Phase II Status Report:

Analytical Assessment of Field Data to Predict Moisture Buildup in Roof Sheathing of Sealed Attics

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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
PRAT	Probabilistic Risk Assessment Toolkit
RH	Relative Humidity

EXECUTIVE SUMMARY

Traditional single-family residential houses have attic soffit and ridge vents that air exchange between the attic and the outside environment. Leaky ductwork in these vented attics lead to energy penalties. To conserve the lost energy, a new construction method evolved by spraying polyurethane foam insulation to the underside of roof sheathing thereby sealing the attic vents and containing the duct leakages within the attic. However, due to differences in the moisture buffering properties and drying rates between the wood sheathing and the spray foam insulation, a condensation potential arises that could lead to moisture accumulation at the sheathing-to-insulation interface. This research seeks to better understand the condensation potential in order to develop a design guideline for the use of spray polyurethane foam insulation in sealing attics.

The Florida Building Commission (FBC) contracted the University of Florida (UF) and Oak Ridge National Laboratory (ORNL) to monitor the hygrothermal performance of four houses with open-cell spray polyurethane foam (ocSPF) insulated attics in hot-humid climate zone 2A of Florida. The four homes were surveyed and selected with the help of Florida Roofing and Sheet Metal Contractors Association (FRSA). Selected field locations are in West Palm Beach, Venice Beach, Orlando and Gainesville. The air tightness of the building envelope and the duct systems were determined using blower door and duct blaster equipment. The moisture movement in the attic is studied for a whole year by using temperature, humidity and moisture sensors installed within the attic. The data collected is used to validate a numerical toolkit developed by ORNL, Probabilistic Risk Assessment Toolkit (PRAT) that can predict the hygrothermal movement in sealed attics and the moisture content in the wood roof sheathing. Various parameters affecting the hygrothermal performance are considered by this toolkit to accurately predict the actual conditions in a sealed attic. The selected input parameters for the analysis are: leakage areas from 1) the attic to the outside, 2) indoor space to the outside and 3) indoor space to the attic as well as 4) the attic duct leakage, 5) interior heat generation, 6) interior moisture generation and 7) thermostat set points. A sensitivity analysis detailing the effect of most affecting input variables will be performed.

We compared the time histories of hygrothermal properties of the four Florida attics against 1000 annual PRAT simulations for a prototype house model in climate zone 2A and found some agreement. This research is ongoing and the next step will be to include measured house characteristics in the PRAT model to improve the predictive accuracy of the toolkit. The results will lead to the development of sealed attic guidelines that the FBC can review for inclusion in the Florida Energy Conservatory Code.

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.

1. INTRODUCTION

The goal of this project is to evaluate the moisture content accumulation in the roof sheathing of sealed attic homes in Florida. The Florida Building Commission (FBC) contracted the University of Florida (UF) and the Oak Ridge National Laboratory (ORNL) to monitor the hygrothermal performance of four single-family residential homes in Florida. In Phase I (Prevatt et al. 2016); we selected and instrumented four homes from Florida locations, namely; West Palm Beach, Venice, Orlando and Gainesville. The four houses are located in the hot-humid climate zone 2A of Florida (Table 1). The West Palm Beach house is near the northern border for climate zone 1A. All houses had attics sealed with open-cell spray-applied polyurethane foam (ocSPF) insulation. This report summarizes the progress of combined experimental and analytical work performed to date.

Table 1. Characteristics of Selected Florida Homes

Characteristic	House 1	House 2	House 3	House 4
Location	West Palm Beach	Venice	Orlando	Gainesville
Attic	Sealed ocSPF	Sealed ocSPF	Sealed ocSPF	Sealed 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 / Condition 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
Roof deck insulation ($h \cdot ft^2 \cdot °F/Btu$)	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
***FECC code in effect during application of spray foam to seal attic by prescription requirement.**				

1.1 Field Data Acquisition

In Phase I Prevatt et al. (2016), we installed temperature, relative humidity and moisture sensors in each of the four attics to monitor the movement and potential storage of moisture in the roof sheathing. Acquisition of this field data is an ongoing process, done wirelessly through data loggers that upload the data every day. We conducted air leakage tests using blower doors and duct blasters to quantify the overall air-tightness of the building envelope and the duct air leakage.

1.2 Probabilistic Risk Assessment Toolkit (PRAT)

For Phase II, ORNL developed a Probabilistic Risk Assessment Toolkit (PRAT) that can predict the indoor climate and moisture content in the roof sheathing. This toolkit utilizes three software packages – Building Energy optimization, BEopt (Christensen et al.(2006)) and Energy Plus (Crawley et al.(2000)) developed by the Department of Energy (DOE) for building energy simulations and WUFI 1D (Karagiozis et al. 2011) for hygrothermal modelling to predict the roof sheathing moisture content.

2. SCOPE OF WORK

The project proposal states the following milestones and deliverables (Table 2).

Table 2 Phase 2 Milestones and Deliverables

Task	***Milestone & Deliverables***	***Completion Date***
Task 1.	**– Benchmarks of PRAT against Field Data**	
	• Roof sheathing moisture content compared to probabilistic moisture content distribution from toolkit	February, 2017
	• Simulations using fixed details from field sites for comparing moisture content in field to simulation result	March, 2017
	• Interim Report showing comparison of field data to PRAT simulations	30 April, 2017
Task 2.	**– Sealed attic Sensitivity Analysis and Recommendations**	
	• Complete PRAT simulations	April, 2017
	• Complete sensitivity analysis to see which probabilistic variables most affect each attic design	May, 2017
	• Final Report summarizing sensitivity analysis and recommendations to FBC to construct moisture durable sealed attics	15 June, 2017

Task 1 of the project is to benchmark the probabilistic toolkit against field-measured data. The scope of work for Task 1 is as follows.

2.1 Identify Key Variables Affecting Moisture Accumulation in Roof Sheathing

- Develop prototype house model for climate zone 2A using BEopt software
- Use Energy Plus to compute indoor and attic climate and air leakage for prototype model
- Use Energy Plus generated outputs and outdoor climate in WUFI 1D software to predict the probabilistic roof sheathing moisture content
- Compare field-measured and prototype model results to identify key input variables affecting moisture content accumulation in roof sheathing

2.2 Benchmark Toolkit with Field-measured Data

- Develop analytical models of the four field homes using the BEopt software
- Use Energy Plus software to compute the climates of the indoor conditioned space and the semi-conditioned attic space. Energy Plus uses the field measurements for air leakage in the computations.
- Compute probabilistic roof sheathing moisture content using WUFI 1D software
- Benchmark Toolkit against field measured temperature, relative humidity and moisture content data for the roof sheathing

3. LITERATURE REVIEW

This literature augments the literature review presented in the Phase I report, Prevatt et al. (2016). Main findings from the literature review are also summarized in Table 3.

3.1 Properties of Wood and Spray Foam Insulation

Rudd (1999) studied the effects of moving the insulation from the ceiling to the roof plane, producing sealed semi-conditioned attics. Based on computer simulations, he observed that the higher attic relative humidity at nighttime drives the moisture into the wood and the solar radiation pushes moisture back into the attic during the day. Lstiburek (2006) recommended climate zone specific construction methods for unvented attics. For all climate zones, Lstiburek suggested the use of a fire retardant and air barrier separating the insulation from the interior of the house.

3.2 Behavior of Sealed Attics in Hot-Humid Climates

Shreyans (2011) conducted field evaluations before and after installing ccSPF insulation under the roof sheathing in a vented attic home. He observed a 5% reduction in energy consumption and 20^{o} F reduction in peak summer attic temperatures. Shreyans used WUFI to simulate the long-term moisture content of the sheathing and observed a potential for accumulation of moisture greater than 20% in ccSPF-retrofitted attics susceptible to air leaks and roof leaks. However, the peak moisture contents in the simulated unvented roof assembly was lesser than the vented roof assembly. (Colon, 2011) studied the hygrothermal behavior of an ocSPF sealed attic house in Florida for a whole year. Colon observed diurnal relative humidity (RH) fluctuations in the attic and seasonal variation of moisture in the attic. An increase in the moisture content levels was observed during the winter months of October through February, however within the 20% threshold for mold growth. Grin et al. (2013) studied the effect of rainwater intrusion through roof leaks on the moisture durability of sealed attics. Using WUFI and field studies, the report concluded that roof systems with ocSPF allowing less than 1% of the annual rainfall total leakage were safe against moisture accumulation and roof decay.

3.3 Hygrothermal Analysis of Sealed Attics

Pallin et al. (2013) investigated four unvented and four vented houses in mixed-humid climate and found that homes with sealed attics had reduced energy consumptions and despite high interior moisture levels, there was no sign of material degradation in the attic. Pallin suspected that his numerical models devoid of air leakage parameters could not accurately represent field house characteristics and recommended the inclusion of air leakage testing for future studies. Boudreaux et al. (2014) performed building energy simulations and hygrothermal analysis on one of the sealed attic homes from Pallin study and determined that size of air leakage areas and indoor moisture generation rates affected the moisture performance of sealed attics by producing moisture contents greater than the 20% threshold for mold formation and decay. Boudreaux also discussed the variables affecting the indoor air comfort of sealed attic homes. Indoor moisture generation rates and attic-to-outside air leakage were found to be the deterministic variables using Energy Plus simulations.

3.4 Other Literature

Straube et al. (2002) studied several parameters affecting the moisture performance of unvented attics. Using WUFI simulations, Straube determined that outdoor climate and interior humidity levels affected the condensation potential at the roof sheathing. Straube concluded that code specific ocSPF and ccSPF insulations produced moisture levels below 20% at the roof sheathing. Miller et al. (2016) compared thermal and hygrothermal performance of an attic sealed with closed-cell spray foam, and an attic sealed with open cell spray foam to a conventionally vented attic in a hot, humid climate. The vented attic showed less moisture movement in the sheathing than those sealed with either open- or closed-cell spray foam. Miller concluded that the use of permeable spray foam in a hot humid climate inadvertently allows moisture buildup at the sheathing. The moisture transfers back to the attic air as solar irradiance bears down on the roof. Lstiburek (2015) came to similar conclusions that a moisture accumulation potential is imminent in ocSPF-sealed attics in hot-humid climates. Lstiburek recommended the use of a dehumidifier in the attic if ocSPF was used to seal the attic.

Table 3 Literature Review on Sealed Attics

Author & Year	Published by	Research Purpose	Methodology	Climate Zone	Discussion
Rudd et al. 1999	ASHRAE Journal	Effect of sealing attic with spray foam insulation	Finite element modelling	2,3	High attic humidity at night increases moisture content in sheathing. Solar radiation during day drives moisture back into the attic
Lstiburek et al. 2006	Building Science Corporation	Guidelines to construct sealed attics	Computer simulation + field evaluation	1-7	Use of thermal barrier separating occupied zone and unoccupied attic
Straube et al. 2010	Journal of Building Physics	Condensation potential at sheathing to insulation interface	WUFI simulations + field measurements	6,7	Outdoor climate and high indoor moisture generation can cause condensation. Moisture levels below 20% observed
Shreyans, 2011	University of Florida	Effect of retrofitting attic with ccSPF	WUFI + field evaluation	2	1in ccSPF enough to reduce mean attic temperatures from 124°F to 105°F, in turn reducing energy consumption by 26%
Colon, 2011	Florida Solar Energy Commission	Behavior of ocSPF unvented attics	Field evaluation	2	Diurnal relative humidity patterns and seasonal variation in moisture content, below the 20% threshold
Grin et al. 2013	Building America Report	Effect of rain water intrusion through roof leaks in unvented attics	WUFI simulation + field evaluation	2,3	Safe leakage limit of 1% of the annual rainfall above which moisture problems occur causing decay and deterioration of wood
Pallin et al. 2013	Oak Ridge National Laboratory	Comparison of vented and unvented attics	WUFI + field evaluation	4	Unvented attics had lesser energy consumption and despite high indoor and attic RH levels, no sign of material degradation
Boudreaux et al. 2014	Oak Ridge National Laboratory	Hygrothermal analysis of unvented attics to identify parameters affecting moisture accumulation	Energy Plus + WUFI simulations	4	High indoor moisture generation rates and high air leakage areas can cause moisture content > 20% in roof sheathing
Miller et al. 2016	ASHRAE Conference	Comparison of ocSPF, ccSPF sealed attics with vented attics	WUFI simulations	2	High attic humidity levels serve as a potential for moisture accumulation in hot-humid climates
Lstiburek, 2015	Building Science Corporation	Behavior of ocSPF sealed attics in hot-humid climates	Computer simulations	2	Moisture buildup can be controlled by using a dehumidifier in the attic

4. FIELD DATA FOR FOUR FLORIDA HOUSES

For each of the four Florida homes, the data acquired through air leakage testing and installed attic sensors are analyzed to quantify the moisture accumulation in the roof sheathing. The results of the field-testing are presented in Tables 4 and 5.

4.1 Air Leakage Testing

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.

The envelope of House 2 was the most air tight of all four homes; its Air-Change per Hour value in 50% (ACH50) was 2.2, compared to 5.2 for House 4, 6.7 for House 1 and 8.6 for House 3. House 1 was poorly sealed and had the largest air leakage from the attic, 2,510 CFM as compared to all other homes that has air leakage of less than 700 cfm. However, the total duct leakage in House 2 in cfm per square foot of footprint was roughly the same as in the other three houses.

For House 2 the duct leakage to the attic could not be determined directly, so we instead measured the duct leakage to the conditioned space and subtracted this from the total duct leakage yielding duct leakage to the attic. To determine the duct leakage into the conditioned space, we connected one duct blaster to the return vent and one duct blaster to the attic access and performed the test.

Table 4 Envelope Air Leakage Results

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	-

Table 5 Duct Leakage Results

Parameter	House 1	House 2	House 3	House 4
	West Palm Beach	**Venice**	**Orlando**	**Gainesville**
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

4.2 Reducing Measured Climate Data

Each house has 16 sensors installed in the attic to measure the temperature, RH and moisture content at various locations. All homes had a similar layout of sensors for consistency interpretating data among the 4 homes. These measured parameters are available in engineered units. The moisture content of wood is measured in the form of electrical resistance and is converted into % MC using an algorithm developed by ORNL and benchmarked against data from Garrahan (1989), Carli, TenWolde and Munson (2007) and Huber Engineering (2013).

Table 6 Location of Sensors

Type of Sensor	Location of Sensor
A – MP and T/RH at center of cavity; MP near joist	14-ft, 6-in away from ridge on north
B – MP and T/RH at center of cavity; MP near joist	10-in away from ridge on north
C – T/RH at center of cavity	14-ft, 6-in away from ridge on south
D – T/RH outside the building envelope	Under eave on east wall

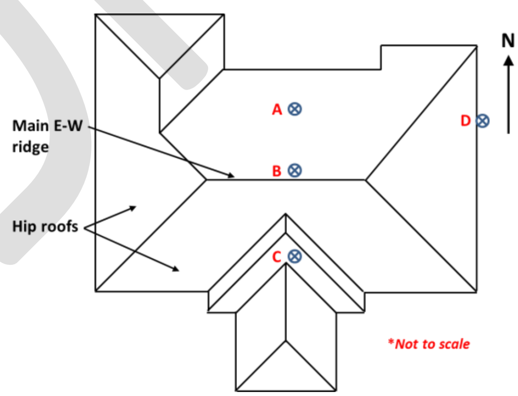


Figure 1 Location of Sensors in House 4 - Gainesville

Data is measured every 30-s and is reduced as raw data averages over 15-minute, 60-minute, and 24-hour intervals. Post processing of the raw data yields weekly or annual records containing data averages over 15-minute and 60-minute intervals for all four houses. We have analyzed 60-minute data in this report.

4.3 Time History of Moisture Content

The following figure shows the time history of the moisture contents for all four home locations (Figure 2). The moisture content levels remain well below the 20% level throughout the summer. Starting from about October, the data shows a slight increase in the moisture content. However, the measured moisture levels are still well below the point of inception for mold, mildew or wood rot, Figure 2.

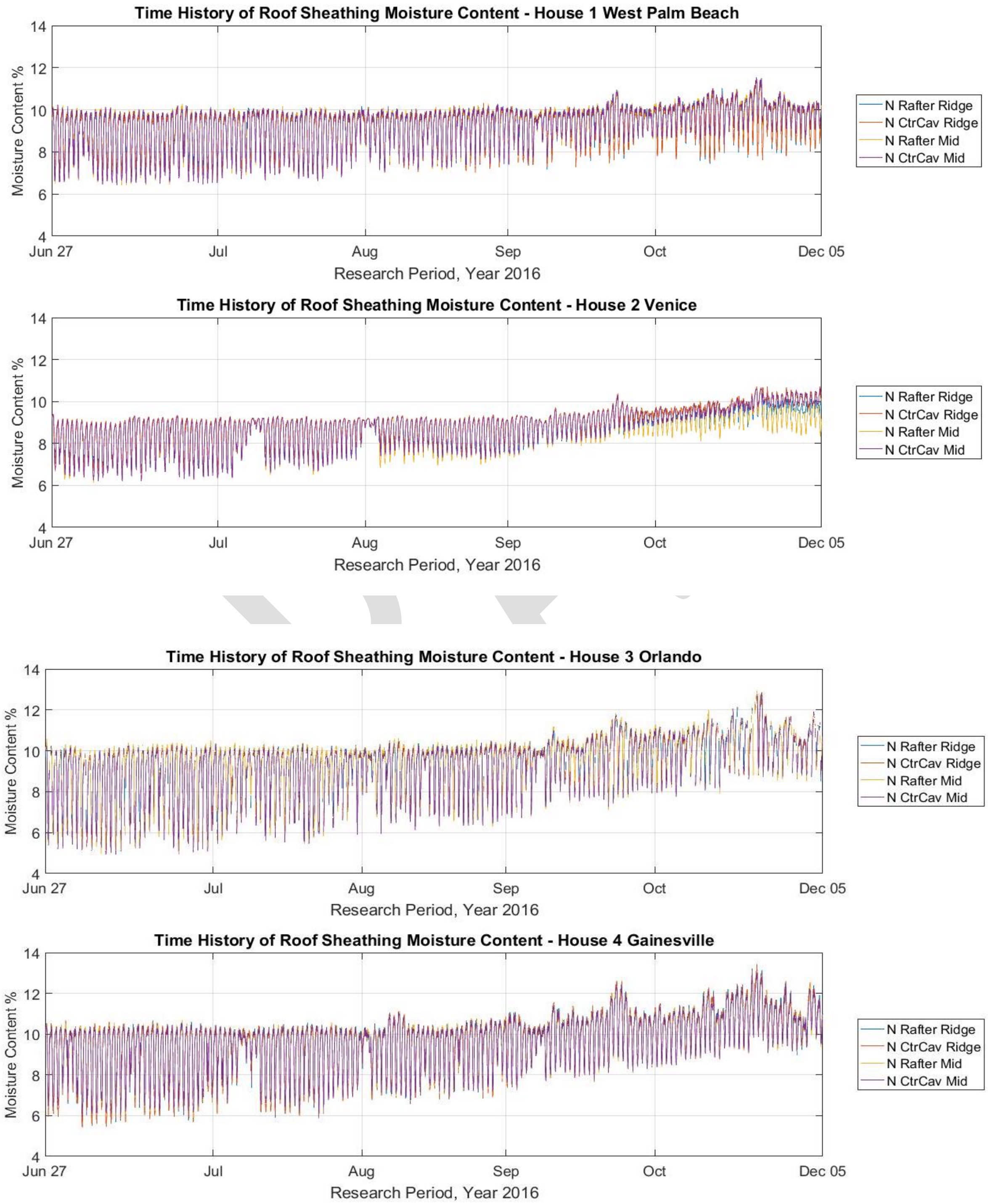


Figure 2 Roof Sheathing Moisture Content in Four Homes, Jun'16 to Dec'17

4.4 Hurricane Matthew Effect in House 1

In early October 2016, Hurricane Matthew tracked along the eastern seaboard of Florida and it affected our results. House #1, situated in West Palm Beach was the closest to the path of the hurricane. The measured data is used to visualize the hygrothermal behavior of the attic during the hurricane. Cloud cover and precipitation caused the sheathing's temperature to drop about 15°C below temperature levels shown for three consecutive and earlier days, Figure 3. In addition, the relative humidity measured in the attic does not show the same trends observed for the three earlier days seeing clearer sky. The diurnal variation of the moisture content of the roof sheathing also differed from that observed for the three earlier days. Cloud cover shaded the roof during the storm, the roof was wet from precipitation but the moisture content did not raise or drop during the afternoon hours as observed for the three earlier days of data. The differences in trends are due to the presence (3 days prior to storm) and absence (during storm) of solar radiation.

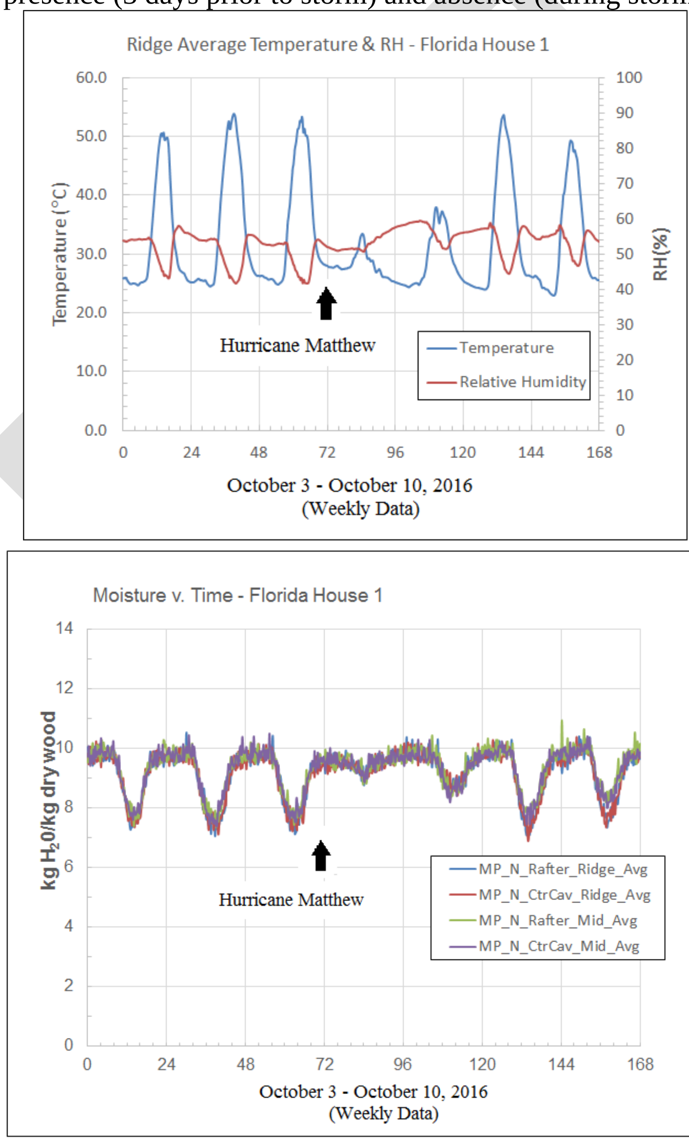


Figure 3 Effect of Hurricane Matthew on Measured Climate of House 1, October 3rd – 10th, 2016

4.5 Indoor Climate vs ASHRAE Comfort Zone

ASHRAE Standard 55 defines an indoor comfort zone - a range of ambient house temperatures and humidity ratios resulting in indoor conditions comfortable to occupants. The green shaded area in Figure 4 represents this comfort zone. We compare field-measured indoor climates with ASHRAE comfort zone to determine the occupant comfort levels in the sealed attic homes. House 1 is a retrofit home and has a large attic-to-outside leakage area. House 2, 3, 4 had spray foam installed at the time of construction and have smaller attic-to-outside leakage area. We have identified an inverse trend between attic air leakage and indoor air comfort.

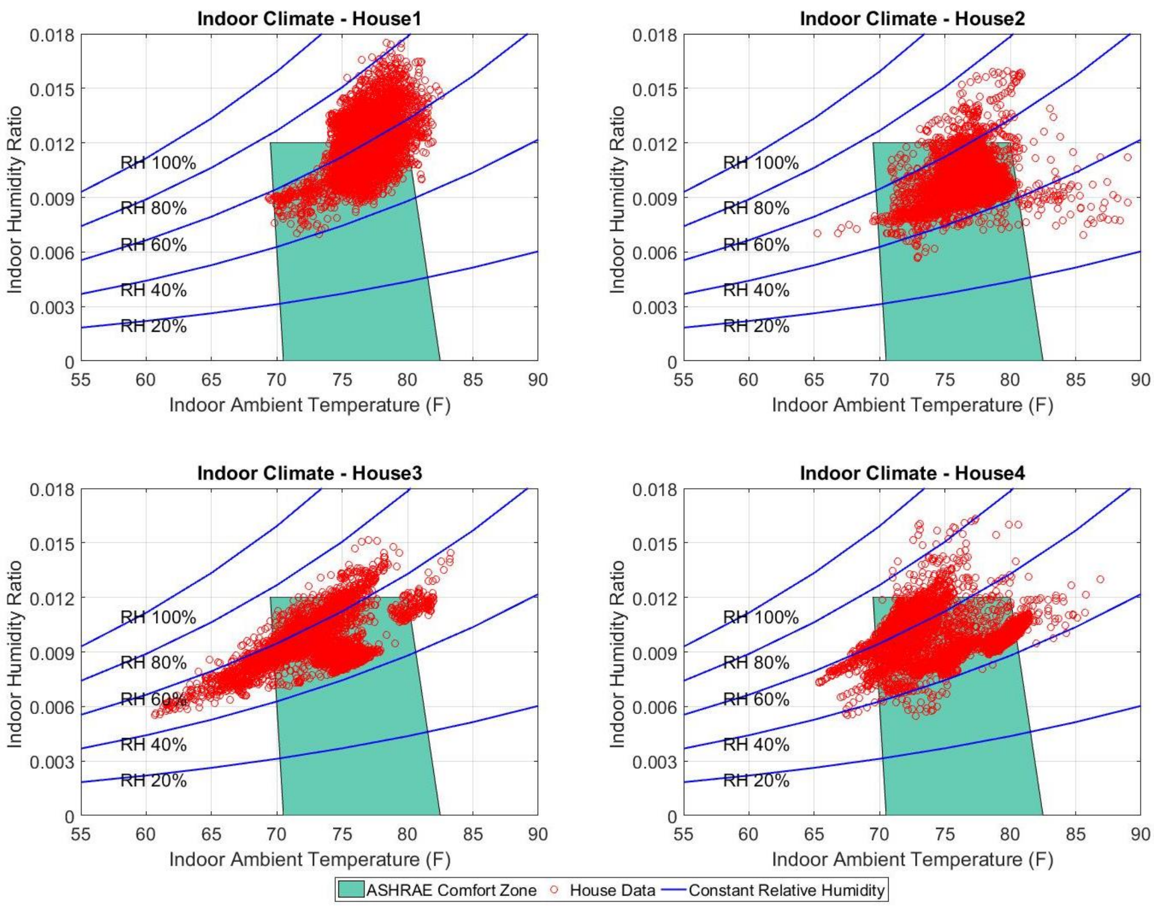


Figure 4 Comparison of Measured Indoor Climate vs ASHRAE Comfort Zone. Red circles indicate measured hourly data. The blue lines represent the humidity levels in the indoor conditioned space of all four homes. The indoor air comfort is quantified by the percentage of red dots within the green shaded area.

5. STRUCTURE OF THE PROBABILISTIC RISK ASSESSMENT TOOLKIT

The Probabilistic Risk Assessment Toolkit is a probabilistic toolkit for predicting the indoor climate and roof sheathing moisture content. The toolkit utilizes Building Energy Optimization software (Christensen et al. 2006) to numerically model the four field houses with specific plan dimensions and construction materials. House characteristics such as air leakage and occupant behavior are varied to produce probabilistic indoor climate and attic air climate using Energy Plus (DOE 2011), a building energy simulation software. The Energy Plus output data in combination with actual external climate data are fed into a roof configuration numerical model developed in WUFI 1D (IBP 2011), a hygrothermal analysis software, which predicts the moisture content accumulation at the interface of roof sheathing and ocSPF. Table 7 tabulates the inputs required by each software of the toolkit.

Table 7 PRAT Inputs

Building Energy Optimization BEopt	Energy Plus E+	WUFI 1D
• House location and climate throughout the research period • House geometry and material properties • Building occupancy conditions (number of people, fans, lights, how many meals cooked per day, number of baths per day etc.) • Measured thermostat temperatures • HVAC schedules • Effective Leakage Areas (ELA) for leakages from attic to outside, living space to outside, living space to attic.	• Attic duct leakage • Interior moisture generation rate • Interior heat generation • Thermostat set points	• Roof section details • Air leakage rates from E+ • Outdoor Climate

5.1 Probabilistic Assessment of Prototype House

In preparation for the field study, ORNL used BEopt to model a generic single-family two story home specific to climate zone 2A. A base Energy Plus input file (.idf file) was created and, on command, Energy Plus varied the base inputs stochastically to produce a statistical database of simulations for evaluating the probability of moisture accumulation in the roof sheathing. We have used the numerical results for this preliminary prototype model to identify key variables affecting the moisture performance of sealed attics.

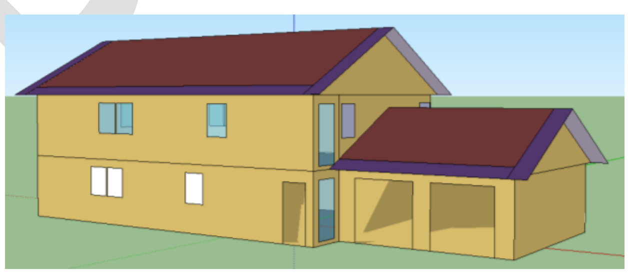


Figure 5 Prototype House Model Created in BEopt for Climate Zone 2A

The key input variables used in the simulations and the test matrix follow in Table 8:

Table 8 Matrix of Key Input Variables

Input Parameter	Low	Medium	High
Attic Floor Leakage Area (in^2)	14.59	23.44	34.50
Attic to Outside Leakage Area (in^2)	11.64	59.53	329.08
Indoor to Outside Leakage Area (in^2)	7.29	52.07	245.64
Duct Leakage Rate (kg/s)	0.0003	0.0055	0.021
Indoor Moisture Generation Rate (lb/hr)	5.68	19.31	50.10

The outputs from E+ includes temperature and relative humidity of the interior space and attic space as well as air flow from the attic to the outside (since no attic is perfectly sealed) for each of the 1000 simulations for Climate Zone 2A.

5.2 Comparison of Simulated and Measured Data

Preliminary simulations that were conducted by ORNL for Climate Zone 2A are displayed in Figure 6 and 7 comparing the values for simulated and measured relative humidity and temperature, respectively. Temperature and relative humidity. The blue band represents the simulation set for 1,000 1-year long simulations, and the red band represents the measured field data for each home to date. The measured attic temperatures for all houses have a similar pattern, and fall above the mean of the simulated temperatures. The measured relative humidity values vary over the diurnal cycle for each house, and are generally below or around the mean of the simulated set.

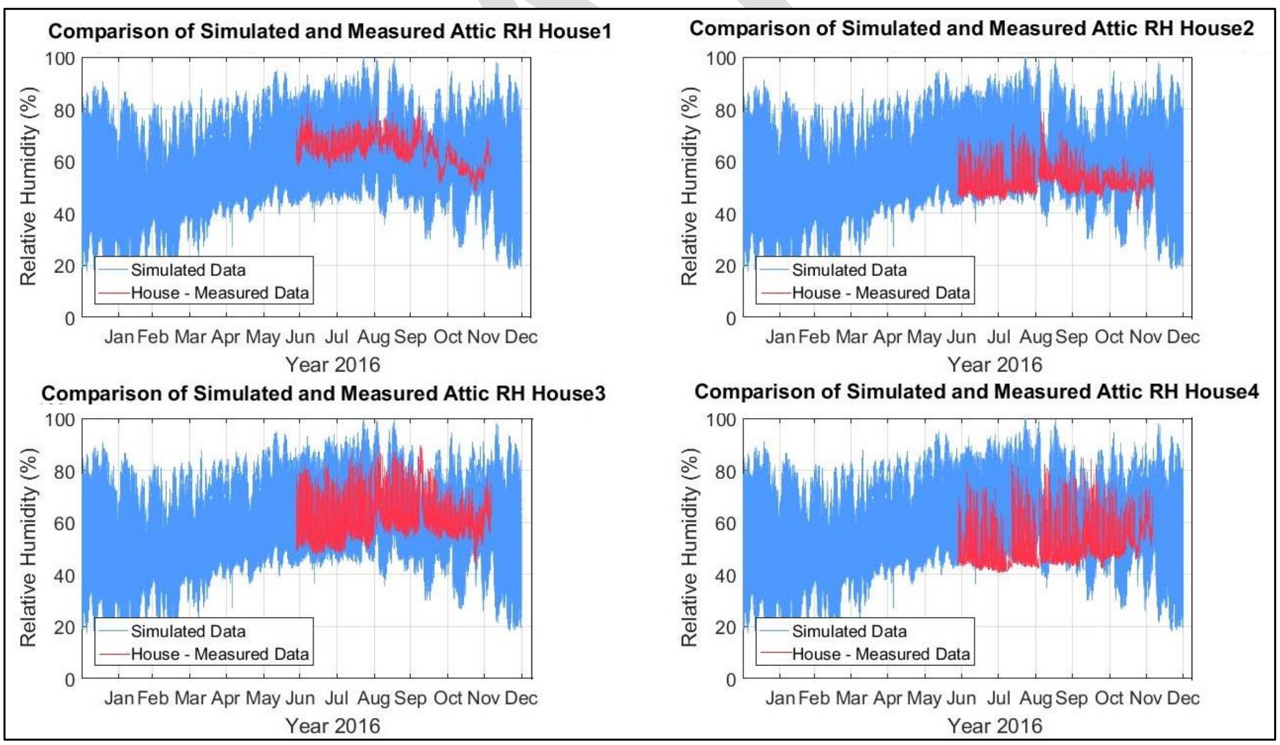


Figure 6 Comparison of Measured and Energy Plus Simulated Attic Relative Humidity. Blue band is simulated data for Climate Zone 2A; red band is Florida field data per home.

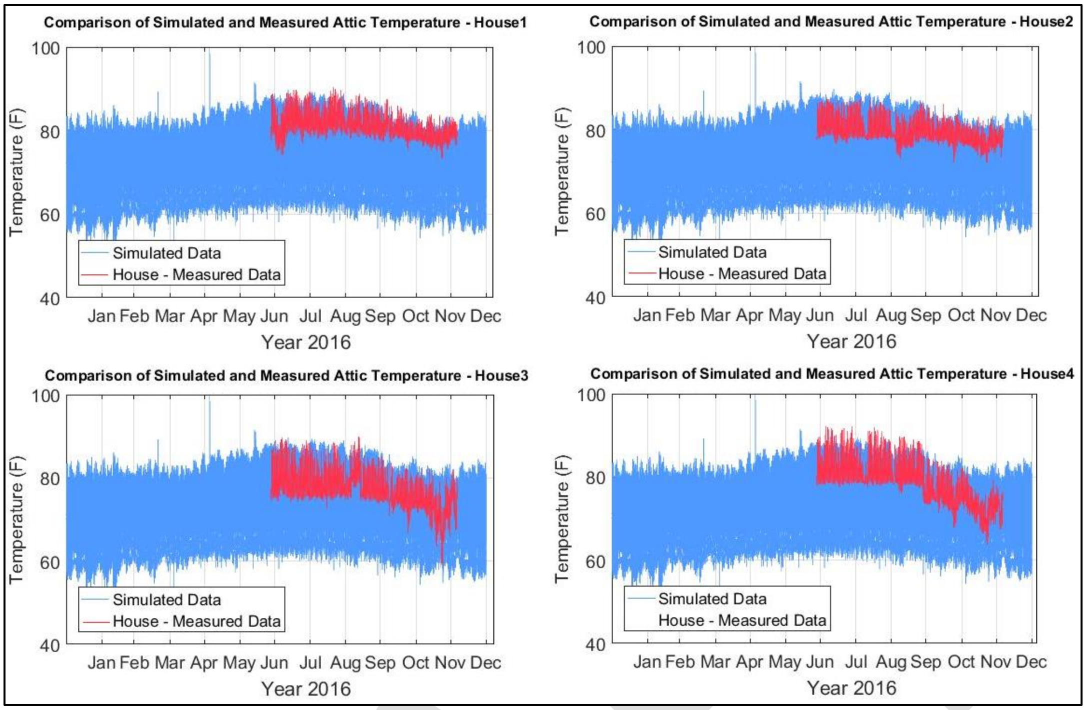


Figure 7 Comparison of Measured and Energy Plus Simulated Attic Temperature Blue band is simulated data for Climate Zone 2A; red band is Florida field data per home.

Moisture content at the roof sheathing to insulation interface is displayed in Figure 8. It is to be noted that the preliminary WUFI 1D simulations show that the moisture content values are higher than actual field measurements. This is because the prototype house used to generate the WUFI simulations was a Building America base case home. Better agreement is expected once the actual field results and benchmarks are used.

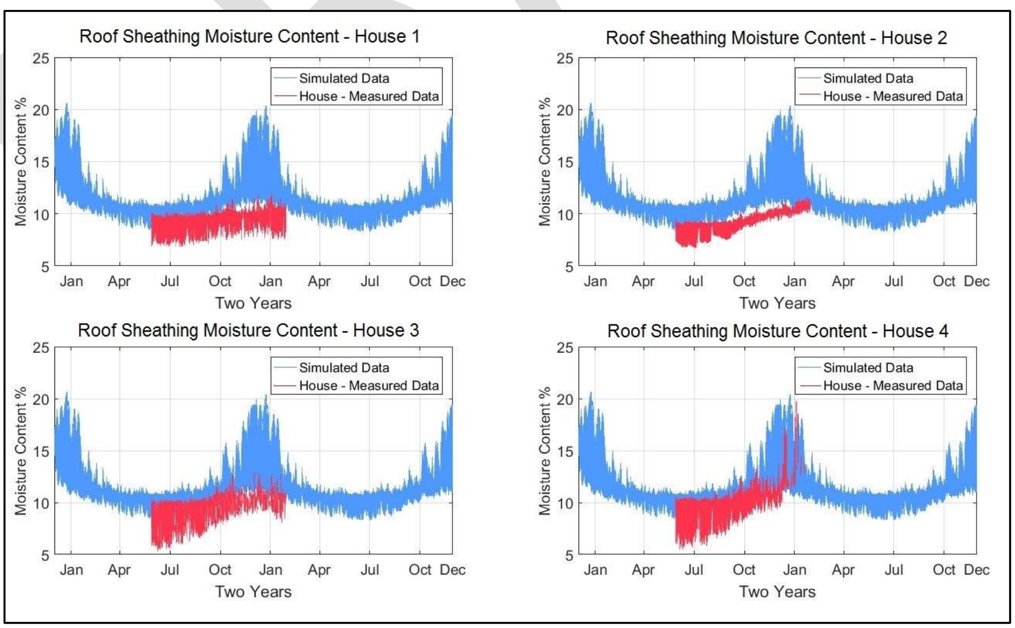
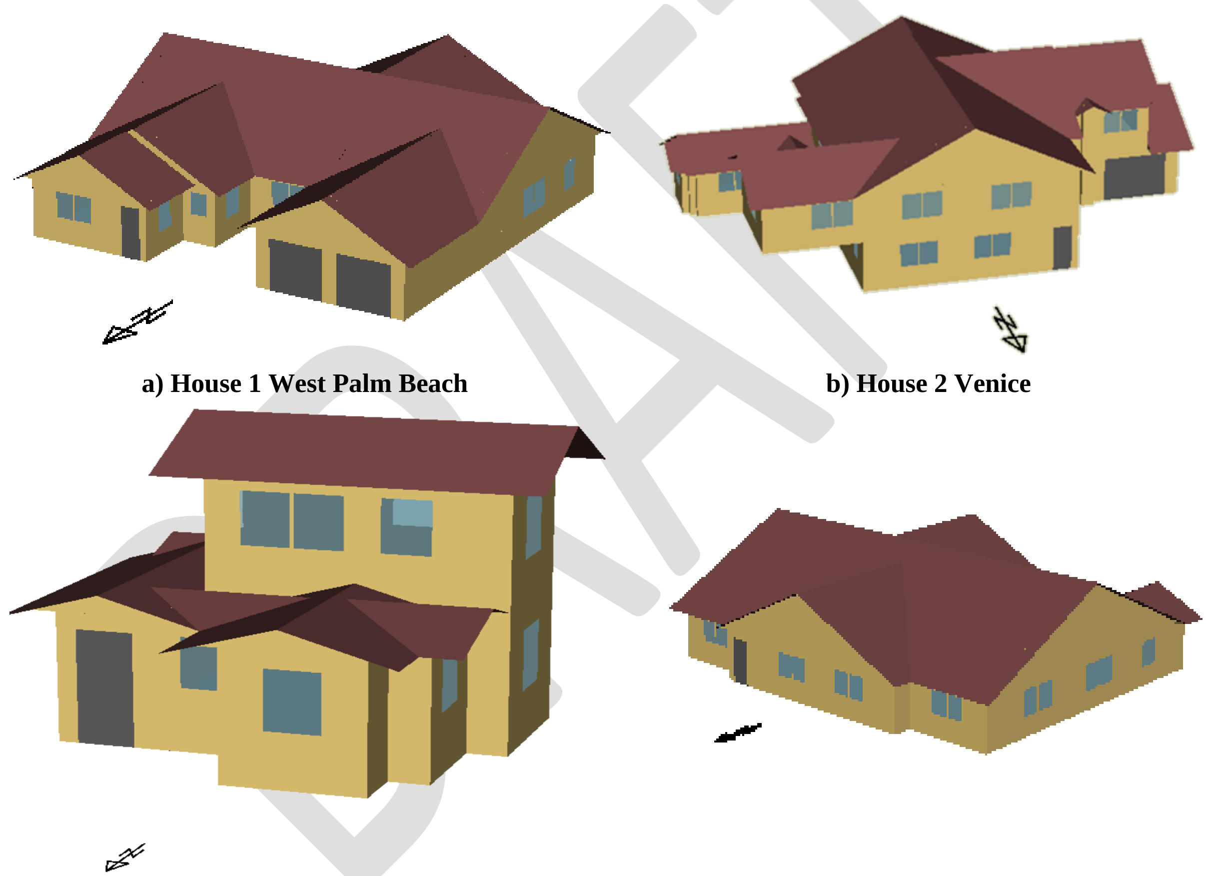


Figure 8 Comparison of Measured and WUFI Simulated Roof Sheathing Moisture Content. Blue band is simulated data for Climate Zone 2A; red band is Florida field-measured roof sheathing moisture content at ridge.

5.3 Probabilistic Assessment of Florida Field Homes

In Phase I, students from the University of Florida and an ORNL summer intern recorded pertinent characteristics of each single-family residence. Information included dimensions of all rooms in the conditioned space, slope and style of the roofs, the roof structure, size of the attic and the type and dimensions of the spray foam insulation. In addition, the students documented building envelope dimensions and materials for the exterior wall cladding, exterior windows and foundation and roof. The ORNL intern used the field-measured house characteristics and the BEopt (v 2.6.0.1) program to develop into numerical models, Figure 9. The analytical models include the house physical characteristics of mechanical ventilation, space conditioning and associated conditioning schedules, lighting, water heating and appliances, Table 3. The spray foam insulation was installed during initial construction in three of the four homes, and it was added during retrofitting of the fourth home. Questionnaire data for all four homeowners were reported by Prevatt et al. (2016). The BeOpt models illustrated in Figure 9 will be used to generate input files for Energy Plus, which, in turn will be used in the PRAT software package.



a) House 1 West Palm Beach **b) House 2 Venice**

c) House 3 Orlando **d) House 4 Gainesville**

Figure 9 The Florida homes were modeled using NREL's Building Optimization tool (BeOpt, vesion 2.6.01) from which EnergyPlus input files were generated for use in PRAT simulations.

Table 9 Salient Features of Selected Florida Homes

Component	House 1 West Palm Beach	House 2 Venice	House 3 Orlando	House 4 Gainesville
Roof				
Cladding	Standing seam metal	Barrel Concrete tile	Asphalt shingle	Asphalt shingle
Pitch	3/12 at perimeter 6/12 at ridge	6/12	4/12	6/12
Structure	Hip	Hip	Gable and Hip	Hip
Underlayment	30# felt paper	WR Grace Peal & Stick	2(15# felt paper)	30# felt paper
Sheathing	Plywood	OSB (5/8-in)	Plywood(5/8-in)	Plywood(5/8-in)
Framing	2 by 4 Truss at 24” oc	2 by 4 Truss at 24” oc	2 by 4 Truss at 24” oc	2 by 4 Truss at 24” oc
Date Attic Sealed	2010	2012	2002	2007
Rood deck insulation ($h{\cdot}ft^2{\cdot}{}^\circ F/Btu$)	R-15: 4” ocSPF	R-21: 5.5” ocSPF	R-15: 4” ocSPF	R-27: 7” ocSPF
Attic floor insulation ($h{\cdot}ft^2{\cdot}{}^\circ F/Btu$)	Gypsum board R-0.45	Gypsum board R-0.45	Gypsum board R-0.45	Gypsum board R-0.45
Wall				
Interior sheathing	Gypsum board	Gypsum board	Gypsum board	Gypsum board
Framing	8-in Conc. Block.	1st Floor: 8-in Conc. Block 2nd Flr: 2×6 studs at 16” oc	1st Flr: 8-in Conc. Block 2nd Flr: 2×6 16” oc	8-in Conc. Block
Insulation ($h{\cdot}ft^2{\cdot}{}^\circ F/Btu$)	R-6: 1” EPS	R-19: 5½” FG Batt	R-19: 5½” FG Bat 1-in EPS on Conc Block	R-5: ¾’-in PIR R-Max™
Exterior sheathing	OSB	2nd Flr OSB	2nd Flr OSB	OSB
WRB	15# felt paper	15# felt paper	15# felt paper	N/A
Cladding	Stucco	Stucco	Stucco	Brick
Exterior Paint	Light yellow	Light tan	Light Tan	NA
Fenestration				
Window Type	Double, Low-e, Argon	Double, Low-e, Argon	Double, Low-e, Argon	Double, Low-e, Argon
Foundation				
Slab-on-Grade	Yes	Yes	Yes	Yes
Above grade cladding	NA	Stone	Stone	Stone
House Geometry				
Conditioned Area	2,043 ft^2	3,592 ft^2	2,348 ft^2	3,055 ft^2
Conditioned Volume	29,670 ft^3	42,183 ft^3	22,115 ft^3	29,022 ft^3
Attic Volume	6,800 ft^3	7,692 ft^3	5,106 ft^3	14,002 ft^3
HVAC				
Duct Sizes in Attics	Main: 24-in Branch: 6 & 8-in	Main: 24-in Branch: 6 & 8-in	1st Floor Attic no ducts; 2nd Floor attic had ducts	Main 18-in Branch: 6 & 8-in
Air-Conditioner	2 (2RT Lennox)	NA	NA	Carrier (3RT) Goodman (2RT)
Heat Pump	NA	2 (2½ RT TRANE)	Lennox (3RT)	NA
Dehumidifier	NA	UltraAir	NA	Master Bath

6. PRELIMINARY RESULTS

The UF and ORNL team initiated field data acquisition in June 2016 and so far they have collected and reduced 39 weeks of field measurements. The data is collected weekly. BEopt models of the four homes were developed and will be used in Energy Plus and WUFI simulations to complete the thermal and hygrothermal analysis for the four homes.

A set of preliminary probabilistic analyzes were made and compared to the collected filed data. Comparison of simulated and measured attic relative humidity was within the bounds of Energy Plus results, Figure 6. Predicted and measured temperature of the sheathing (Figure 7) show the measure temperatures to be on the high side of the Energy Plus computations. Moisture content of the sheathing predicted by the WUFI tool is higher in all homes than the field measurement Figure 8. Actual house measurements will be used by the PRAT toolkit to complete the benchmarks against the field data and make recommendations regarding the durability of the roof sheathing.

The field measures to date show a diurnal variation in the moisture content of the roof sheathing. The serendipitous occurrence of Hurricane Matthew helped illustrate the effects of solar irradiance and driving rain on the moisture content of the sheathing. Moisture movement is more strongly affected by solar irradiance provided a well-installed roof assembly adequately protects the roof.

Field measures of the moisture content of the sheathing were observed to show some accumulation of moisture starting in early October. However, the level of the moisture content is well below the threshold for mold, mildew or wood rot. While the open-cell spray foam is inadvertently holding moisture against the sheathing, its effect to date is marginal based on the levels of moisture measured in the sheathing.

7. FUTURE SCOPE

For Task 1, the goal is to benchmark the toolkit with field-measured data. The preliminary simulations created using the toolkit for the prototype house indicate that the field-measured attic temperature and relative humidity fall within the simulated parameters (Figure 6, Figure 7). However, the probabilistic moisture content in the roof sheathing predicted by the toolkit (Figure 8) is subsequently greater than the field-measured moisture contents. A better match for the three parameters: temperature, relative humidity and moisture content is expected once the specific numerical models are used in the toolkit (Figure 9).

For Task 2, the field-measured specific house characteristics will be employed in the probabilistic risk assessment toolkit along with outdoor climate to produce indoor and attic temperature, relative humidity and moisture content. These modelled parameters will be compared with the field-measured parameters to benchmark the toolkit. Once benchmarked, a range of input variables for each house will be produced (Table 8). Input parameters will be varied to simulate temperature, relative humidity and moisture contents specific to each house (blue bands in Figure 6-8). A sensitivity analysis will determine the effect of each input parameter on the moisture accumulation in the roof sheathing.

The final report due on 15th June, 2017 will contain the following information:

- Benchmarks of the probabilistic toolkit against field-measured data
- Variations in key input variables to produce simulated temperature, relative humidity and moisture content
- Sensitivity analysis to determine the effect of input parameters on simulated data
- Recommendations to the FBC with a range of the input variables producing moisture durable sealed attics with least condensation potential at the sheathing to insulation interface

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APPENDIX A: FLORIDA BUILDING CODE

House 1 was built in 1962. The building owner had spray foam applied to the attic in 2010. All other homes had foam installed during construction. Reroofing is regulated by the existing FECC at the time of construction as an Alteration Level 1. Section 601.2 specifies that the current level of energy efficiency may not be reduced, and section 612.1 refers back to the FECC for energy conservation compliance. The term reroofing in the FECC implies a renovation or repair and not alteration. Therefore the prevailing code applicable to the 4 homes is based on the year spray foam was applied to the attic. The listing of residential code requirements for both prescriptive and performance paths of compliance are listed in Table 5.

Section 101.4.1 of the 2010 FECC and Table 101.4.1 were used when pursuing the prescriptive approach to compliance for renovation of existing buildings. The Table indicated that building envelope renovation must comply with sections 402 or 502, subject to both footnotes “a” and “d”. These footnotes made it clear that the current level of energy efficiency may not be reduced; however, the reroof was exempt from further compliance with the FECC if the assessed value of the renovation was less than 30% of the cost of the assessed value of the building. Section 101.4.1 and Table 101.4.1 were not included in the FECC 2014 code.

Section R806.5 of the FECC (2014) enacted changes for unvented and sealed attics. The modification to Section 806.5 requires that air impermeable insulation be applied to the underside of the roof sheathing. If instead an air permeable insulation is selected, then the builder must include sheet insulation above the deck for condensation control. CZ-1A and CZ-2A require R-5 be applied above the deck if permeable spray foam is applied to the underside of the sheathing; however, no insulation is requires for impermeable spray foam applied to the deck’s underside, Table 10.

Table 10 FBC Prescriptive and Performance Based Requirements

FBC	Attic Floor[A] Prescriptive Req.		Attic Floor[B] Performance Req.		Roof Deck[C] Sealed Attic Req.	
	CZ - 1	CZ - 2	CZ - 1	CZ - 2	CZ - 1	CZ - 2
2001	R-30	R-30	R-19	R-19	NA	NA
2004	R-30	R-30	R-19	R-19	NA	NA
2007	R-30	R-30	R-19	R-19	NA	NA
2010	R-30	R-30	R-19	R-19	NA	NA
2012	R-30	R-30	R-19	R-19	NA	NA
2014	R-30	R-38	R-19	R-19	R-0 / R-5	R-0 / R-5

A. Prescriptive Requirement for attic floor.

B. Performance Requirement for attic floor, subject to R405.2.1 of FECC, 2014, R405.2.1 ceiling Insulation.

C. Impermeable spray foam has no R-value requirement above the deck. R-5 is required above the deck for permeable spray foam insulation applied to the underside of the sheathing (see R806.5 requirement, 2014).

APPENDIX B: CLIMATE ZONES OF REVIEWED LITERATURE

In early 2000's researchers from US Department of Energy's Pacific Northwest National Laboratory (PNNL) prepared a climate map of USA based on analysis from 4775 weather sites. This map divided USA into eight zones (1 to 8) based on temperature and three regions (moist, dry and marine) based on moisture as shown in Figure 1. This new map was setup along county boundaries to help builders easily determine the climate zones. This map was adopted first by the 2004 IECC Supplement and it appeared in the ASHRAE 90.1 in 2004. Builders use ASHRAE 90.1 for commercial purposes while various state governments have adopted the IECC 2009 code for low-rise residential structures. IECC 2009 provides information about several building envelope requirements such as R-value, fenestration factor for different climate zones.

Figure 10 shows the IECC climate zones and the location of reviewed research homes in the respective climate zones.

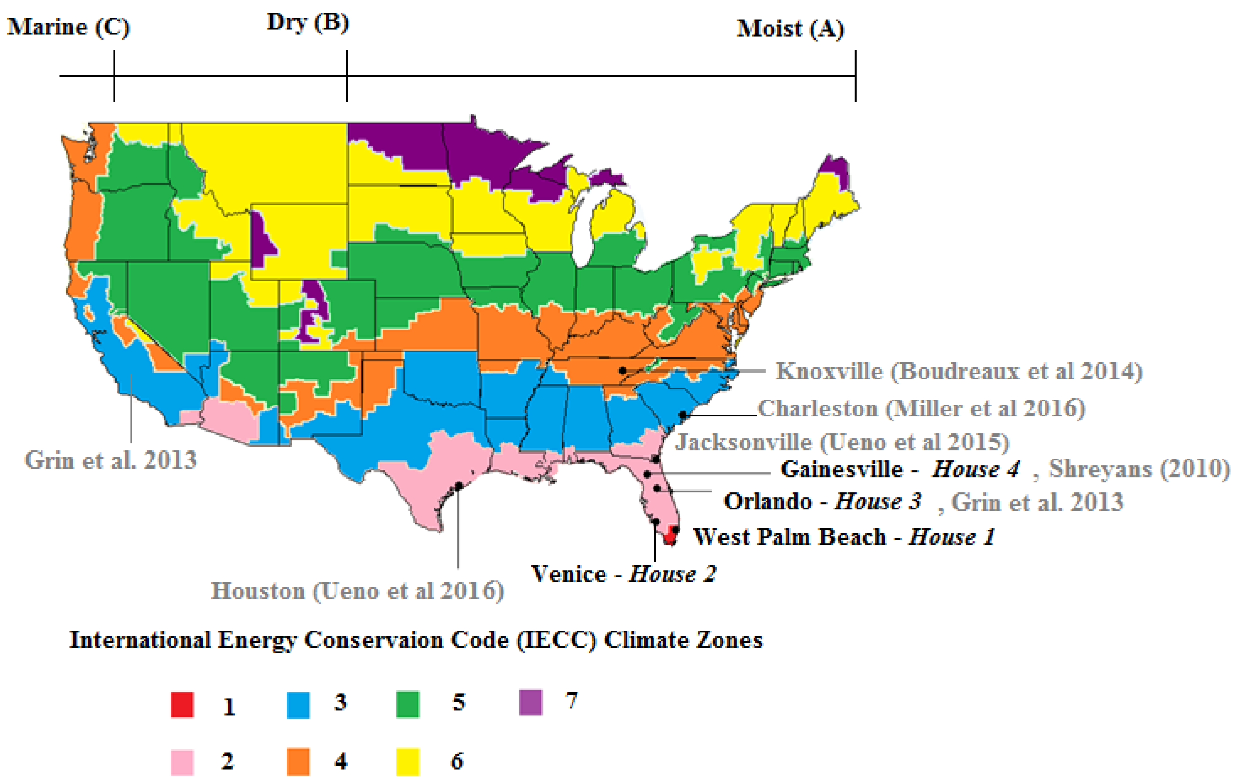

Figure 10 Climate zone map based on IECC 2012. Bold black text indicates the field house locations used in this study. Grey text indicates the field house locations from the literature review.

APPENDIX C: WORKING OF PRAT

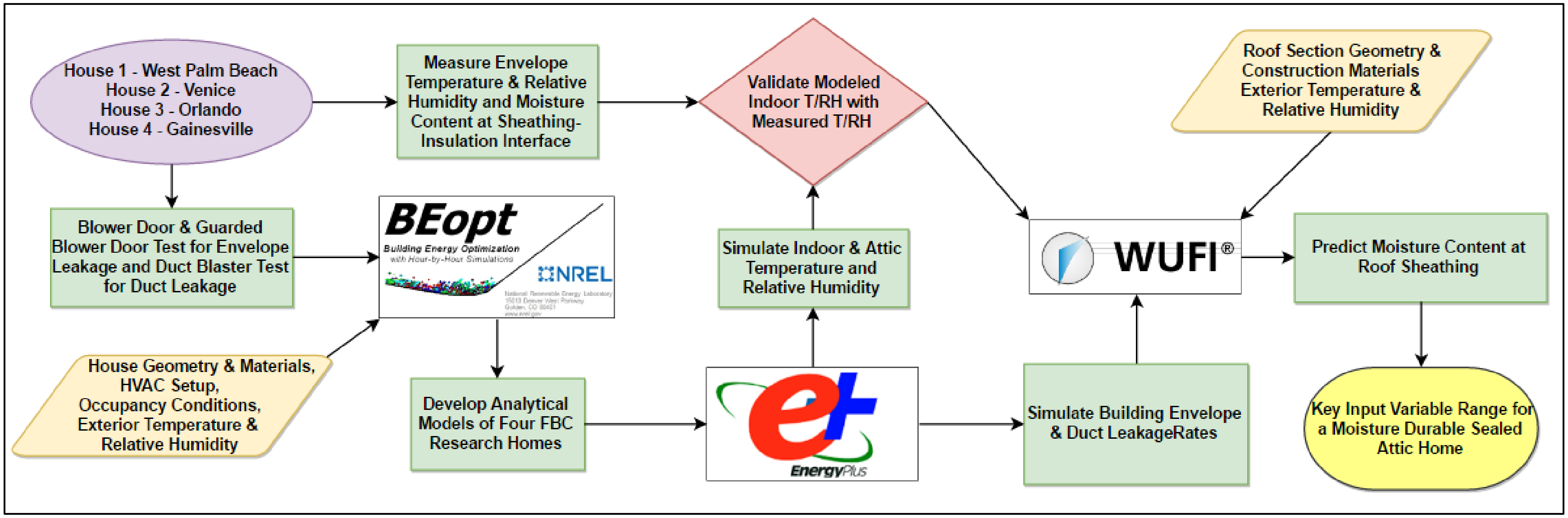

Figure 11 Working of the Probabilistic Risk Assessment Toolkit