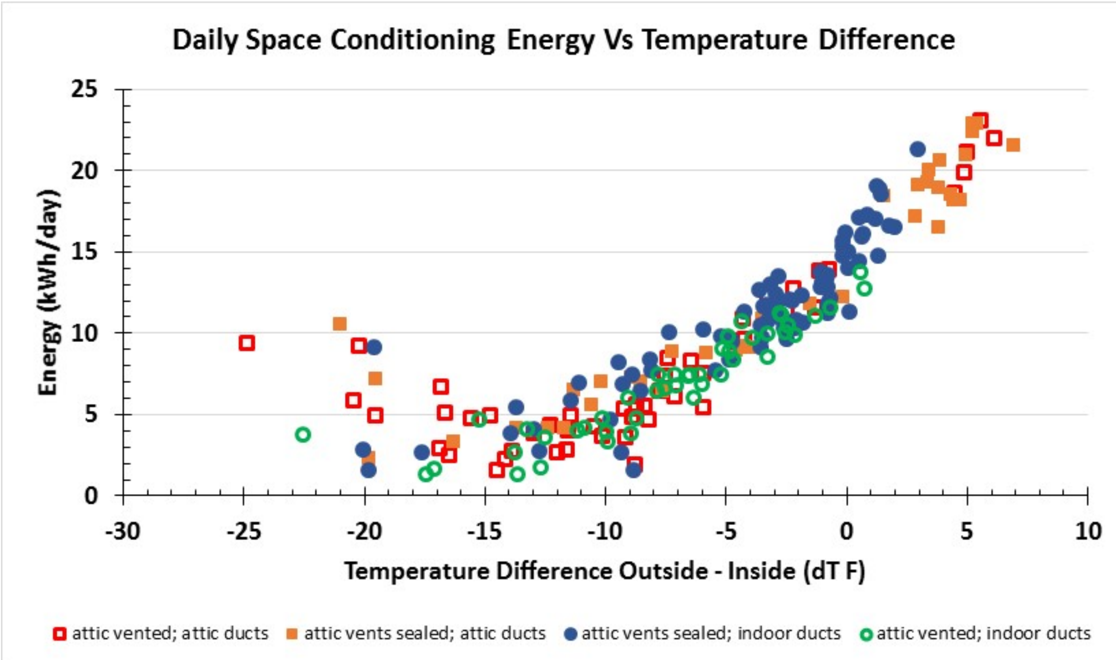


Figure 8. Daily energy data for all four test configurations over the full range of available dT.

Cooling energy analysis was performed for all test configurations limited dT greater than or equal to -15°F.

Figure 9 shows cooling energy with attic ducts in vented attic and also in attic with sealed vents with the least-squares linear regression analysis results.

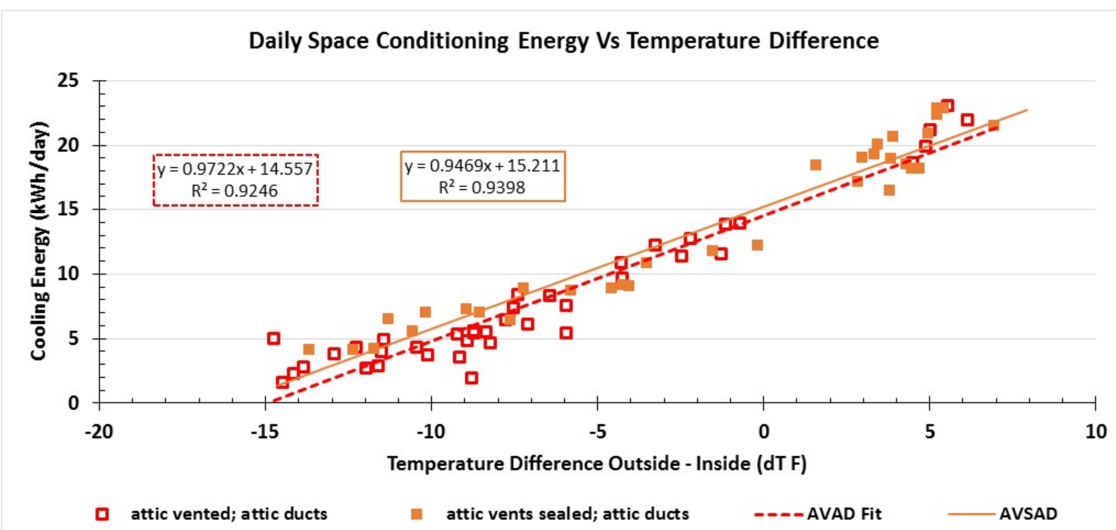


Figure 9. Cooling energy versus dT with attic ducts in the vented and unvented attic test configurations.

Figure 10 shows cooling energy with indoor ducts in vented attic and also in attic with sealed vents with the least-squares linear regression analysis results.

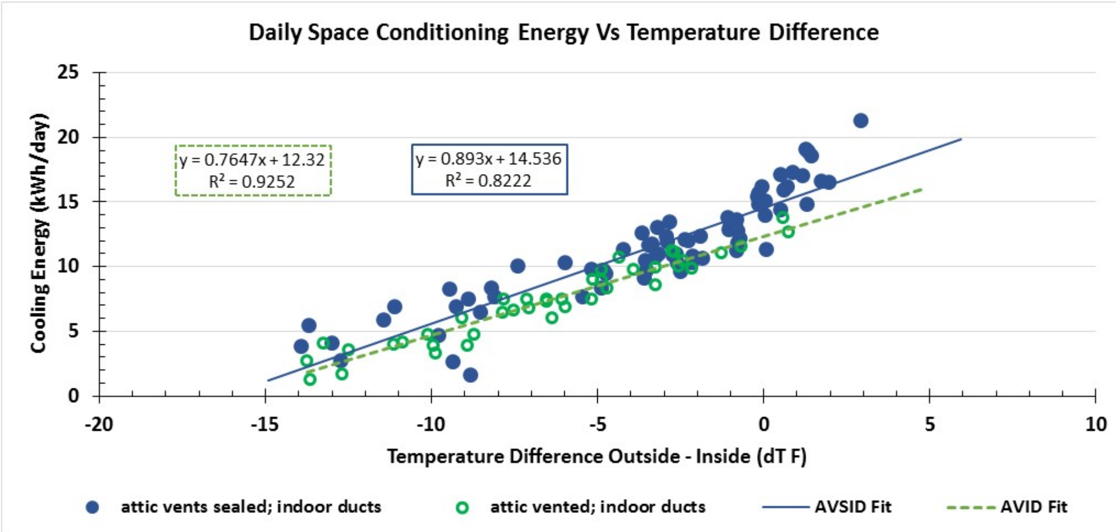


Figure 10. Cooling energy versus dT with Indoor ducts in the vented and unvented attic test configurations.

Predicted Annual Cooling Energy Impacts

The final regression equations from all tests were used with Typical Meteorological Year 3 (TMY3) outdoor temperature to predict an annual cooling energy use. Annual predictions were made for Florida cities of Miami, Orlando and Jacksonville. An indoor cooling setpoint of 75°F was used for indoor temperature. The 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.

The results for all four tests have been arranged to show comparison of the annual energy in two different ways. The first comparison shows the attic vent sealed configurations compared to attic vented configurations. A second comparison shows each configuration compared to attic vented with attic ducts, since this is the most common arrangement in most homes in Florida.

The results of the first comparison of attic sealed configurations compared to attic vented configurations are shown in Table 1. There were only modest differences between cities. The average results are shown in Table 2.

The acronyms used in the tables are as follows:

AVAD- attic vented with attic duct,
AVSAD- attic vents sealed with attic duct,
AVID- attic vented with indoor ducts,
AVSID- attic vents sealed with indoor ducts.

The average results show that sealing the attic clearly increased annual cooling energy. Sealing the attic with attic ducts would increase annual energy use by 211 kWh (5%) which represents about $25 increase in cooling energy costs (@$0.12/kWh). Sealing the attic in the lab home with ducts in conditioned space would increase annual energy use by 687 kWh (18%) which represents about $82 increase in cooling energy costs.

The attic vented with indoor duct (AVID) had the lowest predicted annual cooling energy use. This configuration also did not have measured energy use on days as warm as the other configurations. This was due to project contract final report required just as very warm weather began. It is likely that the projected energy use at warmer temperatures could be greater than the extrapolated result indicates. If so, the predicted energy use for AVID would be somewhat higher and the indicated differences from the references would be less. It is still expected that AVID would use less energy than the references. A previous project (Cummings et al. 2013) using this same cooling system and lab with vented attic found that moving the ducts indoors had a predicted annual Florida cooling energy decrease of 10.5%. A recent energy simulation using EnergyGuage USA with the house lab qualities was run with all ducts in attic, and all ducts indoors. The annual cooling energy difference indicated for a vented attic was 397 kWh (8.8%) difference. The simulation predicted nearly identical increased annual cooling energy from sealing the attic no matter whether the ducts were in the attic or in conditioned space.

Therefore we estimate that sealing attic vents will increase annual cooling energy use between 5%-10% and equate to an increased annual energy cost of approximately $25 to $54.

Table 1. Predicted Annual Cooling Energy at Three Cities Comparing Attic Vent Sealed to Attic Vented

Miami				
	AVAD	AVSAD	AVID	AVSID
Annual kWh	5744	5959	4825	5687
Delta kWh	0	215	0	862
Delta %	0	3.7%	0.0%	17.9%
Orlando				
	AVAD	AVSAD	AVID	AVSID
Annual kWh	4264	4485	3634	4291
Delta kWh	0	222	0	658
Delta %	0	5.2%	0.0%	18.1%
Jacksonville				
	AVAD	AVSAD	AVID	AVSID
Annual kWh	3488	3683	2984	3526
Delta kWh	0	195	0	542
Delta %	0	5.6%	0.0%	18.2%

Table 2. Average Predicted Annual Cooling Energy Comparing Attic Vent Sealed to Attic Vented

	Average Three Florida Cities			
	AVAD	AVSAD	AVID	AVSID
Annual kWh	4498	4709	3814	4502
Delta kWh	0	211	0	687
Delta %	0	4.7%	0.0%	18.0%

The second annual cooling energy evaluation compared all other configurations to AVAD for three cities with results shown in Table 3. There were only modest differences between cities. The average results are shown in Table 4. An attic vent sealed with indoor ducts (AVSID) had about the same impact as AVAD. Comparison among cities shows that AVSAD increased modestly from southeast to northeast Florida. Attic vented with interior ducts (AVID) savings were the greatest savings observed for all cities, and there was a modest decreasing trend in savings from southeast to northeast Florida.

Table 3. Predicted Annual Cooling Energy at Three Cities Compared to AVAD

Miami				
	AVAD	AVSAD	AVID	AVSID
Annual kWh	5744	5959	4825	5687
Delta kWh	0	215	-919	-57
Delta %	0	3.7%	-16.0%	-1.0%
Orlando				
	AVAD	AVSAD	AVID	AVSID
Annual kWh	4264	4485	3634	4291
Delta kWh	0	222	-630	28
Delta %	0	5.2%	-14.8%	0.7%
Jacksonville				
	AVAD	AVSAD	AVID	AVSID
Annual kWh	3488	3683	2984	3526
Delta kWh	0	195	-503	39
Delta %	0	5.6%	-14.4%	1.1%

Table 4. Average Predicted Annual Cooling Energy Compared to AVAD

	Average Three Florida Cities			
	AVAD	AVSAD	AVID	AVSID
Annual kWh	4498	4709	3814	4502
Delta kWh	0	211	-684	3
Delta %	0	4.7%	-15.2%	0.1%

Space Condition Comparisons between Vented and Sealed Attic During Hot and Humid Weather

Table 5 shows a comparison of measured data between the attic duct configurations with and without attic vents during similar hot and humid weather. It can be seen via the outdoor air temperature (Out T), outdoor dewpoint temperature (Out T dp) and horizontal solar insolation (Solar) that the weather conditions are very similar for the 4-5 days selected. The average indoor 5-room air temperatures (In T 5 rm avg.) were the same for the comparison period. The data shows that that the unvented attic (Attic T) was about 2.4 degrees °F warmer on average. An increase in attic air temperature would be expected during the hottest time of day due to decreased ventilation when roof deck radiant temperatures are highest. The attic dewpoint (Attic T dp) decreased by 6.7 °F. Some drop in attic dewpoint would be expected as the ventilation rate of moist outside air decreased after sealing vents.

Table 5. Comparison of Daily Average Interior Temperature and RH During Similar Hot Humid Outdoor Weather Conditions

Test Condition	Out T (°F)	Out T dp (°F)	Solar (kWh/m^2)	In T 5 rm avg. (°F)	In RH (%)	In T dp (°F)	Attic T (°F)	Attic T dp (°F)	# days avg.
Vented Attic and Attic Duct	82.1	71.3	19.7	77.1	46.6	55.1	87.5	65.7	4
Sealed Attic and Attic Duct	82.2	72.1	19.7	77.1	45.3	54.3	89.9	59.0	5
Difference from Sealed Attic to Vented Attic	0.1	0.8	0.0	0.0	-1.2	-0.8	2.4	-6.7	1

The decrease in interior humidity (In RH) and dewpoint (In T dp) are improvements in comfort-related metrics noticed with the sealed attic vents. However, this occurred due to an increase in cooling energy. Table 6 shows the daily average cooling energy (Cool), runtime (Runtime hours), and supply air temperature (Supply Air T) for the same set of days in Table 5. Cooling energy increased by 3.9% in this small sample of days. An increase in runtime would remove additional moisture by the air conditioning. The supply air temperature was practically the same during both tests and interior drybulb air also remained the same. There was no change in cooling system performance that can explain the increased energy and lower RH of the sealed attic.

Table 6. Comparison of Daily Average Cooling Performance During Similar Hot Humid Outdoor Weather Conditions

Test Condition	Out T (°F)	Out T dp (°F)	Solar (kWh/m^2)	Cool kWh/day	Runtime Hours	Supply Air T (°F)	# days avg.
Vented Attic and Attic Duct	82.1	71.3	19.7	20.6	12.5	56.5	4
Sealed Attic and Attic Duct	82.2	72.1	19.7	21.4	13.1	56.4	5
Difference from Sealed Attic to Vented Attic	0.1	0.8	0.0	0.8 (+3.9%)	0.6	-0.1	1

Ceiling Heat Flux Evaluation

In attic studies such as this one it is also useful to consider ceiling heat flux (the rate of heat flow between the attic space and conditioned space across the ceiling). For this study ceiling heat flux was calculated using vertically inline top of ceiling insulation and underside of ceiling surface temperature measurements in an area with no material in the attic airspace between the top of insulation and bottom of roof deck. Figure 15 shows an illustration of the arrangement and location of temperature sensors. The temperature difference across the insulation and ceiling was multiplied by the inverse of the ceiling insulation R-value (R30) to calculate heat flux (in $Btu/ft^2/hr$). Heat flux analysis focused on the ducts in the attic lab configuration. The ceiling heat flux would not be impacted by duct location.

The ceiling heat flux was compared during a typical warm weather day and also during a cooler weather day during minimal cooling loads.

Warm Weather Heat Flux Comparison

Heat flux comparisons used weather-matched attic vented and attic vents sealed days, which required both similar outdoor air temperatures and solar insolation. For the warm weather heat flux comparison, September 24, 2018 and October 15, 2018 provided adequately matched attic vented and attic vents sealed weather conditions, respectively. Figure 11 shows the outdoor air temperature and horizontal solar insolation for each comparison day.

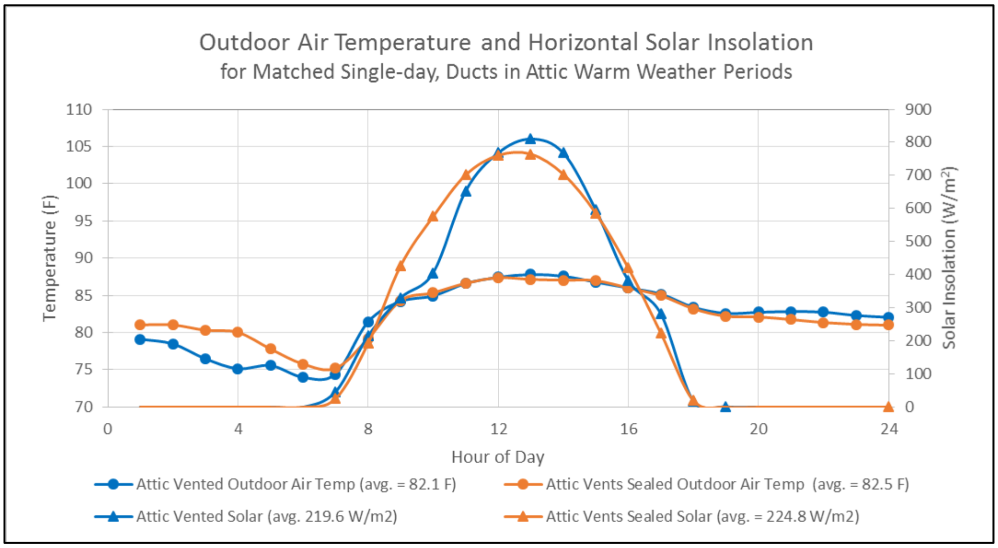


Figure 11. Outdoor air temperature and solar insolation for warm weather ducts in attic heat flux comparison.

The matched single-day, warm weather ceiling heat flux plot for the ducts in attic lab configuration is shown in Figure 12.

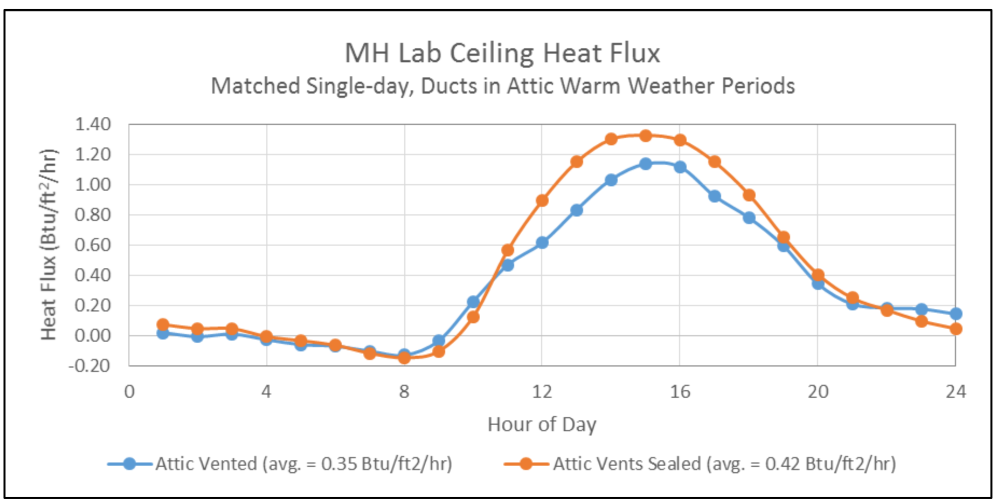


Figure 12. MH lab ceiling heat flux for matched single-day warm weather periods with attic ducts.

While the attic vents sealed configuration heat flux is lower than the attic vented configuration flux for several nighttime and morning hours, for most hours and on average heat flux is higher with the attic vents sealed. This overall result is consistent with the energy use findings of this study described above which showed slightly higher energy use for the attic vents sealed configuration.

Cool Weather Heat Flux Comparison

Cool weather heat flux comparisons again used weather-matched attic vented and attic vents sealed days. For the cool weather heat flux comparison, January 15, 2019 and December 22, 2018 provided the closest available matched attic vented and attic vents sealed weather conditions, respectively. Figure 13 shows the outdoor air temperature and horizontal solar insolation for each comparison day.

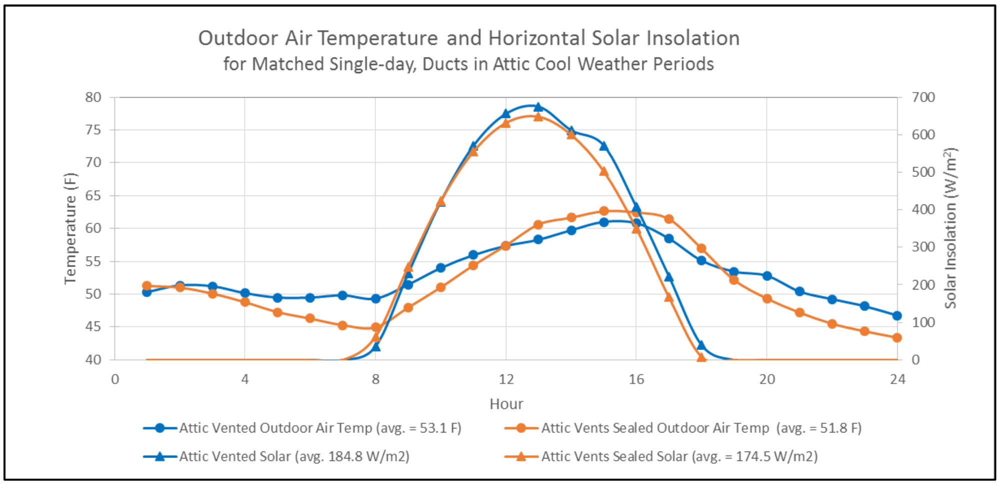


Figure 13. Outdoor air temperature and solar insolation for cool weather ducts in attic heat flux comparison.

The matched single-day, cool weather ceiling heat flux plot for the ducts in attic lab configuration is shown in Figure 14.

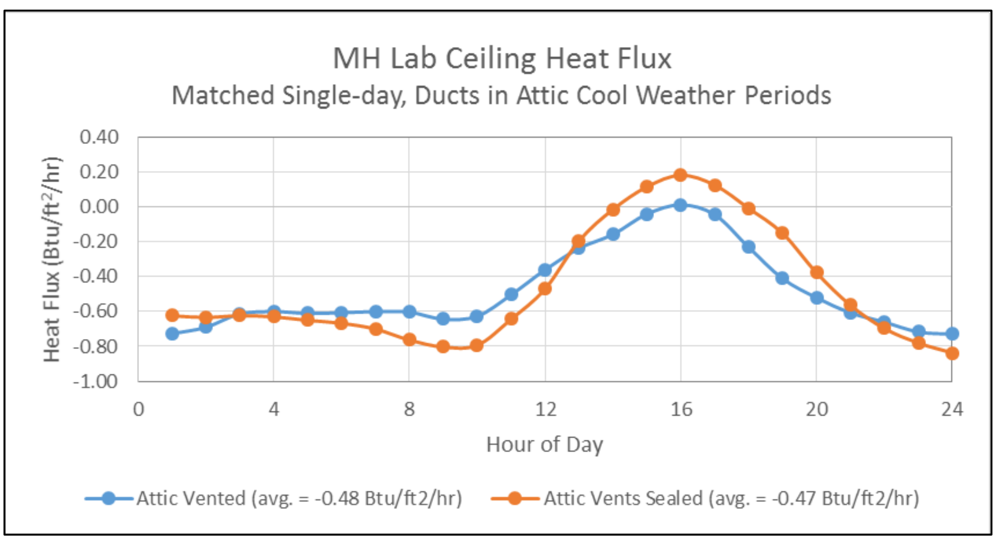


Figure 14. MH lab ceiling heat flux for matched single-day cool weather periods with attic ducts.

Notice that the heat flux for the cool weather comparison is largely negative, meaning that heat flow is mainly from the conditioned space to the attic. The average attic vents sealed configuration heat flux is approximately same as the average attic vented configuration flux, but afternoon and evening heat flux is again higher with the attic vents sealed, and includes some attic to conditioned space heat transfer which does not occur with the attic vented configuration.

The ceiling heat flux comparisons show that the sealed attic vent configuration has higher heat flux than the vented attic during the peak solar period of each type of day. This supports the measured cooling energy results that found that sealed attic vent tests used more cooling energy than the vented attic tests.

Building Materials Moisture Evaluation

Poor moisture control is the most serious concern as it can contribute to increased potential for occupant health and building degradation issues. This research project measured temperature, RH, dewpoint temperature and moisture content of attic roof deck and gypsum ceiling to observe if any detrimental impacts occurred during the testing. Specific concerns evaluated if material moisture levels within the attic were sustained at high enough levels and duration to potentially cause damage. Other concerns were whether surface RH was sustained at high enough levels and duration to potentially cause mold or mildew growth. A third concern was whether surface temperature was maintained at or below dewpoint for sustained periods to allow condensation.

A detailed profile evaluation of attic roof deck, gypsum ceiling surface boundaries, and air conditions was made using data from Omnisense sensors. Temperature, RH, Dewpoint and material moisture content sensors were placed in a vertical arrangement in one representative area of the attic over the master bedroom. These temperature and RH sensors were placed at 6 different heights. The locations from lowest to highest location were:

1) in room air mid-way between floor and ceiling
2) at the interior side of the gypsum board ceiling
3) on top of the gypsum board (and under insulation) in attic
4) on the top surface of insulation,
5) mid-way in attic air between insulation and roof deck,
6) at the underside of the wood roof deck.

Figure 15 shows an illustration of the Omnisense sensor layout arrangement at the red dots.

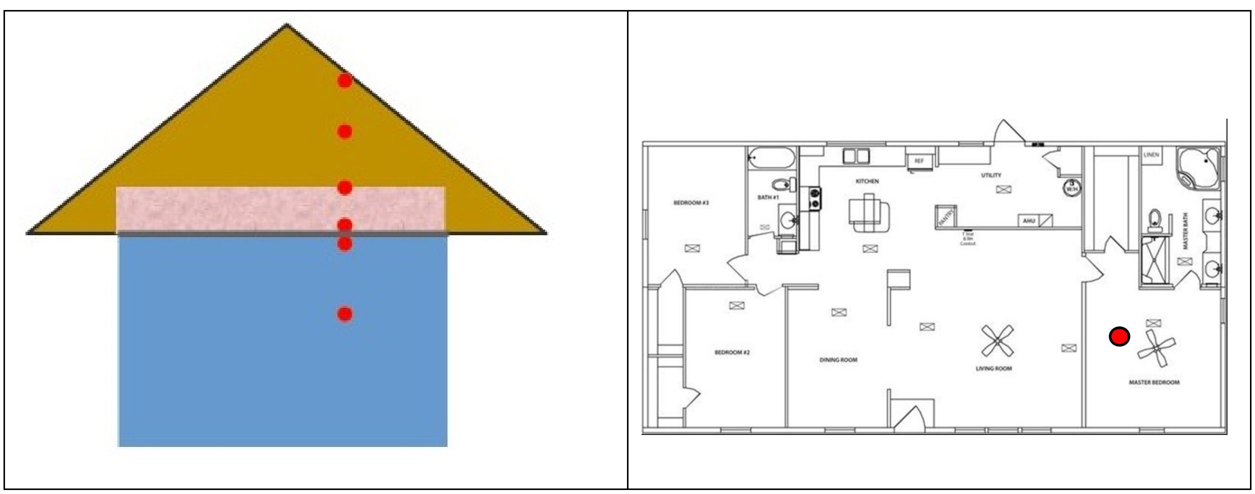


Figure 15. Illustration of the location of vertically arranged temperature, RH and moisture sensors.

The moisture content of a material is a relative measurement indicating the percent of moisture mass in a material. Figure 16 shows the direct relationship between wood moisture content (WMC) and relative humidity. In general, prolonged WMC values exceeding 20% indicate a significantly elevated level of wood moisture, and can result in development of surface molds. WMC values exceeding 28%-30% indicate potential for decay fungi growth to occur that could damage the structural integrity of the wood deck if occurring over prolonged periods without adequate drying cycles. Figure 16 only applies to equilibrium conditions when the RH is unchanged. In reality, the RH swings drastically up and down in an attic resulting in moisture content changes that follow a diurnal pattern.

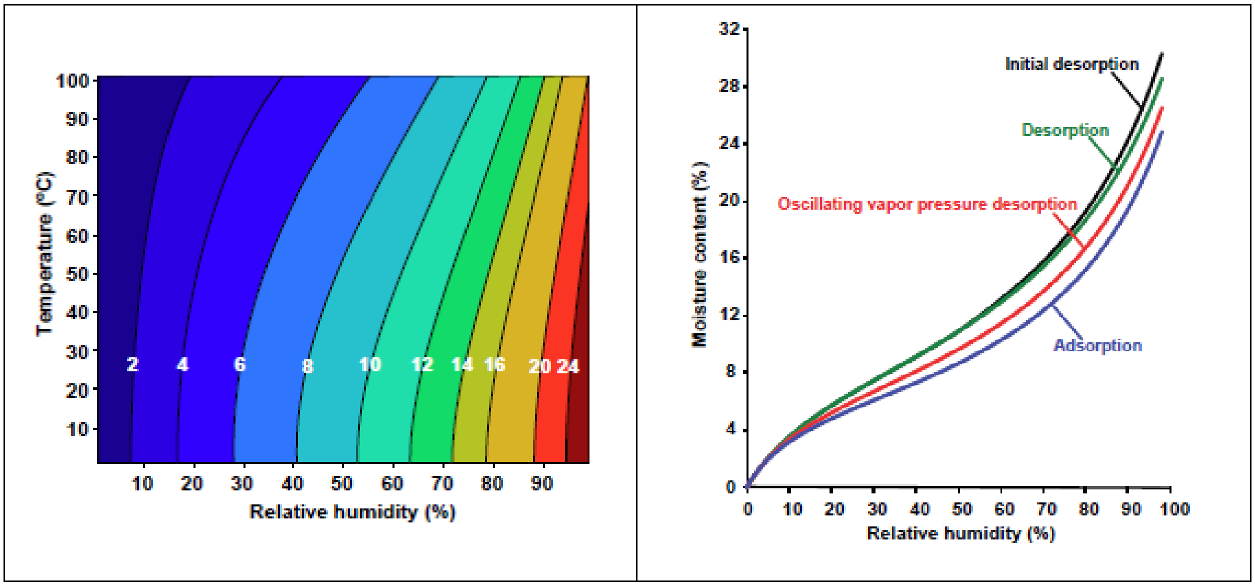


Figure 16. Relationship between equilibrium moisture content of wood and relative humidity (Forest Products Laboratory, 2010).

The term wood moisture equivalent (WME) % is used with the Omnisense sensors. It is indicative of percent of moisture in wood. Although the gypsum board is not wood, the WME % can still be used to indicate if the gypsum ceiling board was becoming too moist using a value of 20% or greater. So while the reading in gypsum may not reflect the true percent moisture content in gypsum, it is scalable and is adequate to determine if a material is becoming too moist. The gypsum would have an actual moisture content of about 0.7% when the WME% reads 20%. Periodic measurements were made using a hand-held Delmorst moisture meter with scales for wood and gypsum to independently verify that materials were not becoming too moist.

For this project, hourly WME% data were collected at three surface locations:

1) at the interior side of the gypsum board ceiling (Indoor Ceiling)
2) on top of the gypsum board (and under insulation) in attic (Attic Ceiling)
3) at the underside of the wood roof deck (Roof Deck).

Figure 17 is a plot of the hourly sensor readings at all three locations over the course of the project. The red vertical lines indicate the different test configurations (changing duct locations and attic venting) which typically required two days to transition between. The attic duct test configurations (AVAD and AVSAD) are labeled in red, with an underline indicating sealed attic vent configuration, and interior duct test configurations (AVID and AVSID) are labeled in blue, with an underline indicating sealed attic vents.

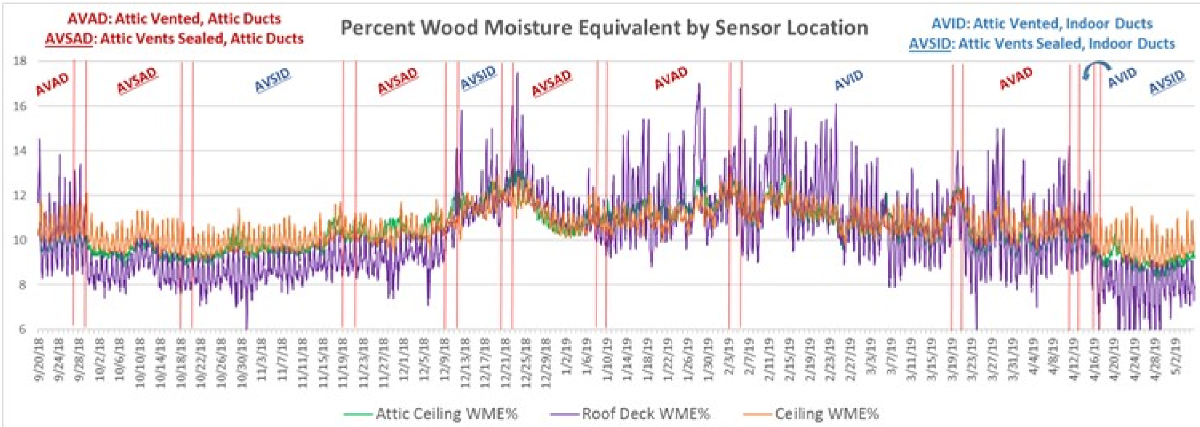


Figure 17. Hourly Wood Moisture Equivalent at three locations.

The plot shows some shifts in WME% after configuration changes; however, ambient conditions are needed for any comparison between configurations which we will look at later. One clear take-away from this plot is that under the tested weather conditions, material moisture was at reasonable levels for all tests. Another obvious observation was that the roof deck moisture (purple) had the highest and widest range in values. The moisture levels on each side of the ceiling were reasonably dry through all tests. Because of this, we focused our moisture evaluation on the roof deck sensor. Also noteworthy is that while the WME does spike toward 20%, the moisture level never rose to dangerous levels in the lab house and the peaks were short-lived. The highest moisture values consistently occurred in the cooler months.

One general trend occurred regardless of test configuration. As an example refer to Figure 18 and focus on WME (red), roof deck temperature (green), and roof deck RH (brown). Starting at midnight the roof deck continues cooling and may even become cooler than the outdoor ambient temperature due to radiative cooling to the atmosphere. The roof deck inside the attic also becomes cooler and the surface RH increases. As the roof deck surface RH increases, the wood roof deck adsorbs moisture and the WME increases. At sunrise, the sun begins heating the roof deck surface that increases temperature and lowers the surface RH. As the surface RH drops moisture is driven out of the roof deck and WME decreases. As the sun sets the roof deck begins cooling and the cycle repeats itself. While the cycle is a diurnal one, the magnitude of change in WME largely depends upon how warm the deck becomes and how much it cools down.

Elevated Periods of Roof Deck Moisture

Figure 17 showed some occurrences of elevated moisture at the roof deck. For each test configuration, the peak WME% was examined for a representative four-day period with similar outdoor and attic conditions during relatively cool weather when the highest WME were typically observed. This magnification shows the diurnal cycle of the moisture content which typically peaks in the morning following the lowest outdoor temperatures. The roof deck moisture quickly dropped over a few hours as the roof was heated by the sun and deck temperature increased. The highest WME measured was 17.5% and was during the Attic Vents Sealed with Attic Ducts and shown in Figure 18. A vertical purple dashed line points out the period in Figure 18 with the highest WME (red line). This peak increased from about 12.5% up to 17.5% during a period of about 15 hours when cool outdoor temperatures that remained below 45 °F (light blue line) for about 10 hours. The roof deck RH increased from about 66%

up to 95% (brown line) when WME peaked at 17.5%. The WME% peaks drop successively in the following two days as the outdoor morning low temperature became warmer each successive day.

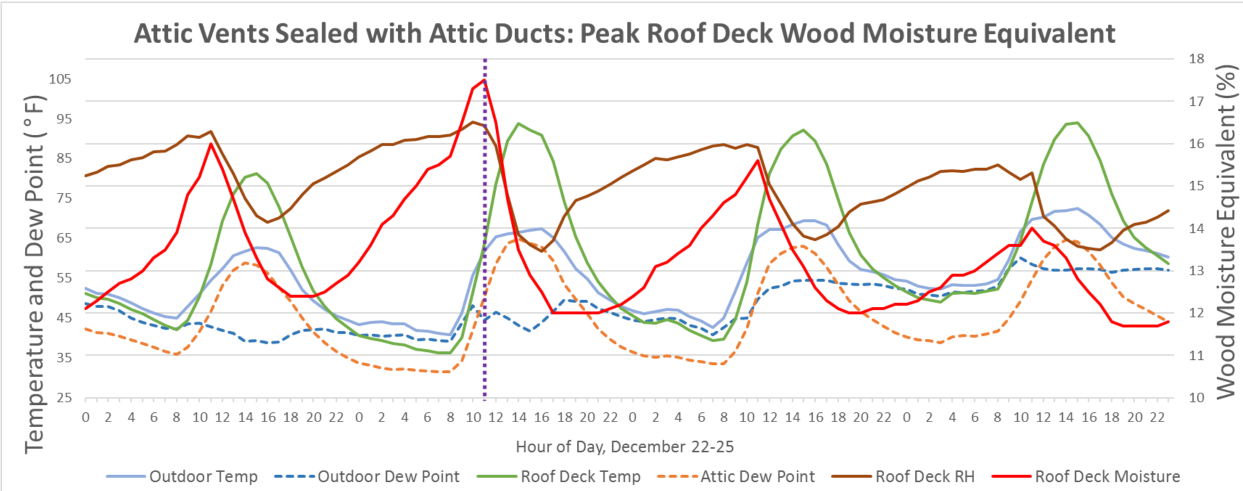


Figure 18. Peak Roof Deck Wood Moisture Equivalent for Attic Vents Sealed with Attic Ducts Configuration.

The highest WME for the Attic Vented with Attic Ducts configuration, plotted in Figure 19, occurred on January 28th and was 17% -- nearly as high as the peak observed during the sealed configuration. One notable difference is that January 27th and early 28th received very low solar insolation. With very little solar heating, the roof deck never warmed up and the roof deck RH stayed higher for a longer period of time than a normal sunny day. These conditions helped to push the attic RH to a sustained 85% plus for an unusually long period of time. The following days show the WME begin to drop as the roof deck morning low temperature increased.

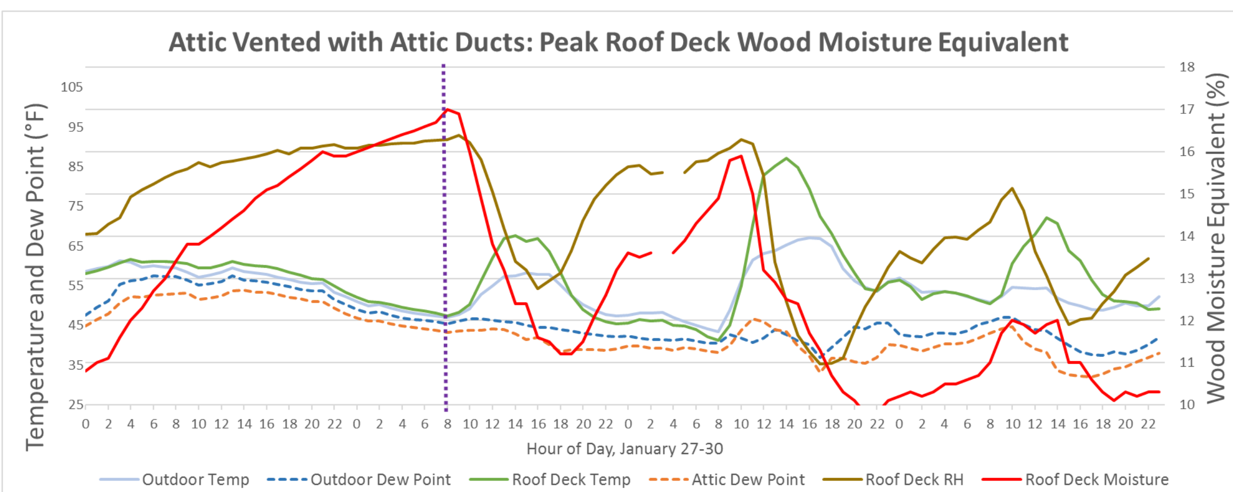


Figure 19. Peak Roof Deck Wood Moisture Equivalent for Attic Vented with Attic Ducts Configuration.

As shown in Figures 20 and 21, peak WME for the interior duct configurations were nearly as high as the peak in the other configurations, each about 16%, and again follow periods of lower outdoor temperatures and high roof deck RH. The peak WME occurred December 12th for the Attic Vents Sealed with Interior Ducts and on February 5th for the Attic Vented with Interior Ducts. The highest peak WME dropped in subsequent days as the low morning roof deck temperature increased just as was observed in the previous WME graphs.

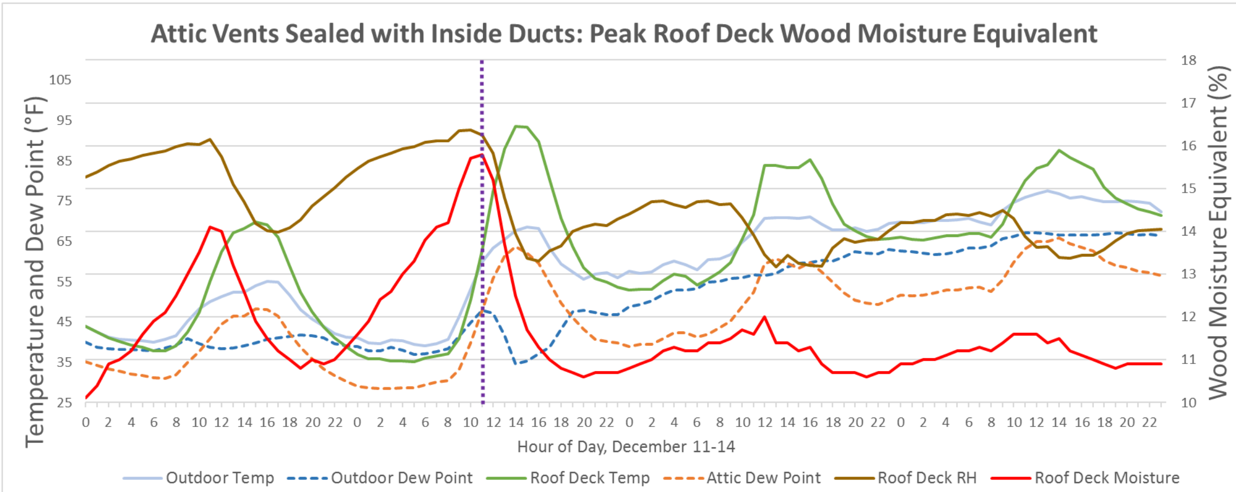


Figure 20. Peak Roof Deck Wood Moisture Equivalent for Attic Vents Sealed with Interior Ducts Configuration.

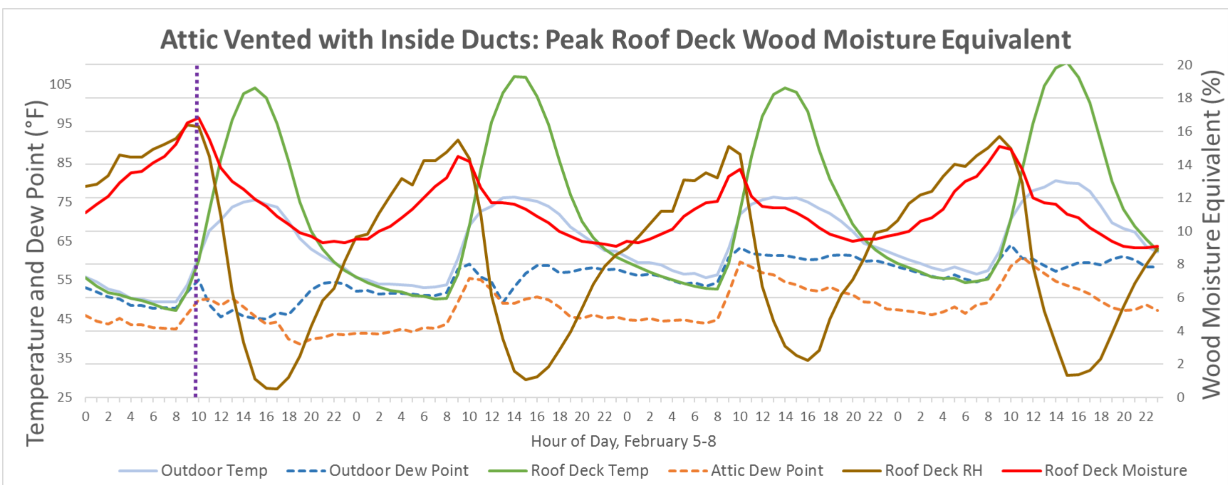


Figure 21. Peak Roof Deck Wood Moisture Equivalent for Attic Vented with Interior Ducts Configuration.

Figure 17 showed that all WME were low during October into December and the again by mid-April. Figures 18-21 illustrate that the highest roof moisture events coincide with the highest roof deck RH which also coincides within hours following the coolest roof deck temperatures. These figures focused on the periods when the highest roof deck WME occurred, however, these were not high enough for long enough duration to be of concern about moisture related issues at the roof deck under the weather conditions experienced during the lab house tests.

Attic and Ceiling Moisture Comparisons

To allow for further attic and ceiling comparisons among test configurations, groups of days with similar weather were evaluated under three different weather conditions: Hot Humid, Mild, and Cool. The days chosen for each of these three weather conditions are profiled in Appendix A where we highlight the similarity in outdoor temperatures, outdoor dew points, solar insolation, and rainfall.

Attic and ceiling moisture comparisons were based upon measured dew point, RH, temperature, and WME of the Omnisense surface measurements at the interior ceiling, attic ceiling, and the roof deck. The following evaluations compare Attic Vented with Attic Vents Sealed. Not all four test configurations had test data during the each representative weather condition so some comparisons only have two tests. This was not significant since duct location did not impact the attic and ceiling moisture conditions. The ducts were reasonably airtight and very well insulated. The values shown represent averages over the period indicated.

Looking at the Hot Humid condition first, the Attic Vents Sealed with Attic Ducts are compared to the Attic Vented with Attic Ducts. The Hot Humid period, which represents conditions during a significant part of a year in Florida, include days with average daily temperatures between 80°F and 84°F. The average temperature, dew point, and RH for each test condition are plotted in Figure 22. The X-axis is subdivided by each sensor location: Ceiling, Attic Ceiling, and Roof Deck. Temperatures differences are nearly identical between test configurations at the different sensor locations. The RH and dew points are slightly higher in the Attic Vented configuration, especially at the roof deck. This is expected with the vented attic within which high outdoor moisture can more readily enter. The interior ceiling surface conditions for both configurations are nearly identical and close to the room air conditions.

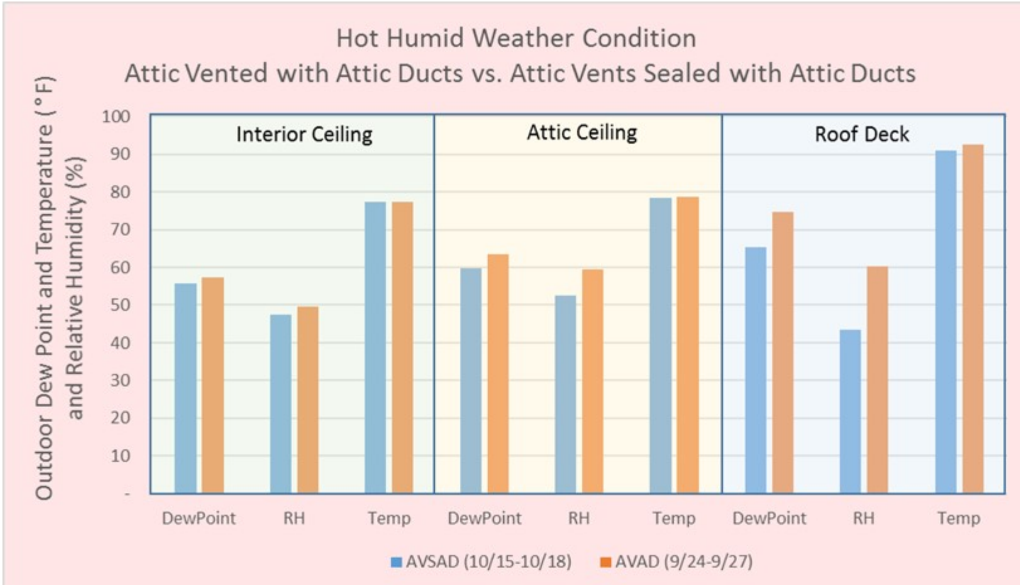


Figure 22. Omnisense average temperature, RH and dew point for Hot Humid weather condition comparison.

In Figure 23 we compare the average wood moisture equivalent at these same locations for these same hot humid periods. The vented attic has slightly higher moisture at all three surface locations, however WME, largely lower during the warmer days overall, is only about 10% on average.

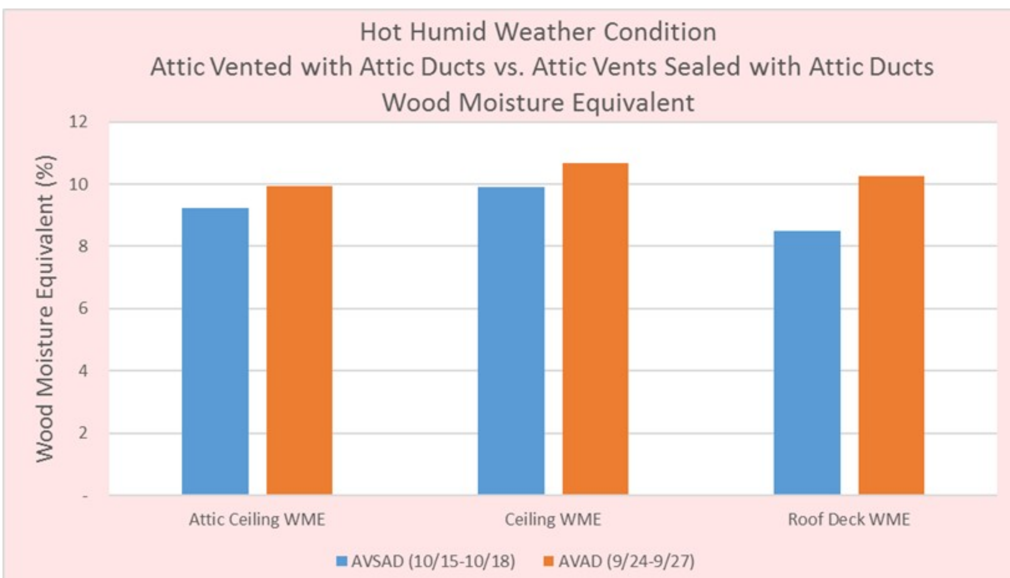


Figure 23. Omnisense average wood moisture equivalent for Hot Humid weather condition comparison.

Measured results during the mild weather comparison is next. The mild condition hones in on a handful of matching days when the indoor-outdoor temperature delta is between -11 ° F and -15 ° F, when hourly outdoor temperature is generally between 50 ° F and 75 ° F, and there is no heating. For this evaluation we are able to compare like days for all four test configurations. As seen in Figure 24 there is little variation in average temperatures, dew points, and RH among the different test configurations. The limited number of days available with like-weather for this evaluation do not warrant a strong statement about any of these subtle differences.

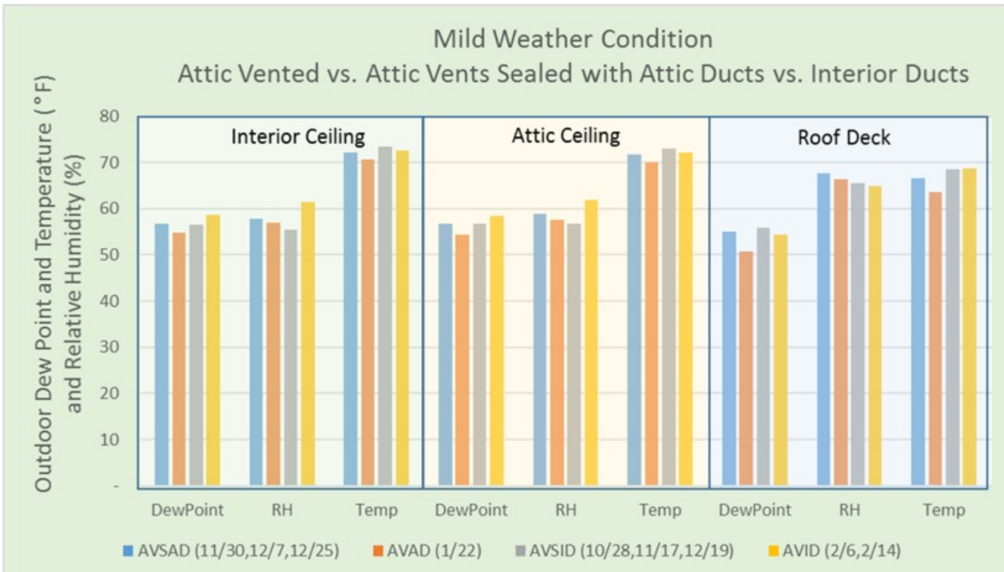


Figure 24. Omnisense average temperature, RH and dew for Mild weather condition comparison.

In Figure 25 we compare the average wood moisture equivalent at these same locations for the same chosen Mild periods. WME is general higher than it was during the Hot Humid condition, but for all test configurations it averaged between 10% and 12%. The moisture detected in the lab home during the mild weather did not approach a level of concern under any test conditions.

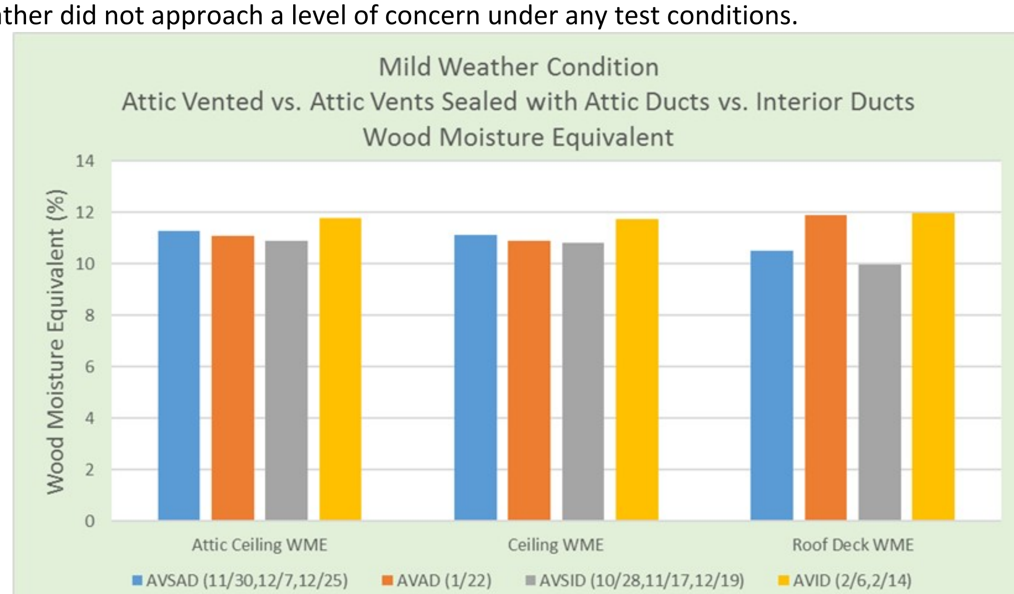


Figure 25. Omnisense average wood moisture equivalent for Mild weather condition comparison.

Comparisons of the same measurements during the cool weather condition follows. The Cool condition are days when the average daily temperature is between 52 °F and 54 °F and includes only two days for comparison. For this investigation we were limited to one day each during the Attic Vents Sealed with Attic Ducts and the Attic Vented with Attic Ducts. The average temperature, dew point, and RH are plotted in Figure 26. Notable is the difference in RH at the roof deck, where the average RH exceeded 80% during the sealed attic test day and was below 70% during the vented attic test day.

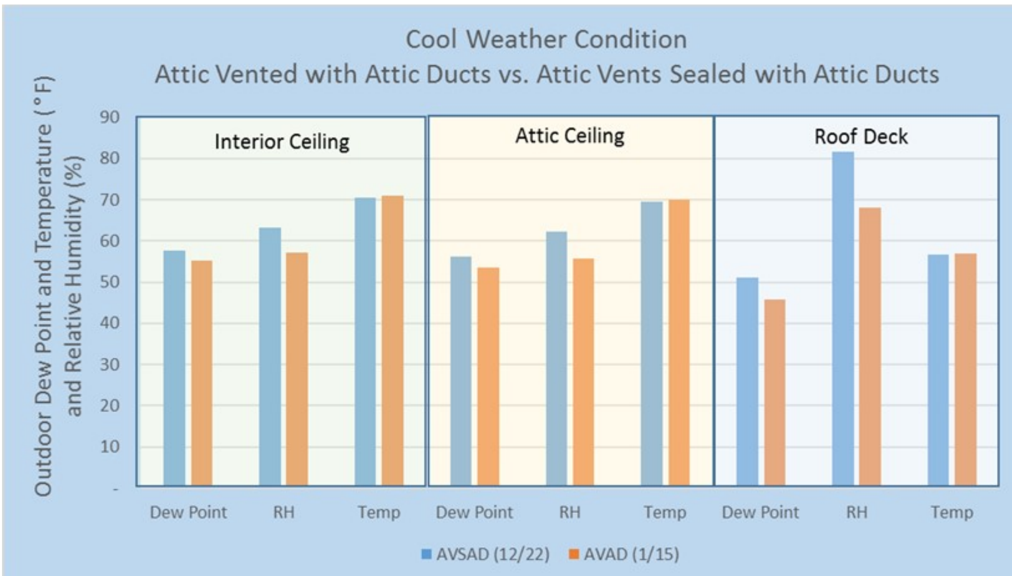


Figure 26. Omnisense average temperature, RH and dew for Cool weather condition comparison.

Coincident with the much higher roof deck RH during the sealed attic test day are higher WME% averages at all three sensor locations, as presented in Figure 27. The roof deck moisture is higher with the attic vents sealed.

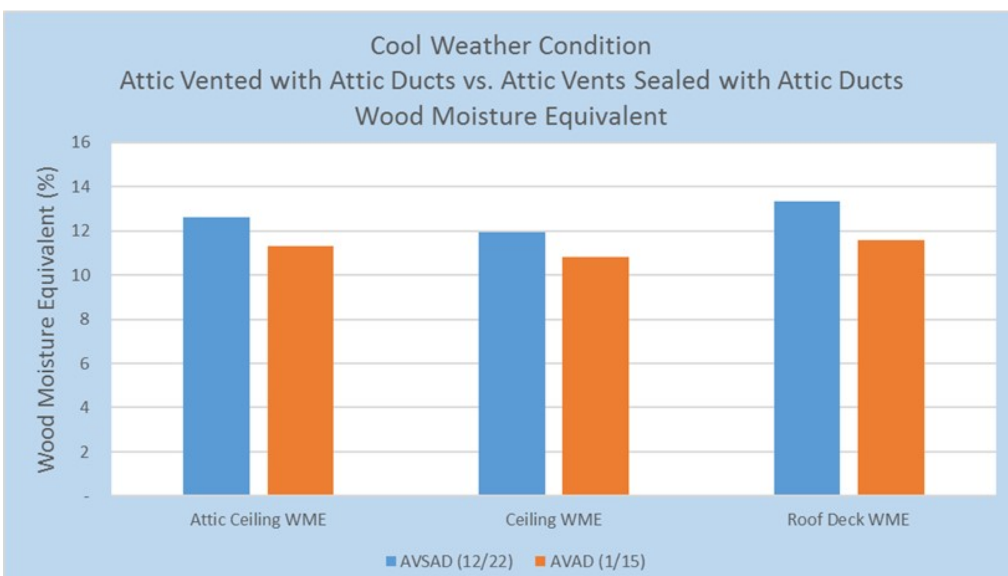


Figure 27. Omnisense average wood moisture equivalent for Cool weather condition comparison.

The marked difference in roof deck RH between configurations led us to compare the daily profiles between each configuration. Knowing that the roof deck sensor consistently had the highest WME% reading in cooler weather, we chose this sensor to compare the diurnal cycle between the vented and sealed vent configurations, which is plotted in Figure 28. (Reference Appendix A to see how closely aligned the weather conditions were on these two days.)

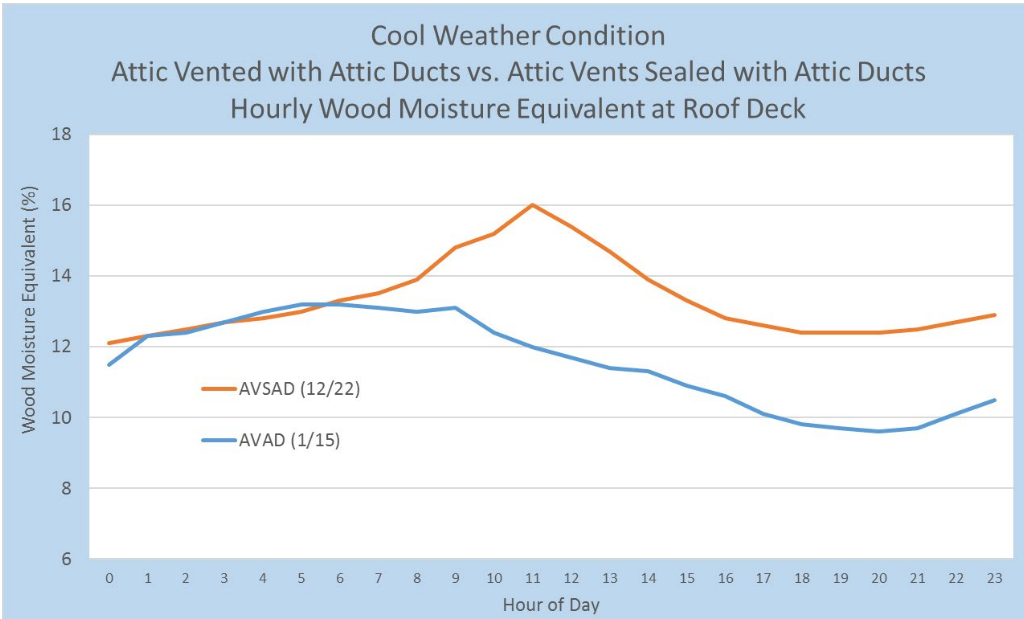


Figure 28. Omnisense hourly wood moisture equivalent for Cool weather condition comparison.

Wood moisture equivalent for both test configurations is close together until about 6:00 am, and then, under the attic ducts sealed test condition, it continues to rise until 11:00am when it peaks at about 16%. This is just two hours after the coldest temperature of the day (see Appendix A cool period outdoor temperature graph). Conversely, WME peaks a little above 13% on the day with the vented attic.

While WME of 16% is not concerning, there is an indication of higher moisture potential during the cooler weather for the sealed vent configuration. Unfortunately, this past winter was relatively mild and thus we were unable to test the sealed vents under colder weather. Future research should be conducted under colder outdoor temperatures to develop a clear conclusion on potential roof deck moisture issues for the sealed vent configuration.

Summary

Currently the attic vent sealed test configurations with insulation on the ceiling and no insulation on the roof deck conducted in this study are not permitted by the Florida Building Code. Unpublished public claims have been made in past Florida Building Commission meetings that cooling energy and indoor RH decrease after attic vents were sealed and insulation remains on the ceiling.

The primary goal of this research was to determine if measureable energy savings would occur from simply eliminating attic venting in a research lab home with R30 insulation on the ceiling plane and having no insulation applied on the roof deck. Another goal of this research was to determine if there were any potential beneficial or detrimental moisture issues associated with eliminating attic venting when R30 insulation remained on the ceiling and the roof deck remained uninsulated.

This report covered a house lab-based experimental study conducted September 20, 2018 through May 27, 2019. The focus of the study was on impacts of sealing attic vents, but test configurations were included to also evaluate impacts with ducts in attic and in conditioned space.
The four tested configurations were:

- Attic Vented with Attic Ducts (AVAD)
- Attic Vents Sealed with Attic Ducts (AVSAD)
- Attic Vented with Indoor Ducts (AVID)
- Attic Vents Sealed with Indoor Ducts (AVSID)

Energy

Testing found that cooling energy for Florida climate increased when attic vents were sealed. The average increase was about 5% with ducts in the attic and about 18% with ducts indoors. The attic vented with indoor duct (AVID) had the lowest predicted annual cooling energy use. This configuration did not have measured energy use on days as warm as the other configurations. This was due to limitations in the project contract period. It is possible that the projected energy use at warmer temperatures could be greater than the extrapolated result indicates. If this were so, the indicated impact would be less than 18 %, but it is still expected that the AVSID configuration would still use more energy than the AVID configuration.

A previous project (Cummings et al. 2013) using this same house lab set-up, same cooling system and ducts with only a vented attic found that moving the ducts indoors had a predicted annual Florida cooling energy decrease of 10.5%. An energy simulation using EnergyGuage USA and the house lab qualities was run with all ducts in attic, and all ducts indoors. The difference indicated for a vented attic was 397 kWh (8.8%) difference. The simulation predicted nearly identical increased energy from sealing the attic no matter whether the ducts were in the attic or in conditioned space. Therefore we expect that sealing attic vents will increase annual cooling energy use between 5%-10% and equate to an increased annual cooling energy cost of approximately $25 to $54.

Mild weather conditions during the project did not produce enough heating season data to be able to determine heating energy use impacts.

Evaluation of ceiling heat flux daily profiles showed a greater heat flux from the attic to indoors particularly during the warmest time of day when the attic vents were sealed. Ceiling heat flux daily profiles during warm weather indicated periods of a few overnight hours when the attic vents sealed configuration had a lower heat flux than the vented attic configuration. It is believed that the radiative cooling of the roof deck was better contained in the tighter attic. During these brief early morning periods, the cooling load during the sealed attic was actually lower. However, as the sun begins heating up the attic the sealed attic becomes hotter and the net result is a higher cooling load.

Moisture Impacts

The prolonged periods of high moisture levels in outdoor air through much of the year in Florida allow for higher potential moisture issues in buildings particularly when building surface temperature approach the air dewpoint at the surface. Prolonged periods of high relative humidity at surfaces is also a concern as this increases the potential for mold and mildew growth.

Sensors were installed to measure material moisture content, temperature, RH, and dew point. Sensors were placed in a vertical profile at material surfaces as follows:

- on the interior side of the gypsum board ceiling (Indoor Ceiling)
- on the top of the gypsum board (and under insulation) in attic (Attic Ceiling)
- on the underside of the wood roof deck (Roof Deck).

The profile also included temperature and RH measurements at the mid height of interior space under the other sensors and at mid height in the attic.

The ceiling and roof deck moisture content was never at sustained level of concern during all tests. The ceiling moisture remained reasonably low during all tests. The roof deck consistently had the highest and most fluctuating WME values. The highest hourly roof deck moisture measurements approached 17%-18% as outdoor morning low temperatures reached 45°F or lower. Roof deck moisture varied in a diurnal cycle in all test configurations with a peak following the coldest low morning temperatures, then quickly dropping as the sun heated the roof deck.

The building moisture evaluation included a comparison between vented attic and attic vents sealed configurations at similar sets of weather conditions. The central cooling duct location of a tight and well-insulated duct system did not impose a moisture impact upon building material moisture. To normalize the moisture data among test configurations, we rigorously selected days of like-weather under three differing weather conditions -- Hot Humid, Mild, and Cool – where for each condition the daily profiles for outdoor temperature, outdoor dew point, and solar insulation were aligned as close as possible. For each weather condition, we investigated the dew point, RH, temperature, and moisture content of the surface measurements taken at the interior ceiling, attic ceiling, and roof deck locations.

These measurements showed little variation among the different test configurations during the Hot Humid and Mild weather conditions. The average moisture content was lower for the sealed attic vent configuration than the vented attic configuration during the Hot Humid and Mild comparisons. During the Hot Humid and Mild conditions, material moisture content was generally low among all test configurations. The attic with sealed vents was only about 8% WME and about 20% lower than the vented attic WME. This was not particularly surprising given the vented attic much more readily transfer higher absolute moisture from outdoors into the attic. The average surface RH was about 60% RH or less at all surfaces for vented and sealed vent configurations.

There was no remarkable difference between the vented and sealed attic during the mild weather comparison. Average dewpoints at different locations stayed between 50°F to 60°F. The average RH was between 50%-60%, except at the roof deck where the average was about 65% RH.

During the Cool weather condition, representative of the conditions when the highest WME readings occurred generally, the sealed attic vent configuration experienced higher RH at the roof deck and coincidently higher WME at all locations than did the unvented attic condition. The roof deck RH in the attic with sealed vents was remarkably higher than the vented attic during the cool weather period comparison. It averaged over 80% RH and increases concern regarding mold growth if sustained long enough. The RH did not stay at this high level long enough under our test conditions to result in mold growth or wood damage. Typically the daily diurnal pattern resulted in roof RH dropping down into the upper 50's °F or mid 60's °F during the warmest time of day during colder weather. This breaks the pattern of the periodic high RH levels during mild cool weather.

Comparisons between attic vented and attic vents sealed at different comparable weather conditions showed a clear trend of higher moisture content in roof deck and higher roof deck surface RH in attic vents sealed from warmer to cooler weather. The greatest differences between vented and sealed attic were observed during the coolest weather. Sealing attic vents resulted in roof deck surface RH to increase from 68% RH to 82% RH. The roof deck moisture increased from 11.5% WME up to 13% WME. As reported earlier these were not the highest occurring WME. These are values during comparable weather conditions to allow a comparison. The highest hourly WME around 17% occurred during the coldest hourly temperatures.

The weather during this research project never reached very cold temperatures through the winter period. The lowest hourly temperature did not drop below 40°F. Furthermore there were not several days in a row where this lowest temperature was sustained. Given the observed trend for wood moisture to increase during the coldest outdoor and coldest roof deck temperatures, we feel that the testing did not represent north Florida winter weather adequately. North Florida can experience winter low temperatures around 32F that can occur for several days at a time. The roof deck would be even colder during the early morning hours. It is likely that the roof deck wood moisture could exceed 18% under these conditions and increase concern for potential mold or moisture damage.

Further tests conducted under cooler outdoor temperatures is warranted to develop a more complete understanding of potential moisture issues for the sealed attic vent configuration described in this report.

Conclusion

The primary focus of this research was to evaluate energy and moisture related impacts with conventional attic venting and sealed attic vents with R30 insulation remaining on the ceiling and the roof deck left uninsulated. Currently the attic vent sealed test configurations are not permitted by the Florida Building Code. The outcome from this research was to make recommendations for Florida Building Code modifications if warranted.

This project found that the predicted annual energy results increased annual cooling energy for the three cities of Miami, Orlando and Jacksonville when the attic vents were sealed whether the ducts were in conditioned space or in the attic. The increased cooling energy with the attic vents sealed was due to the attic becoming hotter and increased heat transfer from the attic into the conditioned space. On average the impact from sealing attic vents will increase annual cooling energy use between 5%-10% and equate to an increased annual energy cost of approximately $25 to $54 (@$0.12/kWh).

The potential for moisture-related concerns was evaluated through extensive measurements of temperature, RH, dewpoint temperature, as well as ceiling and roof deck moisture content. No moisture related issues such as condensation, mold or wood rot occurred during the full course of testing of all configurations. Interior and attic ceiling surfaces were at normal levels of moisture, RH and dewpoint temperature under all test configurations. Roof deck conditions were much more dynamic and showed the highest levels and widest range of RH, and moisture content.

Material moisture levels under all test configurations stayed under 20% WME, and only nearly approached this level of moisture for short durations. However, trends did emerge to raise caution about the potential for moisture issues to occur under colder weather conditions than experienced during the test periods.

Comparisons between attic vented and attic vents sealed at different comparable weather conditions showed a clear trend of higher moisture content in roof deck and higher roof deck surface RH in attic vents sealed from warmer to cooler weather. The greatest differences between vented and sealed attic were observed during the coolest weather. Sealing attic vents resulted in roof deck surface RH to increase from 68% RH to 82% RH. The roof deck moisture increased from 11.5% WME up to 13% WME. These were not the highest occurring WME. These were values during comparable weather conditions to enable a comparison to be made. The highest hourly WME around 17% occurred during the coldest hourly temperatures. Occurrences of these happened during both vented and sealed attic tests.

This research evaluation was conducted over a relatively mild central Florida winter. Given the observed trends of increased potential moisture issues at colder temperatures, further research conducted under cooler outdoor temperatures is warranted to develop a fuller expectation of potential moisture issues for the sealed vent configuration described in this report before accepting this particular sealed attic vent into code. The primary moisture concern is for central and north Florida. South Florida homes with R30 insulation should expect a modest increase in energy, but low likelihood of moisture issues with sealed attic vents given the warmer winter weather there.

No Florida Building Code modification recommendations are made for the sealed attic vent as evaluated in this research.

Acknowledgments

The authors would like to thank the Florida Building Commission, and Mo Madani of the Florida Department of Business and Professional Regulation Office of Codes and Standards for supporting this work.

References

Cummings, J., Withers, C. and Kono, J. (2013). Energy and Peak Demand Savings from "Right Sizing" of Fixed Capacity (SEER 13) and Variable Capacity (SEER 22 and 21) Heat Pumps with Attic and Indoor Ductwork for the FPL Service Territory". FSEC-CR-1969-13. Florida Solar Energy Center, Cocoa, FL.

"EnergyGauge USA: Code Compliance and Home Energy Rating Software." (1996-2018). Cocoa, FL: Florida Solar Energy Center. http://www.energygauge.com/usares/.

Fang, X., Christensen, D., Barker, G., and Hancock, E. (2011). *Field Test Protocol: Standard Internal Load Generation for Unoccupied Test Homes*. NREL/TP-5500-51928. Golden, CO: National Renewable Energy Laboratory. Accessed May 2019: https://www.nrel.gov/docs/fy11osti/51928.pdf.

Forest Products Laboratory. 2010. "Wood handbook—Wood as an engineering material." General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Accessed May 2019: https://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr190.pdf

Hendron, R., Engebrecht, C. (2010). *Building America House Simulation Protocols*. NREL/TP-550-49426. Golden, CO: National Renewable Energy Laboratory. Accessed May 2019: http://www.nrel.gov/docs/fy11osti/49246.pdf

Lstiburek, J. (2006). "Understanding Attic Ventilation." Building Science Digest-102, Building Science Corporation. Accessed May 2019: https://www.buildingscience.com/documents/digests/bsd-102-understanding-attic-ventilation

Parker, D. and Sherwin, J. (1998). "Comparative Summer Attic Thermal Performance of Six Roof Constructions", ASHRAE Transactions, June 1998. Accessed May 2019: http://publications.energyresearch.ucf.edu/wp-content/uploads/2018/06/FSEC-PF-337-98.pdf

Rose, W. B. (1991). "More Data on Shingle Overheating with Unvented Roofs", Energy Design Update, March 1991.

Withers, C. (2016). "Energy-Efficient Management of Mechanical Ventilation and Relative Humidity in Hot-Humid Climates" National Renewable Energy Laboratory. DOE/GO-102016-4766. Accessed May 2019: http://fsec.ucf.edu/en/publications/pdf/fsec-cr-2049-16.pdf

Withers, C. and J. Sonne. (2014). "Assessment of Energy Efficient Methods of Indoor Humidity Control for Florida Building Commission Research" FSEC-CR-1976-14 Cocoa, FL: Florida Solar Energy Center. Accessed May 2019: http://publications.energyresearch.ucf.edu/wp-content/uploads/2018/06/FSEC-CR-1976-14.pdf

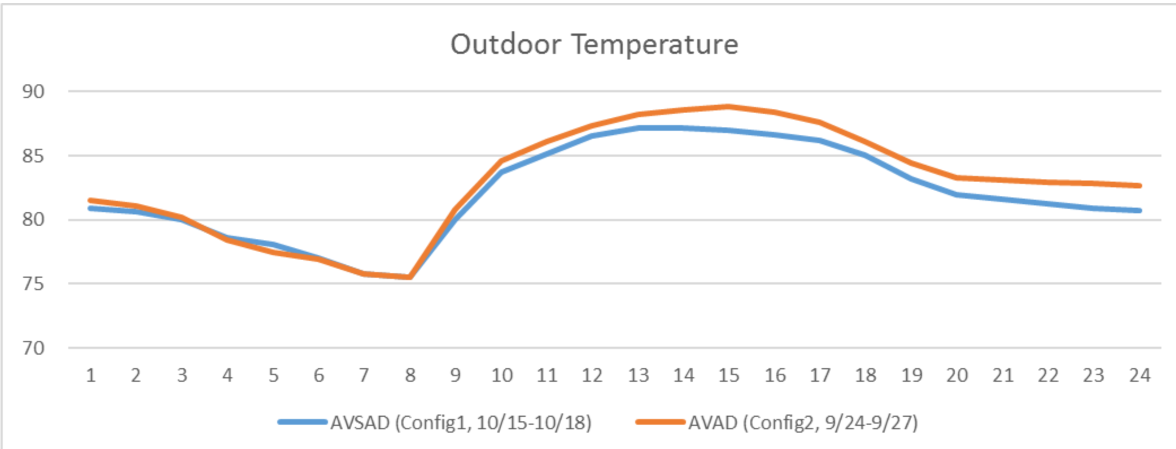
Withers, C., Cummings, J., and Nigusse, B. (2016). Cooling and Heating Seasonal Energy and Peak Demand Impacts of Improved Duct Insulation on Fixed Capacity (SEER 13) and Variable Capacity (SEER 22) Heat Pumps. FSEC-CR-2039-16 Cocoa, FL: Florida Solar Energy Center. Accessed February 2019: http://publications.energyresearch.ucf.edu/wp-content/uploads/2018/06/FSEC-CR-2039-16.pdf

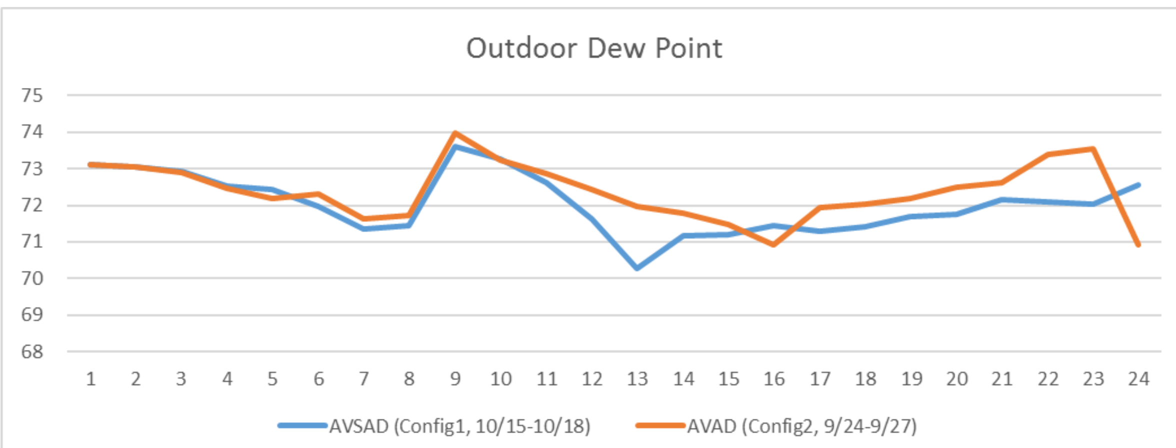
Appendix A

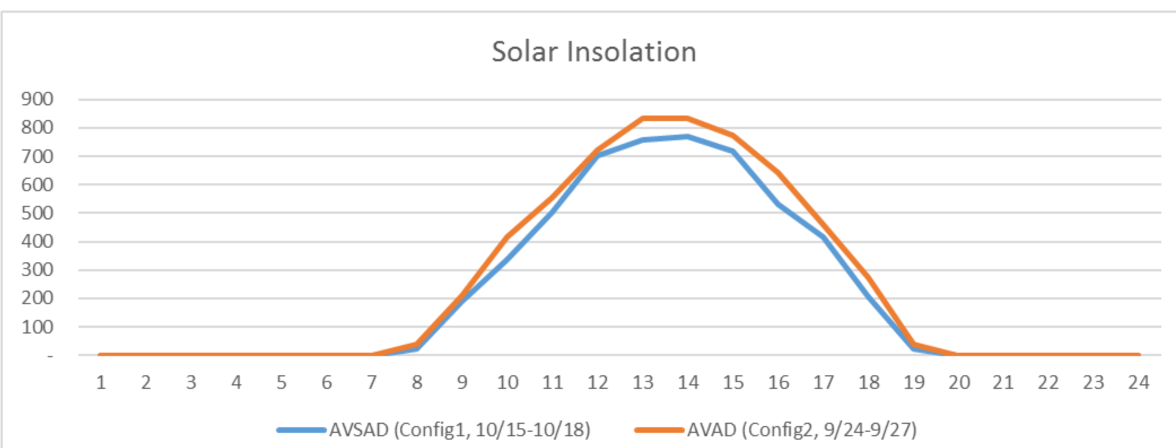
Weather Conditions During Attic and Ceiling Moisture Comparisons

Hot Humid Period Weather Conditions

There was no rainfall in either period or leading up to either period.

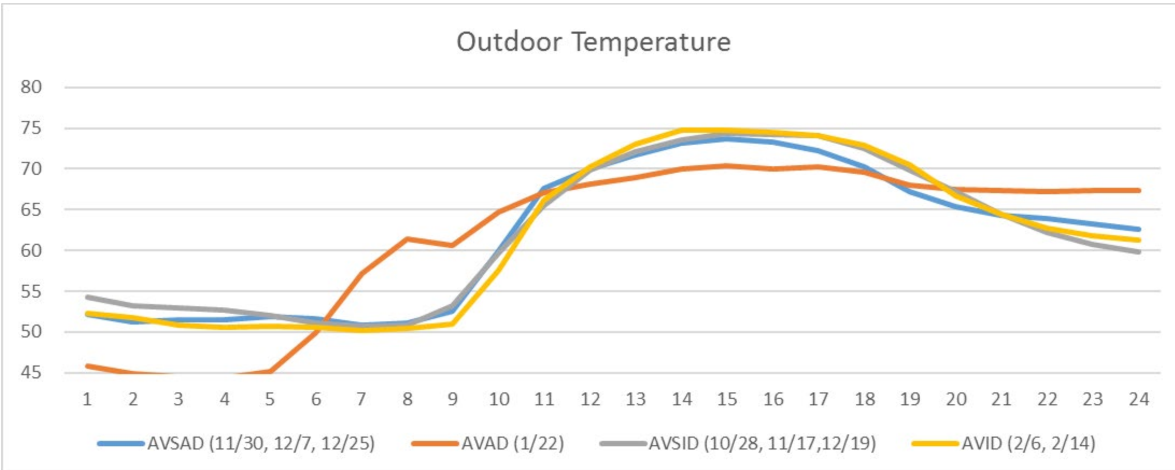


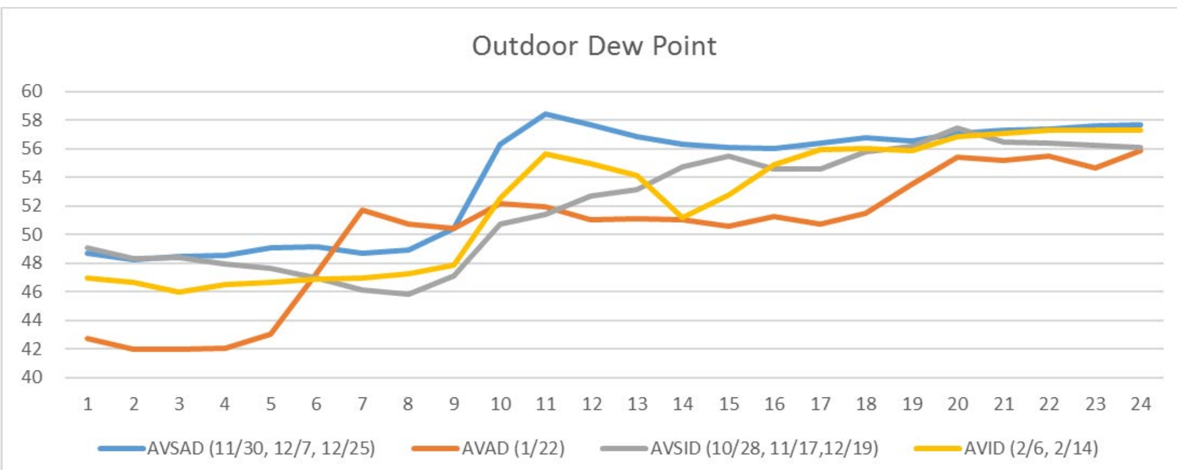


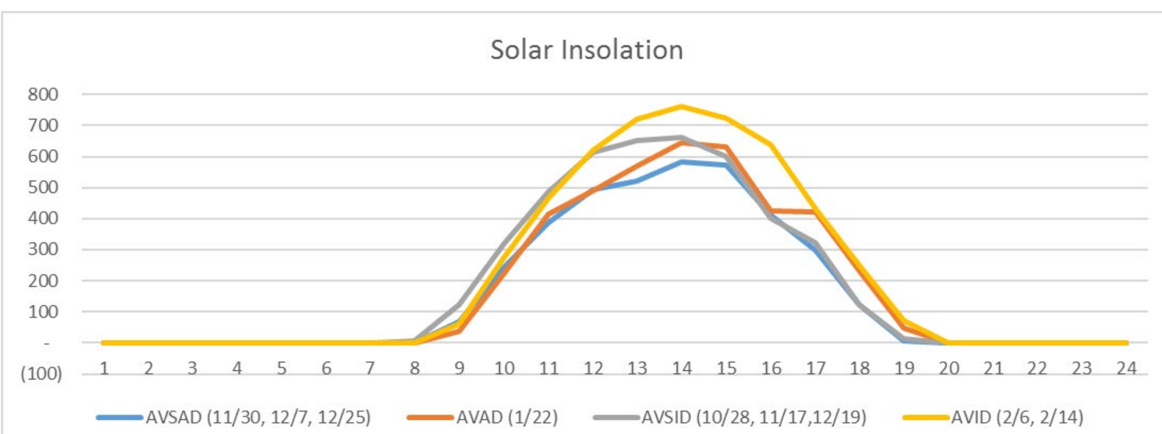


Mild Period Comparison Weather Conditions

There was no rainfall in either period or leading up to either period.







Cool Period Comparison Weather Conditions

There was no rainfall in either period or leading up to either period.