A FIELD STUDY SETUP OF FOUR HOMES HAVING NON-VENTILATED AND SEMI-CONDITIONED SEALED ATTICS

William A. Miller, Ph.D.[1], Philip Boudreaux[2], Simon Pallin, Ph.D.[3], Kaushik Biswas, Ph.D.[4], Tony Gehl[5], Jerry Atchley[6], Nicklas Karlsson[7], Dominic Bednar[8], Roderick Jackson, Ph.D.[9], David O. Prevatt, Ph.D., PE (MA)[10], Anshul Shah[11], Aravind Viswanathan[12], and Mitali Talele[13]

INTRODUCTION

The University of Florida (UF) and the Oak Ridge National Laboratory (ORNL) are evaluating the hygrothermal (heat and moisture flow) performance and durability of sealed attic construction where open cell spray polyurethane foam (ocSPF) insulation is applied directly to the underside of the roof deck. During the 2015-2016 fiscal year and with financial support from the Florida Building Commission (FBC) and the Florida Roofing and Sheet Metal Contractors Association (FRSA), UF and the ORNL Building Technology Research Integration Center (BTRIC) completed Phase I of a study that setup four residential home demonstrations in Florida climate zones CZ-1A and CZ-2A. Field measurements for the homes are listed in Table 1.

The four homes are instrumented for measuring temperature and relative humidity of the indoor living space, the outdoor air and the attic air. In addition, the temperature, relative humidity and moisture content of the roof sheathing are being monitored and recorded by remotely-accessible data acquisition equipment. Air leakage tests on the whole house, on the sealed attic and in the HVAC ducts were conducted on all four homes, Table 1. Digital and infrared images were captured to document the thermal performance of the sealed attics. Field tests commenced on June 1, 2016. Data acquisition will continue for one full year to document heat and moisture flows, which, in turn will be used in a second phase of work to benchmark an analytical tool kit for predicting the heat and moisture flows in Florida's hot and humid climate. The second phase of work is pending approval by the FBC.

KEYWORDS

attic, ventilation, polyurethane foam insulation, moisture, durability

1, 2, 3, 4, 5, 6, 7, 8, 9. Oak Ridge National Laboratory (ORNL), Building Technology Research Integration Center (BTRIC)
10. University of Florida Associate Professor (Structures)
11, 12, 13. University of Florida Graduate Students

1. BACKGROUND

The convenience of the attic space appeals to builders, who all too often install the HVAC unit and the ducts in the attic to conserve living space while completing the rough-in at a low first cost. However, installing the HVAC and ducts inside an unconditioned and ventilated attic is not the most energy efficient option because of the extreme summer and winter operating temperatures occurring in the attic. Parker, Fairey and Gu (1993) simulated the effects of ducts on space conditioning Florida homes and observed that air leakage and heat transfer to the duct were major contributors to the peak electrical burden on the FL utility. Cummings, Toole and Moyer (1990) surveyed some 91 Florida homes for the leakage of air from ducts. They reported average measured leakage rates of roughly 10% of the airflow in supply and return ducts.

TABLE 1. Florida Home Descriptive and Leakage Results.

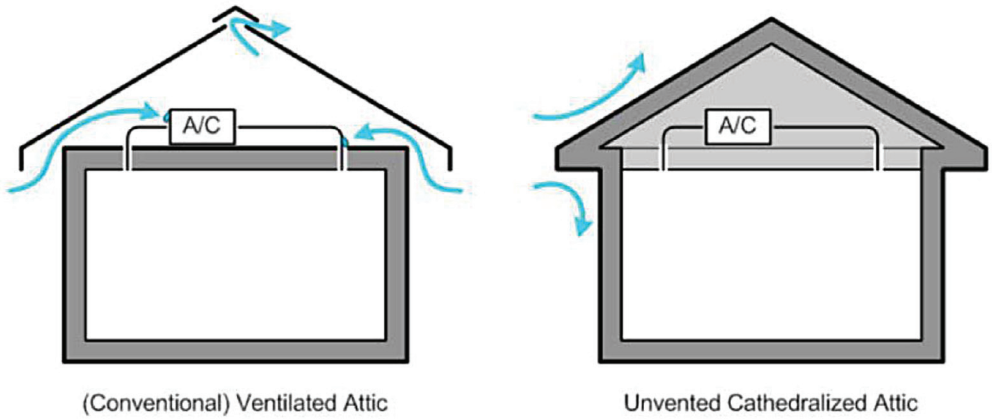
Characteristic	House 1	House 2	House 3	House 4
Location	West Palm Beach	Venice	Orlando	Gainesville
Attic	Sealed using ocSPF	Sealed using ocSPF	Sealed using ocSPF	Sealed using ocSPF
Type of roof	Standing seam metal	Concrete barrel tile	Asphalt shingle	Asphalt shingle
Conditioned Area	2,043 sq. ft.	3,592 sq. ft.	2,348 sq. ft.	3,055 sq. ft.
Conditioned Volume	29,670 cubic ft.	42,183 cubic ft.	22,115 cubic ft.	29,022 cubic ft.
Attic Volume	6,800 cubic ft.	7,692 cubic ft.	5,106 cubic ft.	14,002 cubic ft.
Total ACH at 50Pa	6.7	2.2	8.6	5.2
Leakage Breakdown Attic Space / Conditioned Space	58% / 42%	36% / 64%	12% / 87%	5% / 95%
Total Duct Leakage**	0.11 CFM / sq. ft.	0.16 CFM / sq. ft.	0.26 CFM / sq. ft.	0.21 CFM / sq. ft.
HVAC System	AC with Elec Furnace Air-Handler in attic Ducts in attic	Heat Pump Air-Handler in closet Ducts in attic	Heat Pump HVAC outside No Duct in tested attic	Heat Pump Air-Handler in closet Supply Ducts in attic
Dehumidifier	NA	UltraAir	NA	Master Bath
Roof deck insulation (h·ft²·°F/Btu)	R-15: 4" ocSPF	R-21: 5.5" ocSPF	R-15: 4" ocSPF	R-27: 7" ocSPF
Code minimum R-value/ Active FECC*	R-19: 2010 FECC	R-19: 2010 FECC	R-19: 2002 FECC	R-19: FECC 2007

*Florida Energy Conservation Code (FECC,) in effect during application of spray foam to seal attic.
** Duct Leakage per square footage of conditioned space

To improve envelope performance, researchers opted to literally encapsulate the HVAC and ducts by moving the boundary of the insulating planes to the roofline, gables and eaves of the attic. Conventional attic construction provides a continuous airflow through the attic's soffit vents and out ridge or gable vents, Figure 1. Conventional attics are referred to herein as unconditioned, vented attics; and, it is not part of the buildings thermal envelope. In contrast, an unvented, semi-conditioned (sealed) attic is made part of the thermal envelope. It is encapsulated with polyurethane spray foam, and any duct leakage of conditioned air is contained to provide moderate air temperatures in the attic, Figure 1. The efficiency "feature" of putting ducts in conditioned or semi-conditioned space is typically one of the most energy-savings features, with the potential to be one of the most cost-effective.

The concept was first introduced by Building Science Corp (Rudd and Lstiburek, 1998). They built and monitored test homes in a hot, dry climate and demonstrated that the prototype homes with unvented attics yielded significant cooling and heating energy

FIGURE 1: Illustration of vented attics and unvented attics. (Grin et al. 2013)



savings over a conventional home with a ventilated attic. Transforming residential attics into a non-ventilated semi-conditioned attic space has therefore gained approval among builders, Chasar et al. (2010). However, field data demonstrating successful implementation in all climates are sparse and there still remains an educational gap in the best practices for builders. The dearth of data in hot, humid climates has caused confusion among builders and code officials because of the confounding variables affecting the flow of water vapor in sealed attics.

Miller and Boudreaux (2015) described how some homes with sealed attics perform well in energy and well in water vapor management while others did not. This paper suggested several potential reasons for this variability. Poor workmanship was attributed as a real problem. Improper constructions cause gaps in roof to wall connections, thus leading to air leakage. Field studies conducted by ORNL in the hot, humid climate of Charleston, SC, investigated the thermal and hygrothermal performance of ventilated attics and non-ventilated semi-conditioned attics sealed with open-cell spray polyurethane foam (ocSPF) and with closed-cell spray polyurethane foam (ccSPF) insulation, (Miller et. al 2016). In the ventilated attics the relative humidity drops as the attic air warms; however, the opposite was observed in the sealed attics. Peaks in measured relative humidity in excess of 70 to 90% occurred from solar noon until about 8 PM on hot, humid summer days. Moisture pin measurements made in the wood roof sheathing and absolute humidity sensor data from inside the foam and from the attic air suggest that moisture is transferred through the foam and into the sheathing of sealed attics, Lstiburek (2014).

1.1 Purpose

Four single-family residential structures constructed with sealed attic systems are under field study. The data from this project will be used to document the risk potential of moisture damage to the roof sheathing for Florida homes that are sealed using open cell spray polyurethane foam (ocSPF) insulation. Field data will be reduced and used to assess the potential of moisture storage in the foam and sheathing which can also affect the indoor relative humidity level causing it to sometimes exceed the values prescribed in ASHRAE Standard 55 (2013).

The density of open cell foams ranges from 0.5 to 1.2 lb per cubic foot, with thermal resistance R-values ranging from R-3.6/inch to R-4.5/inch. The two leading manufacturers of ocSPF are Sealection500 and Icynene. When applied, this foam instantly expands more than 100 times its original size. Open-cell spray polyurethane foam is vapor permeable, having a vapor permeance of about 19 perms for a 3-in thickness of foam, Kumaran (2008).

2. SETUP OF THE FOUR HOMES

The FRSA advertised the demonstration opportunity using a flyer and identified 12 home sites from which four homes were selected for field study, as listed in Table 1. Site selection was based on the homes being setup with unventilated, semi-conditioned attics, the type of roof system, placement of the HVAC and the occupation of the homeowner. Homeowners who are builders or who are closely related to construction were given preference because the home's workmanship was better managed by the homeowner, which would hopefully eliminate the effects of poor roof and attic workmanship that could cause water leakage and confound the study.

UF students took dimensions of each single family residence, including the dimensions of all rooms in the conditioned space of the houses. In addition, the students recorded the slope and style of the roofs, the roof structure, size of the attic and the type and dimensions of the spray foam insulation. The exterior wall cladding and details, number and dimensions of exterior windows and foundation were recorded for later use in BEopt[1] model development, Christensen et al. (2006). Homeowners were asked when the attic was sealed and by which Florida contractor. The insulation was installed during initial construction in three of the four houses, and it was added during retrofitting of the fourth house. The owner who retrofitted their home with spray foam insulation was happy with the reduction in heating and cooling utility bills after the retrofit. The peak summer electric bill dropped from about $250 to $150, a 40% reduction.

2.1 Instrumentation

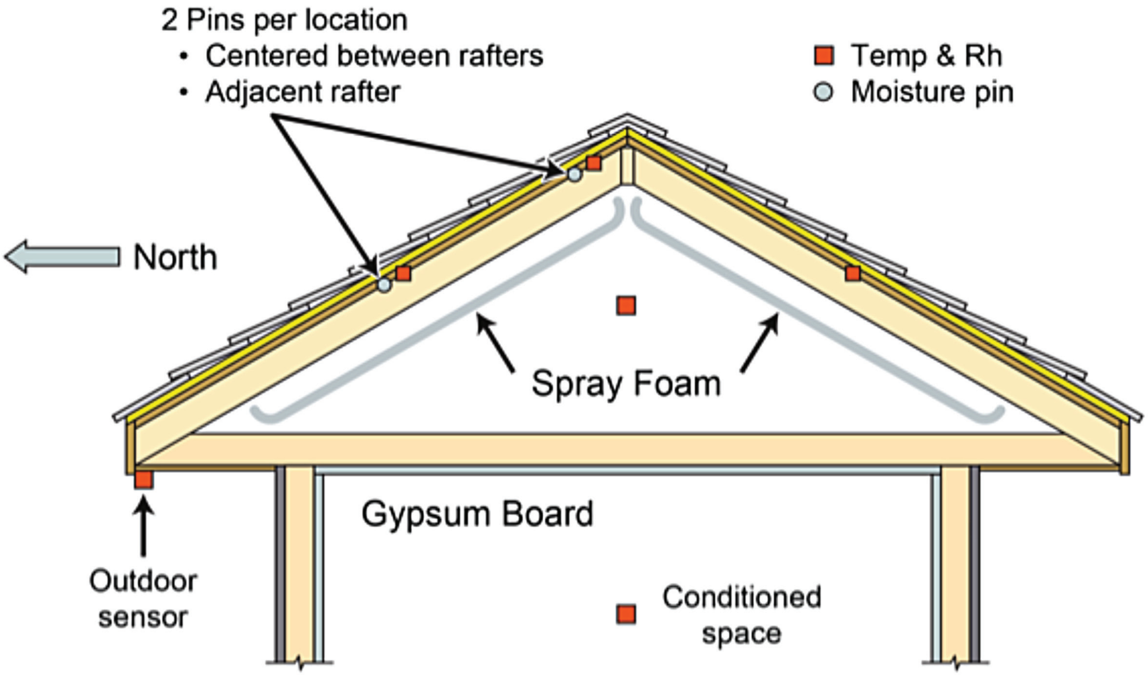
Absolute humidity probes and moisture pins were installed on the adjacent roof decks to analyze the in situ performance of the attics. The absolute humidity probes were fabricated using the technique described by Straube, Onysko and Schumacher (2002). A thermistor and relative humidity sensor were packaged together in a vapor permeable and liquid water repellent cover fabricated from commercially available weather resistive barriers designed to allow passage of water vapor but not liquid water. Thermistor and humidity sensors were calibrated by the manufacturer. ORNL Metrology made checks for a couple of the absolute humidity probes. The probes met the manufactures specification for the temperature response of +/- 0.2°C. Humidity measured by the absolute humidity probes were checked at 25, 50, 75 and 90% RH. The error in RH ranged from 2% of reading at 25% RH and 15°C to 6.5% of reading at 90% RH and 26°C.

The absolute humidity probes and moisture pins were placed in the same pattern for each home to provide consistent comparisons among the attics under field study. Figure 2 shows the placement of sensors. Absolute humidity probes were installed for measuring the outdoor, the indoor and the attic ambient temperature and relative humidity. Absolute

1. BEopt™ (Building Energy Optimization) software. https://beopt.nrel.gov/

probes were also placed on the underside of the roof sheathing about mid-span from eave to ridge. An absolute probe was also placed on the sheathing at the north-side of the roof ridge, Figure 2.

FIGURE 2: Cross-Section of sealed attic showing placement of thermistors, relative humidity sensors and moisture pins in demonstration homes.relative humidity sensors and moisture pins in demonstration homes.



For each home, one set of moisture pins were nailed into the underside of the sheathing adjacent to the absolute probes centered between rafters for the north pitch locations shown in Figure 2. In addition, a second set of pins were installed to the underside of sheathing about 1-in from the rafter. The pins near the roof rafter were in the same rafter cavity as those centered in a rafter cavity.

2.2 Data Acquisition System

Campbell Scientific model CR1000 micro-loggers were setup for remote acquisition and recording of field data. The loggers are equipped with 4 MB of memory, rechargeable battery, a 115 Vac-to-24 Vdc transformer, cellular modem and associated cables. The micro-loggers take measurements of all sensors (Table 2) every 30 seconds and reduce analog signals to engineering units. Averages of the reduced data are written electronically to an open file (internal on logger) every 15 min. Averages are calculated over the 15-min interval and are not running averages; they are reset after each 15-min interval. The electronic format is comma-delimited for direct access by spreadsheet programs. Software running on a server at ORNL is configured to remotely collect data at scheduled intervals from all micro-loggers via cellular connection. Data are stored in server archive which has routine backup for data protection.

TABLE 2. Instruments Scanned by Campbell CR1000 Micro-Logger.

Measurement	Sensor Location	Type of Sensor
Temperature	North roof sheathing near ridge*	Honeywell 192-103LET
Temperature	North roof sheathing at mid-span of roof*	Honeywell 192-103LET
Temperature	South roof sheathing at midpoint of roof*	Honeywell 192-103LET
Temperature	Attic ambient air	Honeywell 192-103LET
Temperature	House ambient air	Honeywell 192-103LET
Temperature	Outside ambient	Honeywell 192-103LET
Relative Humidity	North roof sheathing near ridge*	Honeywell HIH-003
Relative Humidity	North roof sheathing at mid-span of roof*	Honeywell HIH-003
Relative Humidity	South roof sheathing at midpoint of roof*	Honeywell HIH-003
Relative Humidity	Attic ambient air	Honeywell HIH-003
Relative Humidity	House ambient air	Honeywell HIH-003
Relative Humidity	Outside ambient	Honeywell HIH-003
Moisture Pin	North roof sheathing adjacent rafter near ridge	Moisture Pin
Moisture Pin	North roof sheathing center of cavity near ridge	Moisture Pin
Moisture Pin	North roof sheathing adjacent rafter at mid-span of roof	Moisture Pin
Moisture Pin	North roof sheathing center of cavity at mid-span of roof	Moisture Pin
*Sensor centered between roof rafters.		

3. FIELD DEMONSTRATIONS

3.1 House 1: Standing seam metal roof with OCSPF sealed attic

House 1 is located in West Palm Beach, FL, within ASHRAE Climate Zone 1A, defined as hot-humid by ASHRAE 169 (2006) and Florida climate zone (CZ-1A). The FECC (2014) defines a hot-humid climate as a region that receives more than 20 inches (50 cm) of annual precipitation and where one or both of the following occur:

- A 67°F (19.5°C) or higher wet bulb temperature for 3,000 or more hours during the warmest six consecutive months of the year; or
- A 73°F (23°C) or higher wet bulb temperature for 1,500 or more hours during the warmest six consecutive months of the year.

August is the warmest month in West Palm Beach, Florida, with an average high temperature of 32.5°C (90.5°F). The hottest day on record was September 28, 2004, when the temperature hit 38.9°C (102.0°F). During January the average overnight temperature drops to 13.3°C (55.9°F) with the lowest temperature of -5° (23.0°F) being recorded on December 26, 1983. The average annual precipitation recorded for West Palm Beach is 62.4 inches.

Figure 3 shows images of the residence from different directions. This single-story residence has a sealed attic with hip roofs. The home features a standing seam metal roof.

3.1.1 Infrared and digital pictures of attic and interior ceiling

The attic of House 1 is constructed of 2 by 4 trusses that are 24-in on center. The ocSPF was sprayed to a depth of 4-in yielding R-15 of thermal protection for the roof and attic. The FECC (2014) requires new homes to have R-30 insulation placed on the attic floor of unconditioned, ventilated attics.

An infrared image of the ceiling shows the gypsum to have a temperature of about 81°F, Figure 4. The ceiling is not insulated and is only about R-0.45 for ½-in gypsum. Miller et al. (2016) observed that sealing the attic with less than code level of insulation causes the heat flowing through the ceiling to be almost double that crossing the ceiling for an unconditioned,

FIGURE 3: House 1 in West Palm Beach, FL.

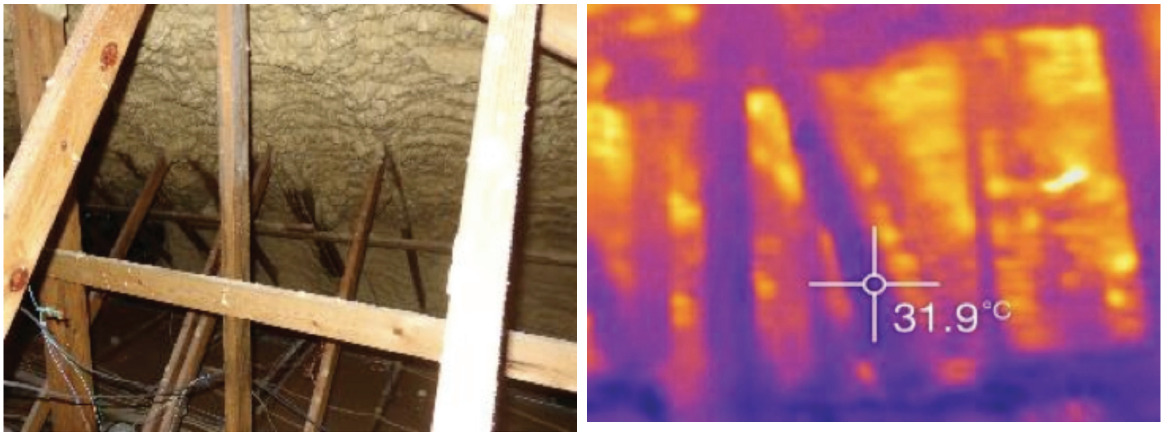
FIGURE 4: Digital and Infrared Picture of West-facing Ceiling and Wall.

ventilated attic. Digital and infrared images of the attic were taken to view heat leakage into the attic, Figure 5. The south-facing roof deck reads about 32.2°C (90°F). Radiation is the major contributor of heat transfer from the roof deck to the ceiling, and the 9°C (5°F) temperature gradient shows there is significant heat flux entering the conditioned space. More spray foam insulation would improve the thermal performance of the attic.

3.1.2 Field results for sealed attic

Seven contiguous days of data for House 1 display the temperature and relative humidity measured on the underside of the roof sheathing for the north-facing roof, Figure 6. The data were used to compute the dew point temperature at the sheathing's underside. The sheathing consistently reaches maximum temperatures of about 60°C (140°F) during the early afternoons.

FIGURE 5: Digital and Infrared Picture of the South-facing Roof and Attic



As expected, outdoor relative humidity readings fall as the sheathing temperature increases, because the moisture bearing capacity of the air also increases. Open cell spray foam has a moisture capacity of only 0.33 kg per cubic meter of foam, while plywood at about 60% relative humidity has a hygroscopic storage capacity of 48 kg per cubic meter of wood. The wood is far more absorbent than the foam and as the sun drives moisture from the wood into the foam there forms a moisture layer at the wood-foam interface. The dew point temperatures (Figure 6) do not show moisture condensing during the July week of field data. However, as the sun bears down on the roof, it drives the moisture in the sheathing through the foam and on into the attic air. The added moisture causes an anomaly in the trends for relative humidity, Figure 7. The relative humidity increases as the attic air increases. During the evening hours the roof surface becomes the coldest section of the roof due to night-sky radiation and much of the moisture in the attic air returns to the sheathing. Again the dew point measures indicate no condensation during either the evening or daytime hours. It will be of keen interest to observe these trends during the milder winter months in Florida.

The homeowners control the indoor ambient to about 77°F (25°C). The indoor relative humidity fluctuates from 50% to almost 80%. At 80% RH the home is at the boundary for comfort but is acceptable because the air temperature remains at about 23.3 to 30.3°C (74F to 86.5F) by ASHRAE 55 (2013).

3.2 House 2: Concrete tile roof with OCSPF sealed attic

House 2 is located in Venice, FL, within Climate Zone 2A, defined as hot-humid by ASHRAE 169 (2006), and Florida Energy Climate Zone (FECZ) 2. The warmest month in Venice is August with an average high temperature of 32.6°C (90.6°F). The hottest day on record was June 29, 1977 when the temperature hit 37.2°C (99.0°F). During January the average overnight temperature drops to 10.7°C (51.2°F) with the lowest temperature of 0° (32.0°F) being recorded on January 4, 2012. The average annual precipitation in Venice is 50.5 inches. Figure 8 shows images of the residence from four different directions.

3.2.1 Infrared and digital pictures of attic and interior ceiling

The attic of House 2 is constructed of 2 by 4 trusses that are 24-in on center. The ocSPF was sprayed to a depth of 5½-in yielding R-21 of thermal protection for the roof and attic. The

FIGURE 6: Sheathing temperature and relative humidity measured between the spray foam and the underside of the sheathing for the north-facing roof deck in West Palm Beach, FL.

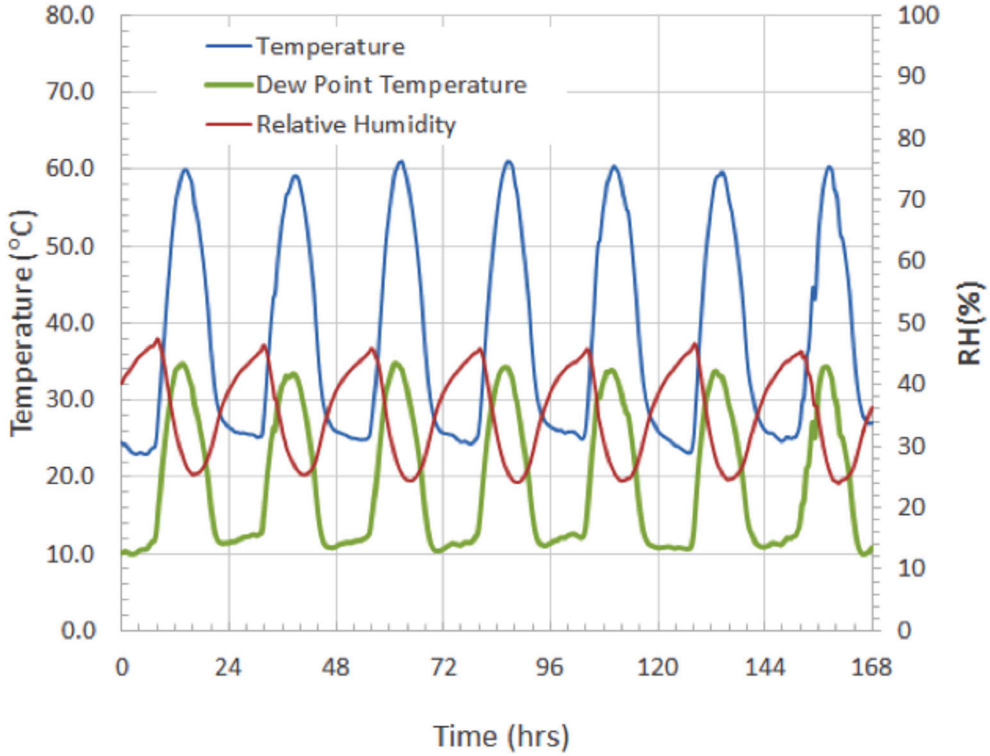


FIGURE 7: The attic air temperature and relative humidity for seven contiguous days of data collected for house 1 in West Palm Beach, FL.

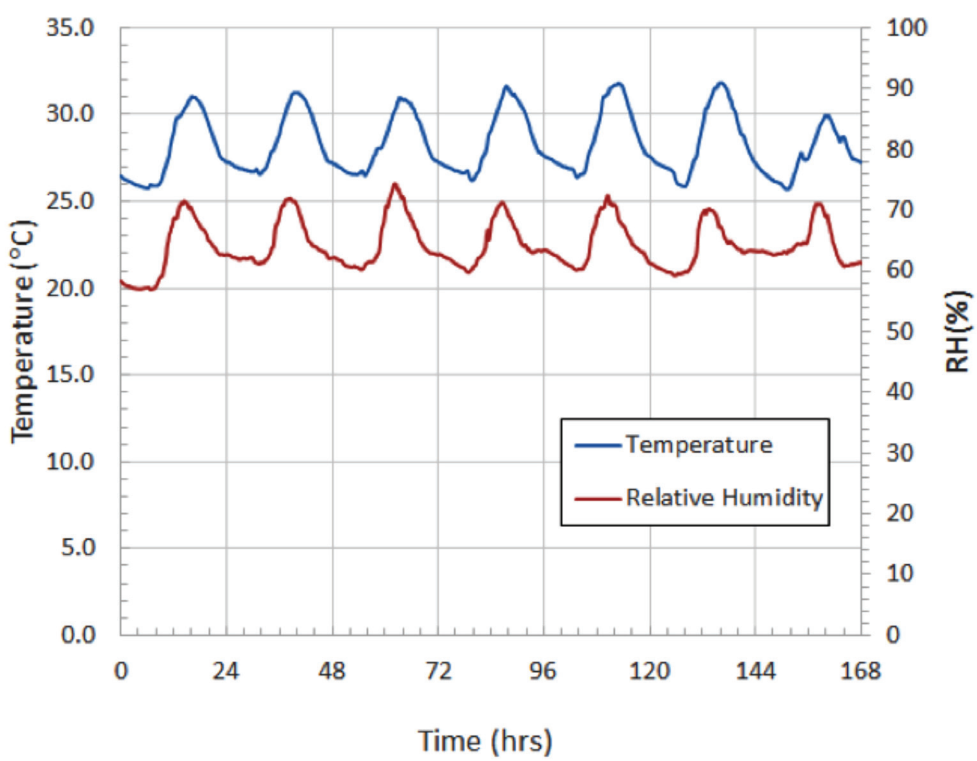


FIGURE 8: House 2 in Venice, FL.

FECC (2014) requires new homes to have R-38 insulation placed on the attic floor of unconditioned, ventilated attics.

Infrared image of the ceiling shows the gypsum to have a temperature of about 26.1C (79F), Figure 9. The ceiling is not insulated and is only about R-0.45 for ½-in gypsum. Digital and infrared images of the attic were taken to view heat leakage into the attic, Figure 10. The south-facing roof deck reads about 28.9C (84F). Again, radiation is the major contributor of heat transfer from the roof deck to the ceiling, and the 5°F temperature gradient shows there is less heat flux entering the conditioned space as compared to House 1. However, more spray foam insulation would improve the thermal performance of the attic.

3.2.2 Field results for sealed attic

Figure 11 presents a full week of July data collected from the instrumentation installed in House 2. The homeowner was a builder, and the home's construction showed excellent workmanship. The home was equipped with a dehumidifier to boost moisture removal from the second floor of the house. The tile roof reduced the effect of solar irradiance and the sheathing temperatures is observed slightly less than that measured for the home in West Palm Beach with a metal roof, Figure 11. As result, the relative humidity does not vary as severely as that measured under the metal roof. There is no evidence for the potential of condensate at the sheathing–spray foam interface, Figure 11. The attic air shows similar increase in relative humidity as observed at the West Palm Beach home, which implies that moistures is driven

FIGURE 9: Digital and Infrared pictures of the attic under the South-facing roof.

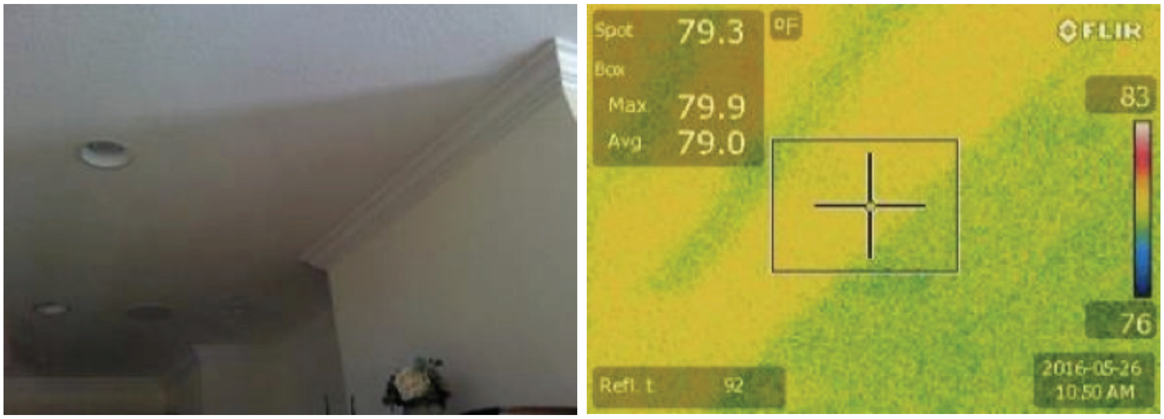
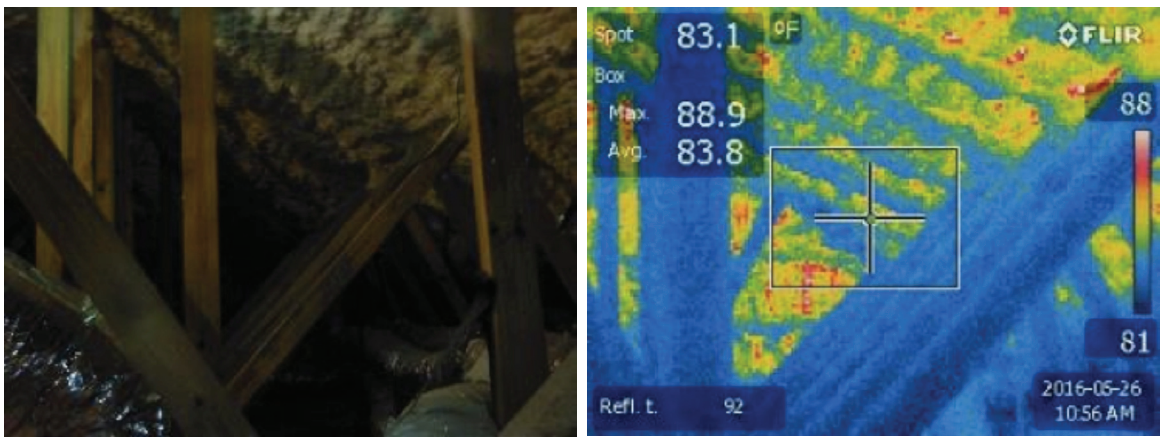


FIGURE 10: Digital and Infrared pictures of the attic.



from the roof deck and into the attic during the daylight hours and back into the foam during the cooler evening hours. The temperature and relative humidity of the attic air are both less than that observed for the outdoor ambient and there is nothing unusual observed for air in this sealed attic. The relative humidity in the attic is surprisingly low.

The homeowners control the indoor ambient to about 25°C (77°F). The indoor relative humidity fluctuates from 50% to 60%, which yields an excellent comfort conditions that is acceptable by ASHRAE 55 (2013).

Partial pressures of the OD ambient, ID ambient, north- and south-facing sheathing, the foam surface and attic air are displayed to illustrate vapor flows in the attic system, Figure 13. The partial pressure of water vapor in the outdoor ambient is almost always greater than partial pressures in the sheathing, attic and indoor conditioned space. Sealed attics investigated by Miller et al. (2016) in a hot-humid climate have shown the partial pressure in the attic and the foam insulation to exceed the outdoor ambient pressure, indicating the potential storage of moisture in the roof deck. The Venice home shows partial pressures at the roof deck and ridge to be larger than that in the attic and there is the potential for diffusion of water vapor from the deck to the attic air; however, relative humidity measures of the attic air (Figure 12) show the diffusion effect marginal. Water vapor pressure in the attic (a semi-conditioned space) is slightly higher than that of the indoor conditioned space, Figure 13.

FIGURE 11: Sheathing temperature and relative humidity measured between the spray foam and the underside of the sheathing for the north-facing roof deck in Venice, FL.

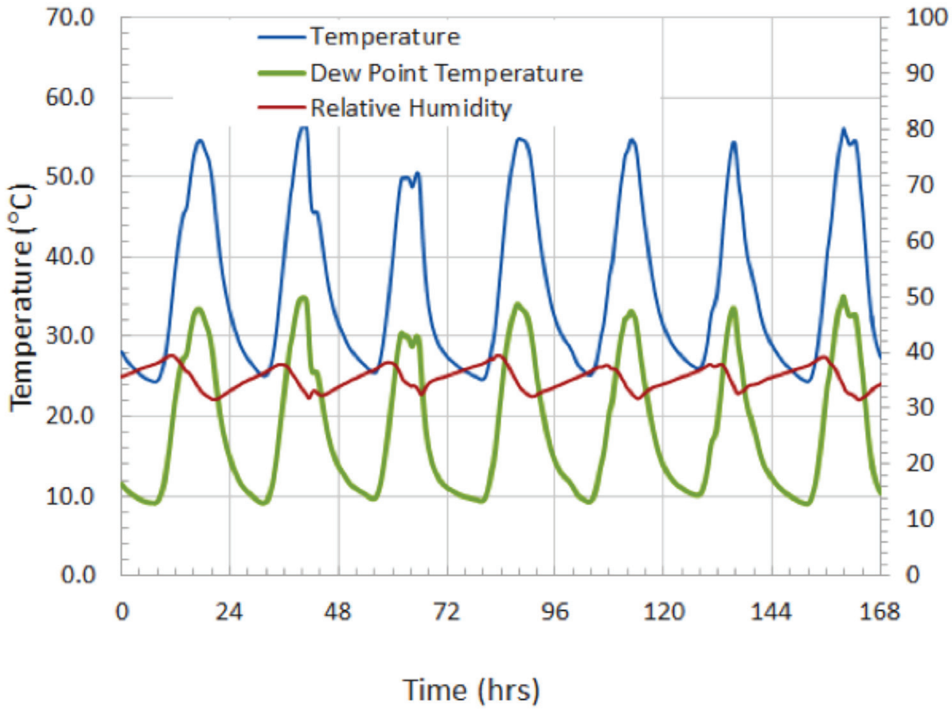
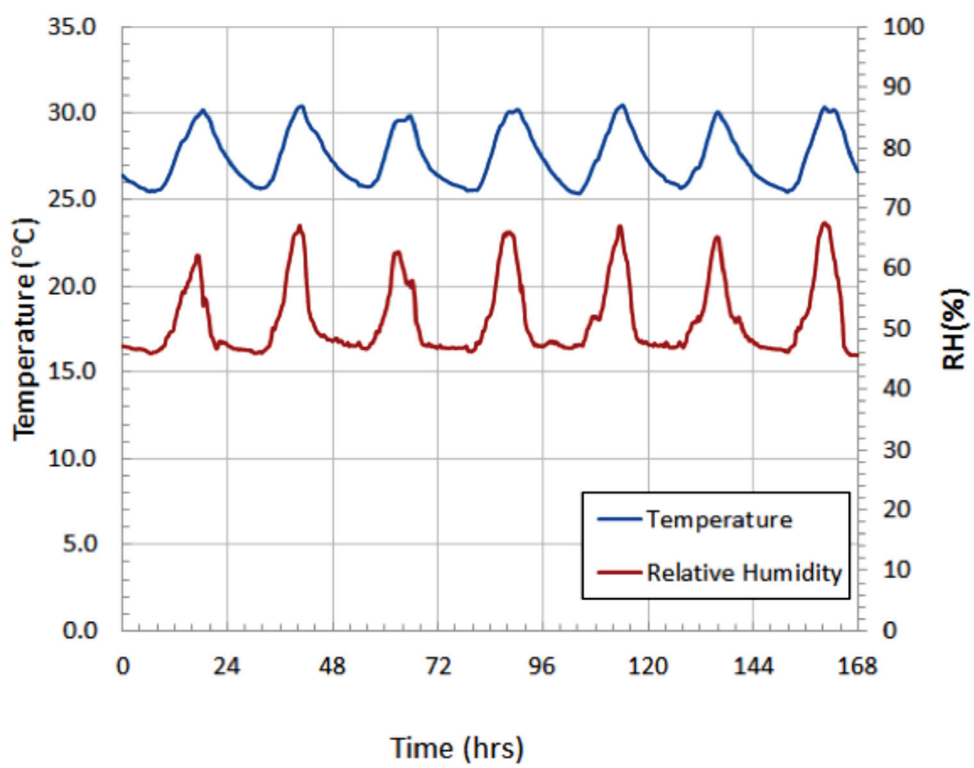
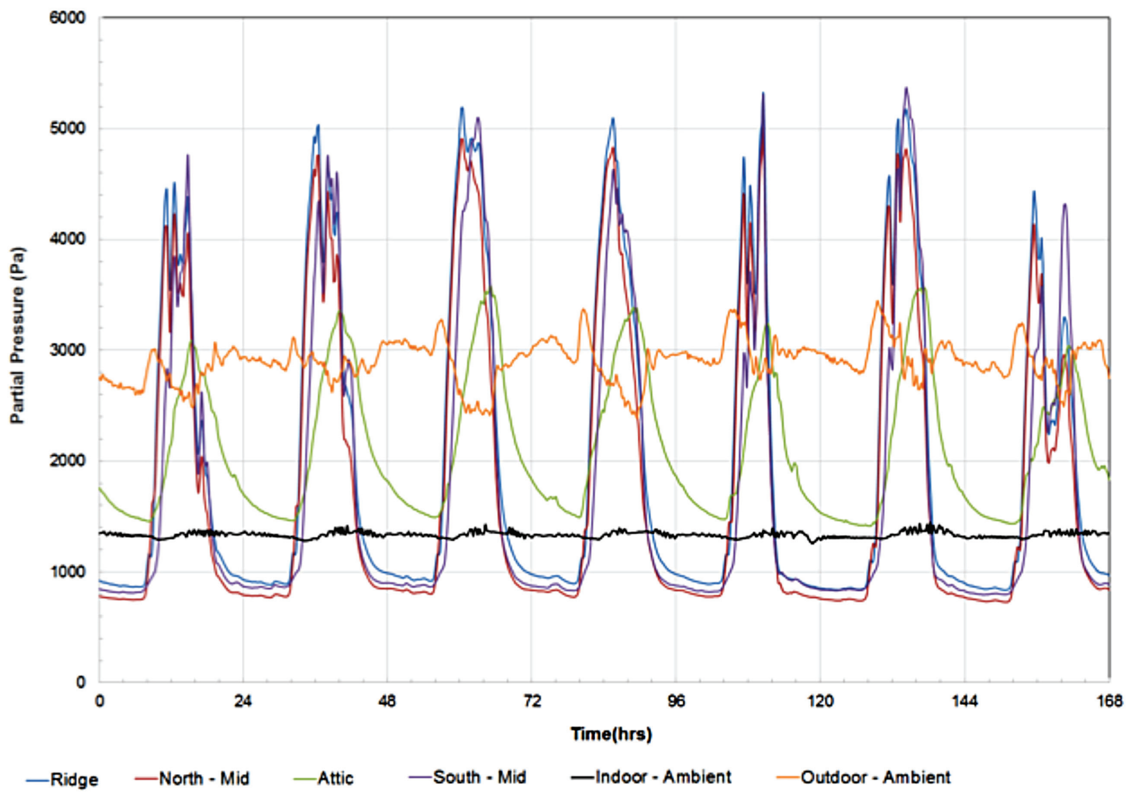


FIGURE 12: The attic air temperature and relative humidity for two contiguous days of data collected for house 1 in Venice, FL.



However, the two TRANE heat pumps and UltraAir dehumidifier have sufficient capacity to remove the latent load. It should also be noted again that the homeowner is a builder who closely managed the construction of the home. The workmanship of the spray foam sealing was excellent. The attic was very clean and well setup with ductwork. Air-handler units were not in the attic. Only the UltraAir dehumidifier was in the attic.

FIGURE 13: The partial pressure of water vapor is shown for the roof deck and attic for two contiguous days of data collected for House 2 in Venice, FL.



3.3 House 3: Asphalt shingle roof with OCSPF sealed attic—HVAC outside

House 3 is located in Orlando, FL, within Climate Zone 2A, defined as hot-humid by ASHRAE 169 (2006) and the FECC. Summers are long, very warm, and fairly humid. Daily thunderstorms are the norm. Winters are mild with periodic invasions of cool to occasionally cold air. July and August are the warmest months in Orlando with an average high temperature of 33°C (91.5°F). The hottest day on record was July 2, 1998 when the temperature hit 38.3°C (101.0°F). During January the average overnight temperature drops to 9.2°C (48.6°F) with the lowest temperature of -7.2°C (19°F) being recorded on January 21, 1985. The average annual precipitation in Orlando is 53.2 inches.

The following images and text are related to House 3 in Orlando, Florida. Figure 14 shows images of the residence from four different directions. The two-story residence has both first- and second-floor attics. Based on accessibility, the attic sensors were located in a sealed, first-floor attic on the northwest part of the house, as shown in Figure 14.

FIGURE 14: House 3 in Orlando, FL.

3.3.1 Field results for sealed attic

The home is a split-foyer type with separate roofs protecting 1st and 2nd floors. The 2nd floor attic was not accessible because of its low 3/12 pitch. Another roof and attic covered the garage and a 3rd attic section was located on the northwest side of the home. The 3rd section served as the test attic. It did not contain ducts or HVAC. The home was well shaded on the west side of the home therefore the roof did not see much irradiance except around high noon. Two split-system air conditioners cooled the building. One air handler was placed in a closet with ductwork run between the 1st and 2nd floors to air-condition the 1st floor. The second unit was placed in a mud room. Its duct was directed up into the attic on the 2nd floor for supplying conditioned air to the upper floor.

Similar to house 1 and 2, as the outdoor air temperature increases, the outdoor relative humidity drops. The temperature and relative humidity of the attic air are both less than that observed for the outdoor ambient and there is nothing unusual observed for air in this sealed attic. Dark heat absorbing asphalt shingles are the roof cover; however, the roof is mostly shaded by trees during the day.

The homeowners control the indoor ambient to about 77°F (25°C). The indoor relative humidity fluctuates from 45% to 50%, which yields an excellent comfort conditions that is acceptable by ASHRAE 55 (2013).

3.4 House 4: Asphalt shingle roof with OCSPF sealed attic

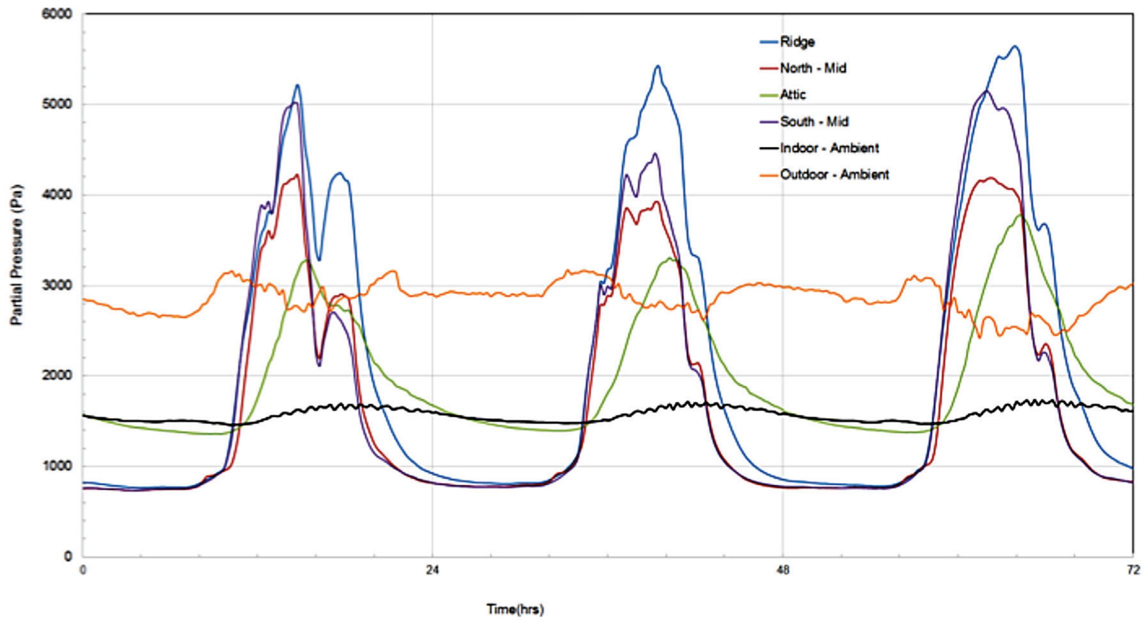
House 4 is located in Gainesville, 40 minutes away from UF campus. Gainesville is classified as Climate Zone 2A being hot-humid by ASHRAE 169 (2006) and the FECC. Summers are long, very warm, and fairly humid. Daily thunderstorms are the norm. Winters are mild with periodic invasions of cool to occasionally cold air. July and August are the warmest months in Gainesville with an average high temperature of 32.8°C (91°F). The hottest day on record occurred in 1952 when the temperature hit 40°C (104°F). During January the average overnight temperature drops to 5.6°C (42°F) with the lowest temperature of -12.2°C (10°F) being recorded January, 1985. The average annual precipitation in Gainesville is 47.3 inches. The following images in Figure 15 are for the Gainesville residence from different directions. This single-story residence has a sealed attic with hip roofs.

FIGURE 15: House 4 in Gainesville.

3.4.1 Field results for sealed attic

The owner of House 4 is retired and occupies the home only during the winter months. He turns the thermostat up to 26.7°C (80°F) during the summer months while he lives up north in Ohio. The setting causes the air-conditioner to remove less latent load from the home. Interestingly, the attic shows excessive amounts of water vapor during hot late afternoons. Three contiguous days of data for House 4 displays the partial pressures of the OD ambient, ID ambient, north- and south-facing sheathing, the foam surface and attic air, Figure 16. The partial pressure of water vapor in the attic exceeds the water vapor pressure in the outdoor ambient during the late afternoon hours. By continuity of water vapor, the only way for this to occur is for moisture stored in the roof deck to be driven out into the attic. The water vapor pressures in the roof deck show the gradient is from the deck into the attic air during the late afternoon. Therefore, heat energy from the sun heats the deck and drives the moisture out of the deck and into the attic air. However, at night the reverse occurs. The partial pressure of water vapor in the attic is greater than that of the roof decks. Therefore, the attic's water vapor diffuses back toward the roof deck which is colder because of night-sky radiation cooling the deck below the outdoor air temperature. The effect is cyclic with the diurnal cycle. Computer simulations are required to judge the amount of storage and accumulation of water vapor in the roof decks over the 1-year field study.

FIGURE 16: The partial pressure of water vapor is shown for the roof deck and attic for two contiguous days of data collected for House 4 in Gainesville, FL.



4. SUMMARY OF AIRTIGHTNESS AND DUCT LEAKAGE MEASUREMENTS

Parker, Fairey and Gu (1993) simulated the effects of ducts on space conditioning Florida homes and observed that air leakage and heat transfer to the duct were major contributors to the peak electrical burden on the FL utility. Cummings et al. (1990) surveyed some 91 Florida homes and measured an average duct leakage rate of 10% of the supply airflow rate. These leaks can cause conditioned air to be dumped directly outside or in the attic or crawlspace rather than delivered to the building. The impact on a particular building will depend on the size of the air duct leak, its location and whether or not the leak is connected to the outside.

The air leakage tests performed in each house were:

1. Duct Blaster Test – To determine the total duct leakage,
2. Guarded Duct Blaster Test – To determine the duct leakage to the unvented attic,
3. Blower Door Test – To determine the airtightness of the house, and
4. Guarded Blower Door Test – To determine the attic leakage to the outdoor ambient.

4.1 Duct Blaster Test – To determine the total duct leakage

A total duct leakage test was conducted to measure the leakage rate in the entire duct system, when the ducts are subjected to a uniform test pressure. The total duct leakage test measured both the duct leakage to the conditioned and unconditioned spaces. To perform the total duct leakage pressurization test, one end of the flexible extension duct was connected to the exhaust of the duct blaster fan and the other side was connected to the return vent of the duct system. All supply vents were blocked, with the duct pressure being measured through one supply vent. A multi-point pressurization test was performed by pressurizing the duct system in the order of 20, 25, 30, 35, 40 Pascals.

4.2 Guarded Duct Blaster Test – To determine the duct leakage to the unvented attic

To determine the duct leakage into the attic, one duct blaster fan was connected to the return of the duct system and a blower door brought the home to the same pressure as the ducts. This negates any airflow between the duct system and the interior of the home, thus the measured leakage is only the duct leakage to the attic. The pressurization test was conducted by pressurizing the attic and the duct system in the order of 10, 15, 20, 25, 30 Pascals.

To perform a multi-point depressurization test, the home was depressurized by one blower door fan, while the duct system was depressurized by using the duct blaster fan. The pressure in the duct system was varied by order of 10, 15, 20, 25, 30 Pascals.

4.3 Blower Door Test – To determine the airtightness of the house

To determine the airtightness of the building envelope, the home is left in usual condition (with attic hatch and garage door closed). The blower door fan is used to pressurize and depressurize the house. This test determines the total leakage out of the building envelope due to constructional leaks – through gaps in doors and windows, gaps in the roof to wall and wall to ceiling connections. The blower door fan was fitted to an external door and all doors and windows were closed. The house was pressurized and depressurized by the blower door fan.

4.4 Guarded Blower Door Test – To determine the attic leakage to the outside of the house

The guarded blower door test was conducted to determine the attic leakage to the outside of the house. This test was conducted by fitting a blower door to an exterior door and two duct blasters to the attic. Two duct blasters were used since one duct blaster fan was not sufficient to pressurize the attic to the required test pressure. This configuration negates any leakage between the attic and the home since they are both at the same pressure. Therefore, the flow through the duct blaster fans is a measure of the leakage in the attic to the outside.

The blower door fan and the duct blaster fans were operated by utilizing the TECLOG software, the blower door fan was used to pressurize the conditioned space. The duct blaster fans were used to pressurize the attic. The blower door fan maintained the test pressure inside the house, the air blown through the duct blaster escaped through the leaks to the outside of the attic. The test pressures were in the order of 30, 35, 40, 45, 50 Pascals. The same test was carried out for depressurization testing as well.

Results of the Duct Blaster Test, Guarded Duct Blaster Test, Blower Door Test, and the Guarded Blower Door Test are listed in Table 3 in order to compare these houses. For House 2 the duct leakage to the attic could not be determined directly, so instead the duct leakage to the conditioned space was measured then subtracted from the total duct leakage results to yield duct leakage to the attic. To determine the duct leakage into the conditioned space, one duct blaster fan is connected to the return vent and one duct blaster fan is connected into the attic opening.

5. OUTCOME

The Building Envelope Systems Research Program at ORNL has factual data on sealed attic performance at two separate field demonstrations (Natural Exposure Test Facility in Charleston, SC and the Campbell Creek Home demonstration in Knoxville. TN). The studies helped

TABLE 3. Air Leakage Test Results for all Homes.

Parameter	House 1	House 2	House 3	House 4
	West Palm Beach	Venice	Orlando	Gainesville
Envelope Air Leakage CFM at 50 Pa				
Total Air Leakage	4298	1820	4143	3718
Attic Air Leakage	2510	656	506	187
Living Space Air Leakage	1794	1164	3624	3531
Envelope Air Leakage Ratio %				
Attic Air Leakage	58%	36%	12%	5%
Living Space Air Leakage	42%	64%	87%	95%
Envelope Air Leakage ACH at 50 Pa				
Total Ail Leakage	6.7	2.2	8.6	5.2
Attic Space Air Leakage	22.1	5.12	5.7	-
Living Space Air Leakage	3.62	1.65	9.6	-
Duct Leakage CFM at 25 Pa				
Total Duct Leakage	115	579	608	655
Attic Duct Leakage	73	116	-	-
Living Space Duct Leakage	42	464	608	-
Duct Leakage Ratio %				
Attic Duct Leakage	64%	20%	0%	-
Living Space Duct Leakage	36%	80%	100%	-
Duct Leakage CFM/ft²				
Total Duct Leakage	0.11	0.16	0.26	0.21

formulate and benchmark a risk assessment methodology, Pallin et al. (2014). The technique predicts the risk of water damage to roof sheathing and the deviance of the conditioned space from the ASHRAE Standard 55 comfort conditions. ORNL has developed an exclusive capability to model and simulate the hygrothermal dynamics of sealed, semi-conditioned attics.

The ORNL/UF team identified homes in Florida with sealed attics from which field demonstrations were setup for documenting data of sealed attics in Florida climate zones CZ-1A and CZ-2A. Data collection commenced June 1, 2016. During the heat of the day for all homes, the moisture content of the sheathing drops which implies that moisture moves from the sheathing, into and through the foam and increases the relative humidity of the attic air. As the sun sets, the roof cools and moisture is reabsorbed from the attic air and the foam back into the roof deck. Absolute humidity probes placed between the ocSPF and the sheathing shows the vapor to not condense; it remains a flow of vapor driven by diffusion. The

FRSA has provided funds to continue data collection to enable assessment of the thermal and hygrothermal performance during the moderate winter months in Florida. The FBC approved continuation of the field study. The ORNL/UF team will conduct analytical assessments in parallel to the field study.

ORNL will exercise and fine-tune the computer toolkit to Florida specific climate and to the Florida Energy Conservation Code (2014). Simulations for the probabilistic modeling of CZ-1A and 2A will identify the key variables impacting indoor comfort and the durability of roof assemblies against moisture. As example, the overall airtightness of the building enclosure and indoor moisture supply has the highest impact on both the indoor climate and the moisture durability of an unvented attic roof construction. In addition, the moisture durability of the roof construction is very sensitive to air leakage rates that are not high enough to substantially affect the temperatures in the air leakage pathway through which it travels. Therefore the simulations would provide the Florida Building Commission guidelines (ranges of permissible air leakage rates) that would classify the risk for a given sealed attic construction. An acceptance criterion for a sealed attic job could be defined and used by the FBC to ensure good sealed attic design.

ABBREVIATIONS:

ACH	Air changes per hour
BEopt	Building Energy Optimization Software
ccSPF	closed cell Spray Polyurethane Foam
FBC	Florida Building Commission
FECC	Florida Energy Conservation Code
FRSA	Florida Roofing and Sheetmetal Association
HVAC	Heating, Ventilation and Air Conditioning
ocSPF	open cell Spray Polyurethane Foam
OSB	oriented strand board
RH	Relative Humidity

DISCLAIMER

This report presents the findings of research performed by the University of Florida and Oak Ridge National Laboratory. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the sponsors, partners and contributors.

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