PHASE II Analytical Assessment of Field Data for Sealed Attics in Florida Climate Zones 1 and 2 – Predicting Moisture Buildup in Roof Sheathing

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EXECUTIVE SUMMARY

The University of Florida (UF) and the Oak Ridge National Laboratory (ORNL) completed an analytical study based on field measurements collected on four homes instrumented for measuring the heat and moisture flows in sealed and semi-conditioned attics.

The Phase II study evaluated the effect of attic heat and moisture flows carried by air convection or driven by diffusion on the durability of the roof sheathing. Open-cell spray polyurethane foam insulation was applied directly to the underside of the roof deck of each home. A Probabilistic Risk Assessment Toolkit (PRAT) was benchmarked against Phase I field measurements for Houses 2 and 4. PRAT used the following inputs: 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 for all input variables revealed that interior moisture generation and heat generation and the set point temperature of the thermostat had the greatest effect on the moisture content of the roof sheathing. The duct leakage into the attic and thermostat heating set point temperature tended to reduce the moisture content of the roof sheathing. The air leakage rate from attic-to-outdoors showed little sensitivity to moisture accumulation in the roof sheathing.

The PRAT assessments and the field measured moisture content of the roof sheathing for the homes in Venice, FL and Gainesville, FL indicated that during the summer and winter periods the moisture content was always below a 20% moisture content level. Therefore there was no risk of mold inception or decay of the wood roof sheathing. The study did not show any detrimental effects of the open-cell spray foam insulation applied to the underside of the roof deck. The PRAT toolkit verified that no condensation of moisture occurs during the time of the field study. All roofs of the test homes were well constructed for shedding liquid water and there was no intrusion of liquid water onto the sheathing.

From the combined analytical and field study, the following recommendations are made to the Florida Building Commission for sealed attics with open-cell spray polyurethane foam under the wood roof deck:

- The field data and analysis showed that section R806.4 of the Florida Building Code provides adequate protection against moisture affecting the durability of roof sheathing.
- Inclusion of a dehumidifier in the sealed attics would keep attic air moisture levels at a safe level; however, its use was not necessary for the 4 homes reviewed in this study.
- If the attic-to-outside air leakage is not well controlled in a sealed attic, then the energy conservation of the home is compromised.

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ABBREVIATIONS:

ACH	Air changes per hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEopt	Building Energy Optimization Software
ccSPF	closed cell Spray Polyurethane Foam
CFM	cubic foot per minute
CZ	climate zone
FBC	Florida Building Commission
FECC	Florida Energy Conservation Code
FRSA	Florida Roofing and Sheetmetal Association
GIHM	Generation of Indoor Heat and Moisture Tool
HVAC	Heating, Ventilation and Air Conditioning
IECC	International Energy Conservation Code
LBNL	Lawrence Berkley National Laboratory
ocSPF	open cell Spray Polyurethane Foam
OSB	oriented strand board
PRAT	Probabilistic Risk Assessment Toolkit
RECS	Residential Energy Consumption Survey
RH	relative humidity
T	temperature
WUFI	Wärme Und Feuchte Instationär

1. INTRODUCTION

During the 2016 summer and with financial support from the Florida Building Commission (FBC) and the Florida Roofing and Sheet Metal Contractors Association (FRSA[1]), the University of Florida (UF) and the Oak Ridge National Laboratory (ORNL) completed Phase I of a study that setup four residential home demonstrations in Florida climate zones CZ-2A, Figure 1. The home in West Palm Beach borders climate zone CZ-1A,

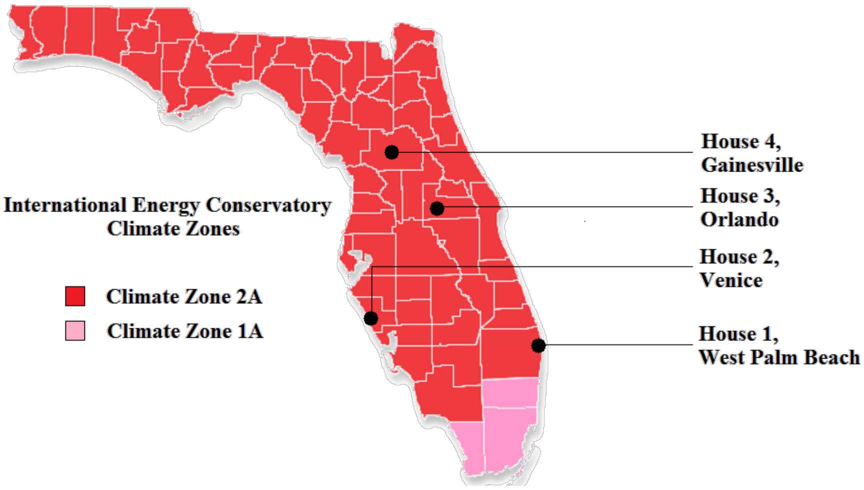

Figure 1 Location of selected sealed attic houses

The four homes were instrumented for measuring temperature and relative humidity of the indoor living space, the outdoor air and the attic air. In addition, instruments were installed for measuring temperature, relative humidity and moisture content of the roof sheathing. Instrument measurements were monitored and recorded by remotely-accessible data acquisition equipment. Field tests commenced June 1, 2016. A full year of data was collected and reduced to document heat and moisture flows.

Air leakage tests on the whole house, on the sealed attic and in the HVAC ducts were conducted on all four homes; results of the field study are reported by Miller et al. ((2016). Table 1 provides salient features of each home’s roof, attic, heating, HVAC[2] system as well as the leakage rates measured in the field, Table 1.

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[1] The FRSA is an alliance of companies actively engaged in the roofing contracting business in the State of Florida.

[2] Heating, Ventilation and Air-Conditioning (HVAC)

Table 1. Characteristics of Selected Florida Houses

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 / 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·ft^2·°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 BACKGROUND

A residential structure is termed as a single-family detached house if the structure has direct access to roadways and personalized air-conditioning and water systems. Single-family residential houses form 60% of the US residential house market, US Census Bureau (2011). Typical single-family residential houses are constructed with slab-on-grade foundations and have air-conditioned indoor spaces, also termed as living spaces and unconditioned spaces like attics and crawlspaces. The space conditioning is provided by HVAC systems with a system of ductworks in each floor. Builders have been placing the HVAC systems and the ductworks in the attic space to maximum utilize the living space area.

The attic spaces traditionally are separated from the thermal envelope of the building by providing air barrier and thermal insulation at the ceiling levels. These attics are known as vented attics and are not conditioned by the HVAC system. Vents at the soffit and ridge levels provide for a continuous air flow between the attic and the outdoor environment. Leaky ductwork systems in the vented attics can lose conditioned air to the outdoor environment leading to energy penalties and rain water intrusion problems during extreme wind events. To minimize these effects, a new idea was proposed to encapsulate the HVAC system and the ductworks within the thermal envelope of the building by shifting the insulation from the ceiling level to the underside of the wood sheathing thereby creating a sealed attic space (Figure 2). The sealed attic space is sometimes semi-conditioned by air leaking from the ductwork system and through the ceiling pane. Spray-applied polyurethane foam insulation is typically used as the insulating material under the wood roof sheathing. The concept of spray foam insulated sealed attics was pioneered by the Building Research Laboratory at the University of Illinois, Rose (1995) and the Building Science Corporation, Rudd et al. (1998).

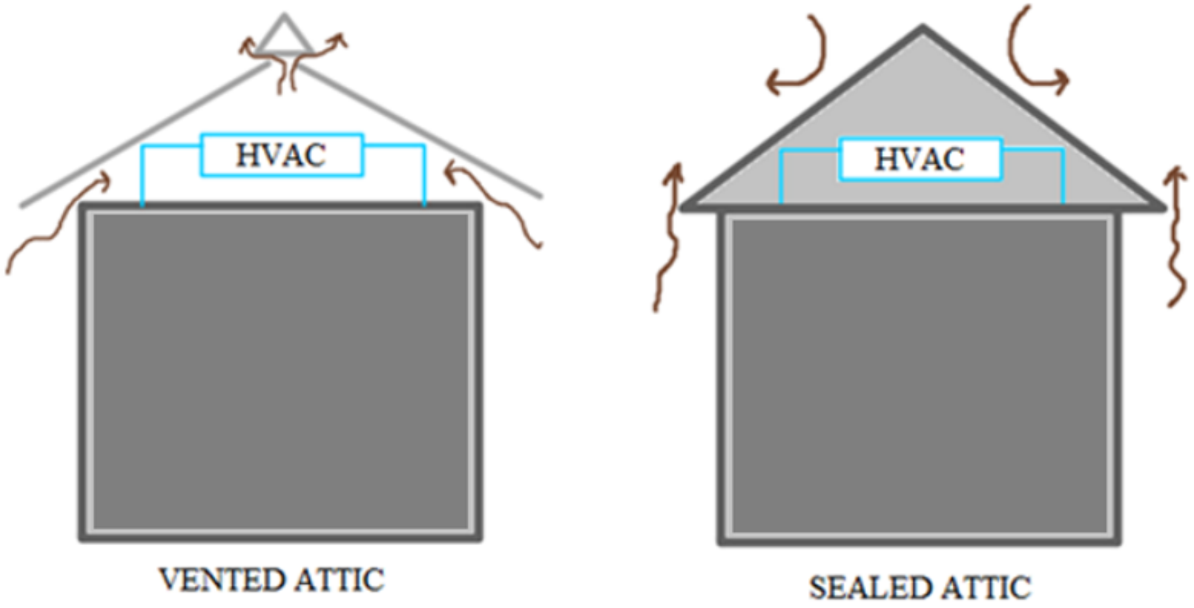

Figure 2 Vented and sealed attics. Dark grey area is conditioned by HVAC and light grey area is semi-conditioned by duct leakage and air leaks through.

The energy saving potential of sealed attic systems have been demonstrated by several building scientists and researchers. Parker et al. (2002) experimentally tested a sealed attic with R-19 insulation to a reference vented attic in Fort Meyers, Florida and observed energy savings potential of 6-11%. While the energy efficiency aspect of a sealed attic construction has urged builders to switch to sealed attics, there is a concern about moisture accumulation at the sheathing-to-insulation interface. Moving the insulation from the ceiling level to the roof deck increases the overall insulated area leading to difficulties in achieving high R-values. R-value is a measure of the thermal resistance of a material. These concerns have led to several experimental and analytical studies on sealed attic constructions.

There are several factors controlling the moisture performance of a sealed attic. Less et al. (2016) and Masters et al. (2015) present a comprehensive literature review on the moisture performance of sealed attic constructions. The moisture movement in a sealed attic is attributed to several factors:

- High indoor and outdoor air humidity
- Rain water intrusion
- Sheathing temperatures below dew point of attic air temperature
- Air leakage from attic to outside environment

Wood moisture content, expressed as the ratio of mass of water in wood to the mass of dry wood is typically around 6% around the time of construction. The above-mentioned factors can increase the moisture content in the roof sheathing to higher values over 20% and in some cases exceeding 30% leading to wood rot, mold formation and loss of structural capacities. This concern is especially prevalent in hot and humid climates, such as in Florida. Florida has two climate zones, CZ-1 and CZ-2 both defined as hot-humid by the International Energy Conservatory Code and ASHRAE.

1.2 MOTIVATION

The International Energy Conservation Code (Table 806.5, 2012) provides minimum requirements for sealed and insulated attics, Table 2. The 2010 energy conservation supplement to the Florida Energy Conservation Code (FECC) provided measures for putting the supply and return ducts inside the building thermal envelope (Section 403.2, 2010 of FECC). 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 requiring for impermeable spray foam applied to the deck's underside,

Table **3**.

Table 2 IECC Code Requirements for Sealed Attics

Climate Zone	Minimum Air-Impermeable Insulation R-value	2012 IECC Total R-value Requirements
2B and 3B tile roof only	0	30
1, 2A, 2B, 3A-C	5	38

Table 3 FBC Code Requirements for Sealed Attics

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).						

The prescriptive guidelines for sealed attics does not provide for a single standard procedure to apply spray polyurethane foam insulation to the underside of the wood deck. Builders are confounded by the lack of information in the codes and typically fail to achieve the total R-value for roof insulation of R-30 and R-38 for climate zones CZ-1 and CZ-2. The failure to achieve code level insulation could lead to potential moisture problems such as mold formations or air leakage problems leading to energy penalties, defying the reason for sealing the roof deck. Hence the Florida Building Commission has been in search of quality information on sealed attic construction to include in the next version of the Florida Building Code, to aid builders achieve good quality of sealed attic constructions.

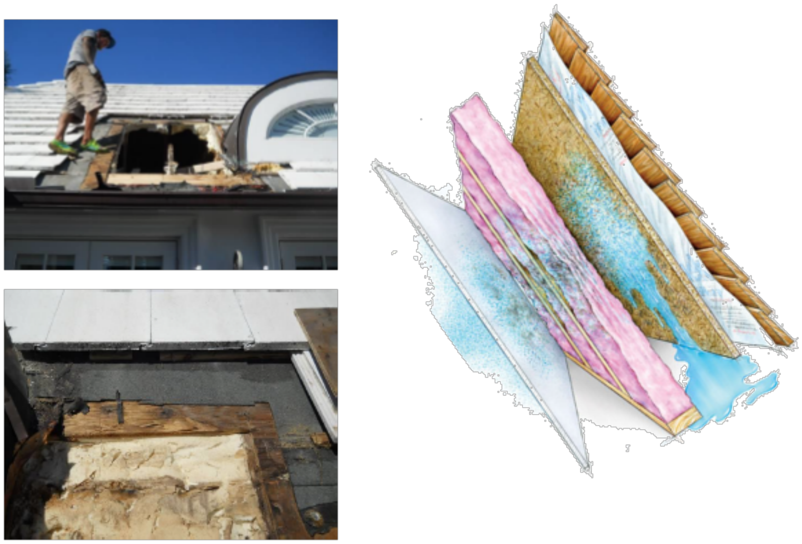

Figure 3 Condensation problems in roof deck as demonstrated in Green Building Advisor, 2010 (right). Moisture Problems in a ccSPF insulated sealed attic Prevatt et al. 2015 (left).

2. PROJECT OVERVIEW

2.1 OBJECTIVE

The goal of this project is to evaluate the moisture content accumulation in the roof sheathing of sealed attic houses 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 houses in Florida. In Phase I (Prevatt et al. 2016), we selected and instrumented four houses 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 combined experimental and analytical work performed to analyze the moisture movement in the sealed attics of Florida residential houses.

Table 4 Description of Selected Sealed Attic Houses

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 tile	Asphalt shingle	Asphalt shingle
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
Family	Married Couple no Children	Married Couple no Children at Home	Married Couple no Children	Married Couple no Children at home
Occupation	Metal Roof Specifier, Home Builder	Home Builder	Architect Specifier, Consultant	Retired Nuclear Engineer

2.2 DESCRIPTION OF WORK

2.2.1 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.

2.2.2 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 to predict air temperature and humidity in the indoor conditioned space and the attic space of residential houses and WUFI 1D (Karagiozis et al. 2011) for hygrothermal modelling to predict the roof sheathing moisture content.

2.3 SCOPE OF WORK

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

Table 5 Phase 2 Milestones and Deliverables

Task	Milestone & Deliverables	Completion Date
Task 1. – Benchmarks of PRAT against Field Data		
	Milestones	
	• 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
	Deliverable	
	• Interim Report showing comparison of field data to PRAT simulations	15 April, 2017
Task 2. – Sealed attic Sensitivity Analysis and Recommendations		
	Milestones	
	• Complete PRAT simulations	April, 2017
	• Complete sensitivity analysis to see which probabilistic variables most affect each attic design	May, 2017
	Deliverable	
	• Final Report summarizing sensitivity analysis and recommendations to FBC to construct moisture durable sealed attics	15 June, 2017

2.3.1 Analysis of Field-Measured Data

- Analyze the heat and moisture flows in the sealed attics of selected Florida houses
- Quantify the moisture content in the roof sheathing of the sealed attics for a 12-month period for the selected Florida houses
- Analyze the indoor thermal comfort of the selected Florida houses and identify parameters reducing the indoor thermal comfort

2.3.2 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

2.3.3 Benchmark Toolkit with Field-measured Data

- Develop analytical models of the four field houses 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

2.3.4 Recommendations for Sealed Attic Constructions to the Florida Building Commission

- Provide recommendations to the FBC for moisture durable sealed attic construction
- Provide recommendations for roof deck insulation R-values for least condensation potential

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 6.

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° 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 content 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 houses 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 houses 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 houses. 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 6 Literature Review on Sealed Attics

Author & Year	Publisher	Research Purpose	Methodology	Climate Zone	Author's key results
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 reducing the sheathing MC
Lstiburek et al. 2006	Building Science Corporation	Guidelines to construct sealed attics	Computer simulation + field evaluation	1-7	Suggested the use of thermal barrier separating occupied zone and unoccupied attic to reduce heat flux through the ceiling and risk of fire hazards
Straube et al. 2010	Journal of Building Physics	Condensation potential at sheathing to insulation interface	WUFI simulations + field measurements	6,7	Numerical models suggest that Outdoor climate and high indoor moisture generation can cause condensation. Moisture levels below 20% observed
Shreyans, 2011	University of Florida	Effects on thermal performance on foam retrofitted residential	WUFI + field evaluation	2	Use of ½ in. to 1 in. ccSPF layer reduces the peak attic temperatures from 130°F to 110°F. The overall energy consumption reduced by

Author & Year	**Publisher**	**Research Purpose**	**Methodology**	**Climate Zone**	**Author's key results**
		attics			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 houses, 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 Table 7 and Table 8.

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 houses; 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 houses 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 7 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	-

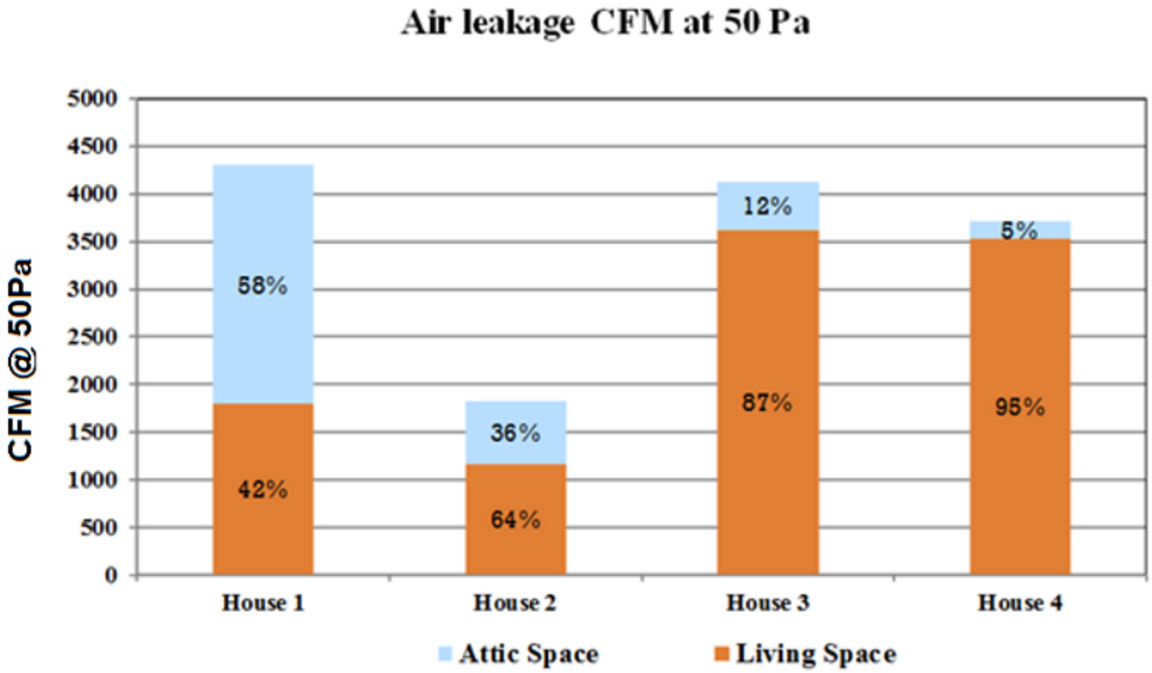

Figure 4 Total Building Envelope Leakage for Test Homes comprises two components; a) Air Leakage from the attic and b) air leakage from the occupied living space

Table 8 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

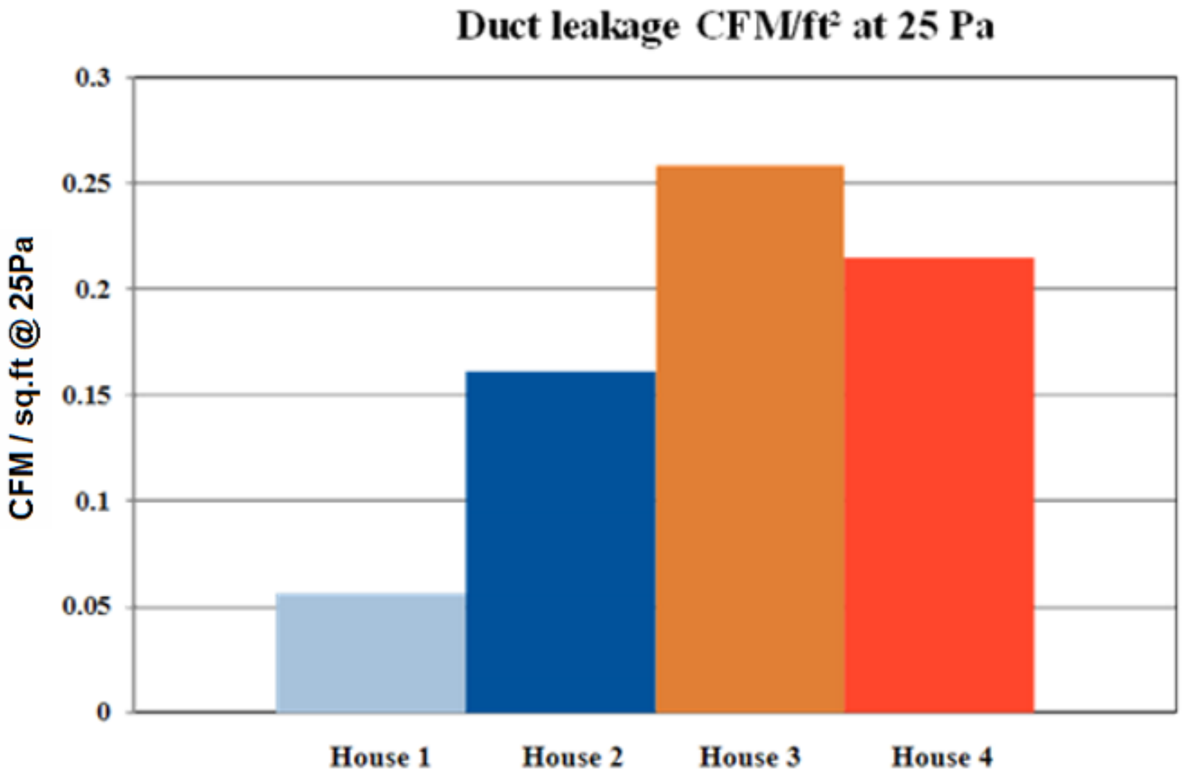

Figure 5 Total Duct Leakage for Test Homes comprises two components; a) duct leakage from the attic and b) duct leakage from the occupied living space

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 houses had a similar layout of sensors as shown in Figure 6 for consistency interpreting data among the 4 houses. 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 9 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

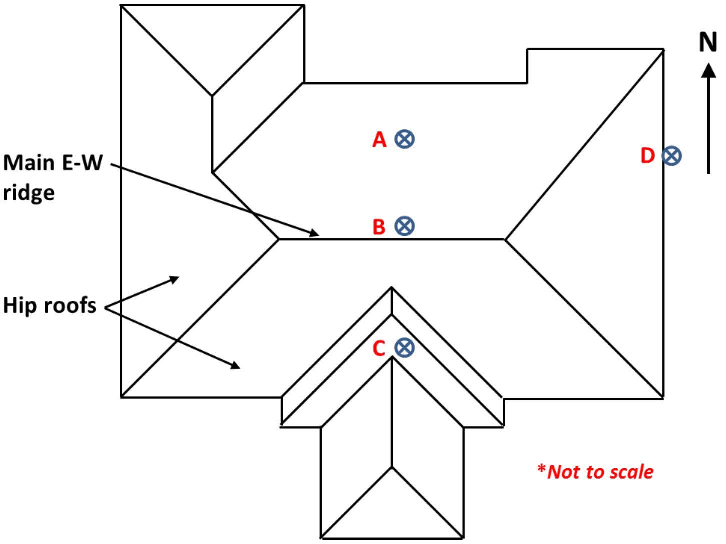

Figure 6 Location of Sensors in House 4. All four test houses were instrumented in the same location to assist in measurement comparisons; details are in Table 9. Locations shown in cross-sectional view in Figure 7.

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.

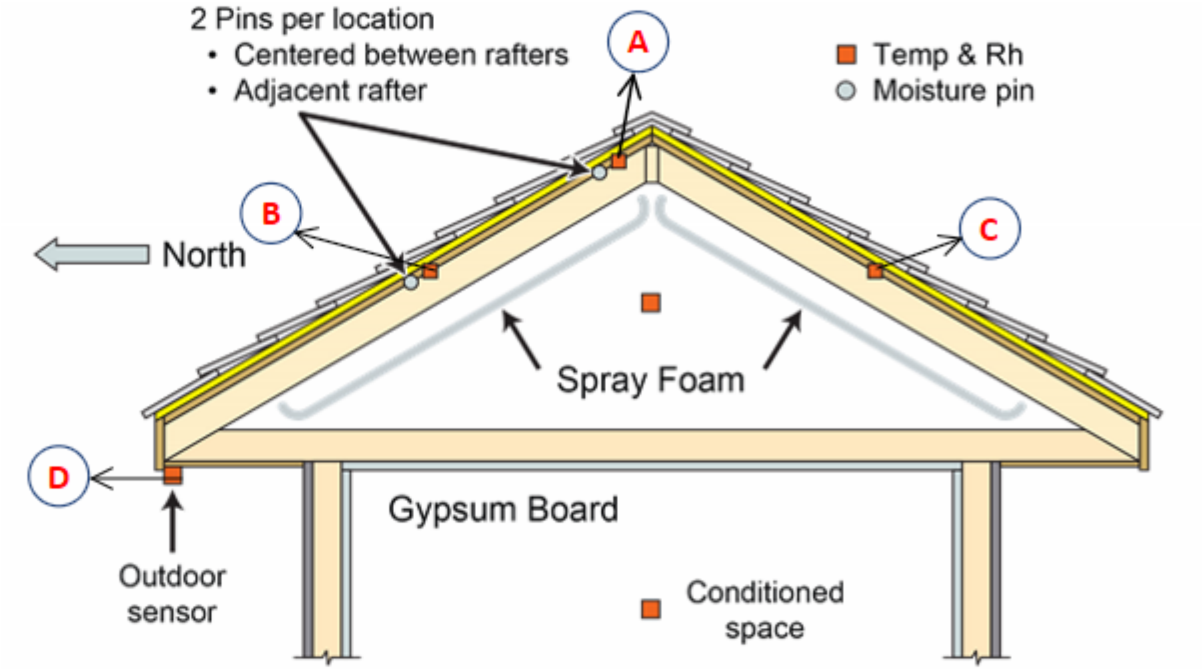

Figure 7 Location of temperature, humidity and moisture sensors installed inside the sealed attic, in the conditioned space and the outside. For actual location of sensors in each attic, refer Table 9.

4.3 TIME HISTORY OF MOISTURE CONTENT

Figure 8 shows the time history of the moisture contents for all four home locations. 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 8. House 4 in Gainesville has a spike in moisture content during January when the house is typically occupied (winter bird house). The cause for the anomaly is unknown.

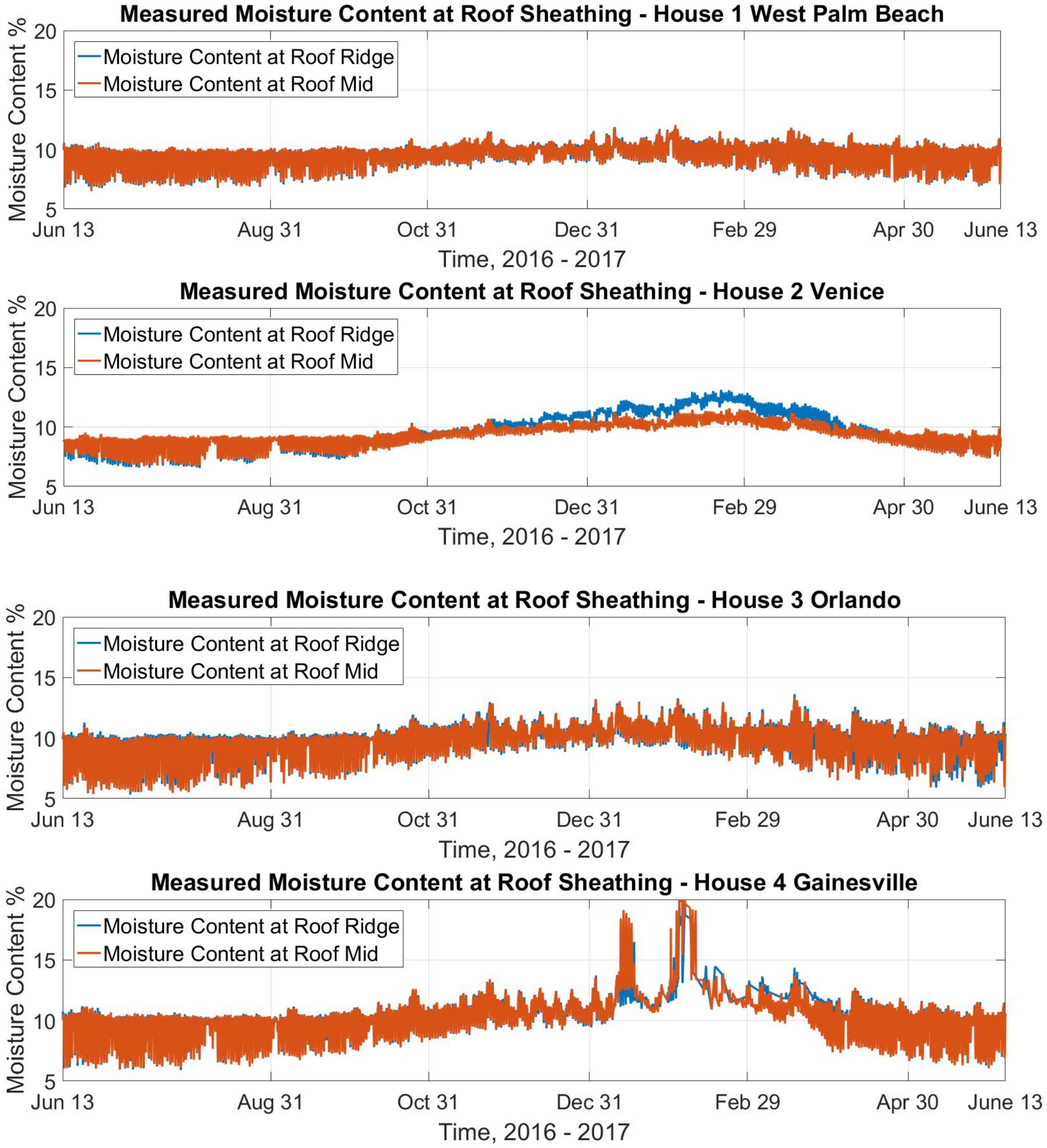

Figure 8 Roof Sheathing Moisture Content in Four Houses, June 2016 to June 2017

4.4 RELATIONSHIP BETWEEN ATTIC TEMPERATURES AND INDOOR TEMPERATURES

Literature review of sealed attics has generally led to an observation that the temperature and humidity in the attic is coupled well with the temperature and humidity of the indoor space irrespective of the leakage occurring at the ceiling level, Less et al. (2016). Transforming a ventilated attic into a semi-conditioned space caused the temperatures in the sealed attics of House 2 and House 4 to closely follow the indoor temperatures, **Figure 9 Measured Attic and Indoor Temperatures**Figure 9. For House 4, the occupied period of the house can be observed when there are most fluctuations in the indoor temperature i.e. between the summer months of November and March, the house was occupied. A typical weekly comparison is presented in Figure 10.

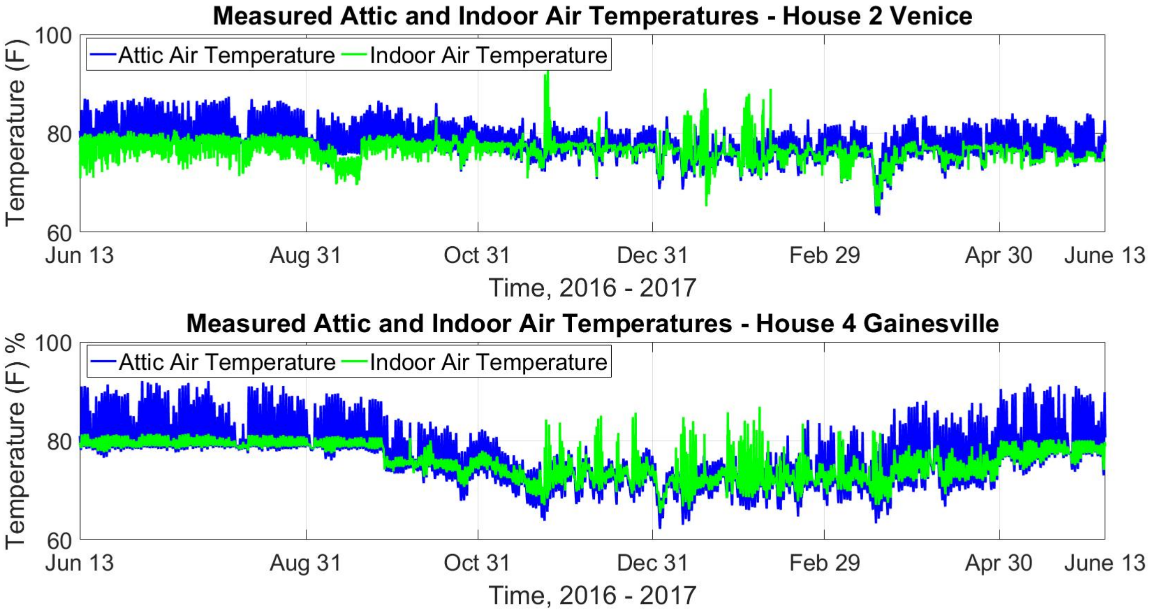

Figure 9 Measured Attic and Indoor Temperatures. Attic temperature and Indoor temperatures are well correlated. This has been demonstrated in several sealed attics in literature review

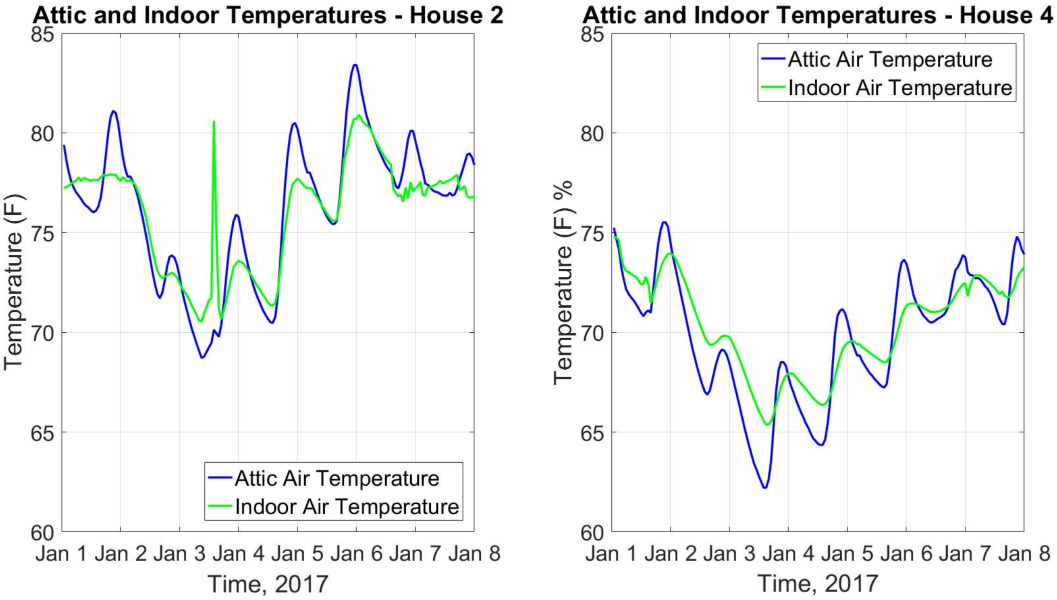

Figure 10 Measured Attic and Indoor Temperatures for a typical week. Both attic and indoor temperatures have good correlation and fluctuate diurnally. For January, House 4 has colder attic temperature.

4.5 RELATIONSHIP BETWEEN MEASURED TEMPERATURES IN VARIOUS LOCATIONS OF A SEALED ATTIC HOUSE

The close relationship between the attic temperature and the indoor temperature can be clearly seen in Figure 11. The outside temperature drives the variations in the indoor temperatures. The temperatures at the roof sheathing are consistent with the outside temperature. The sheathing facing south has higher temperatures than the north facing roof. House 4 located in Gainesville has lower outside temperature in the winter months when compared to House 2. This is a potential reason for higher moisture contents in House 4. Both House 2 and House 4 have well insulated and sealed attics which lead to excellent correlation between the attic and the indoor temperatures.

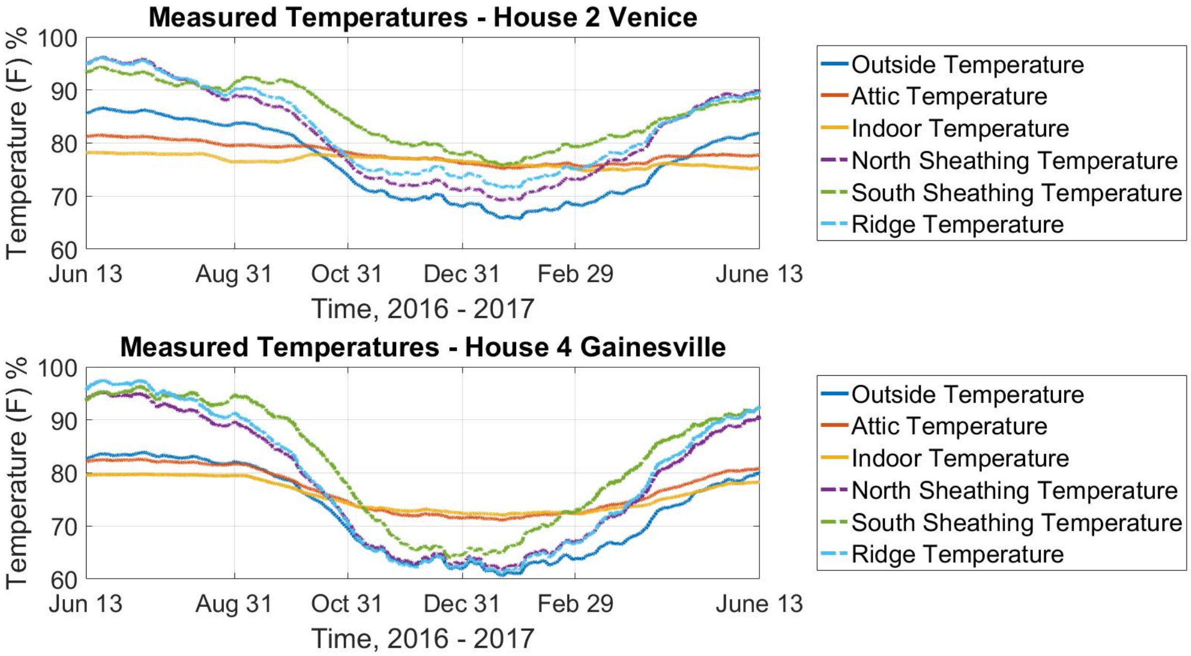

Figure 11 Measured Temperatures from various locations in House 2 and House 4. Figure shows good correlation between attic and indoor temperature. House 4 has lower outside and sheathing temperatures leading to higher moisture contents than House 2 as described in Figure 8

4.6 RELATIONSHIP BETWEEN TEMPERATURE, HUMIDITY AND MOISTURE CONTENT

The attic temperature and humidity controls the behavior of moisture movement in the attic and the roof sheathing. Attic humidity over 80% for prolonged periods can induce more moisture movement and lead to potential moisture accumulation in the attic, Miller et al. (2013) and Salonvaara et al. (2013). The time history and means of attic air temperature and relative humidity is plotted for House 2 and House 4 in Figure 12. House 2 has relatively smaller diurnal swings of temperature and humidity. The humidity in the attic is controlled by means of a dehumidifier and hence the humidity does not climb above 80%, meaning no conditions for moisture movement. House 4 has large diurnal swings in attic humidity and reaches over 80% for a long period during December – June. Alarming humidity values of over 90% and close to saturating humidity occur during this period allowing favorable conditions for moisture accumulation.

The dew point temperature is the temperature at which the air cools to saturation point allowing for the water to condense. Figure 13 and Figure 14 present the comparison of sheathing temperatures and dew points. House 4 has superimposition of both temperatures in the winter period providing for favorable condensation conditions. This also causes the moisture content to spike to 20% in House 4.

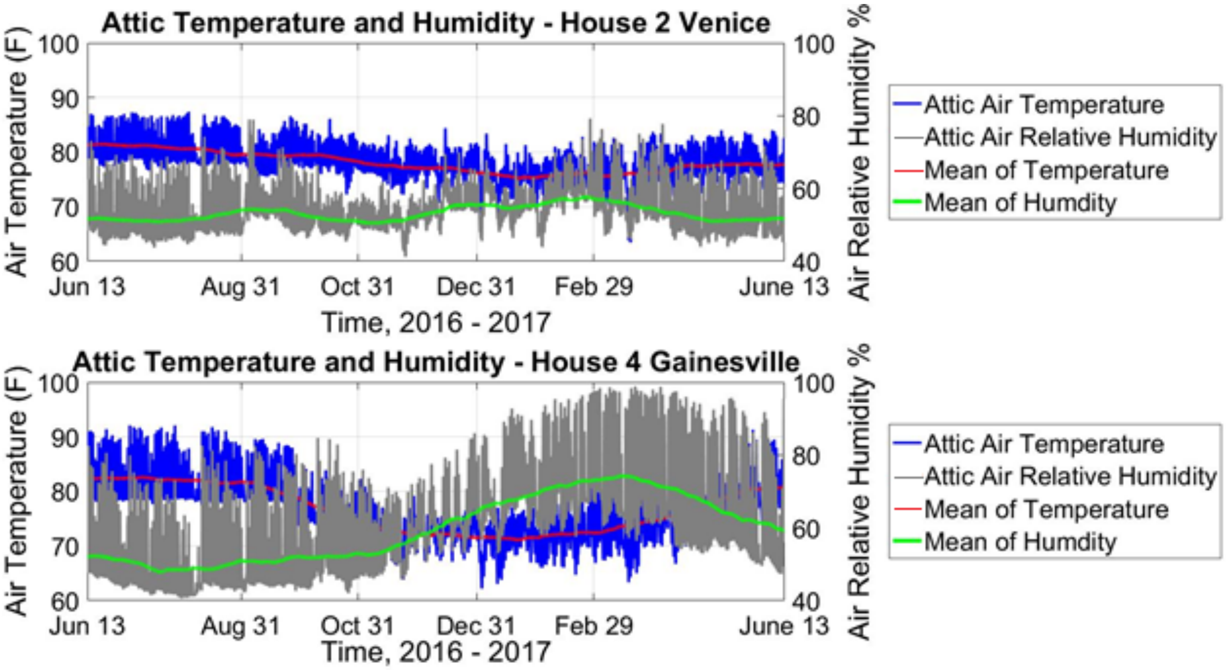

Figure 12 Measured Attic Air Temperature and Humidity for House 2 and House 4. Blue trace and green trace shows air temperature plotted on the left y-axis. Grey trace and green trace shows the air relative humidity plotted on the right y-axis.

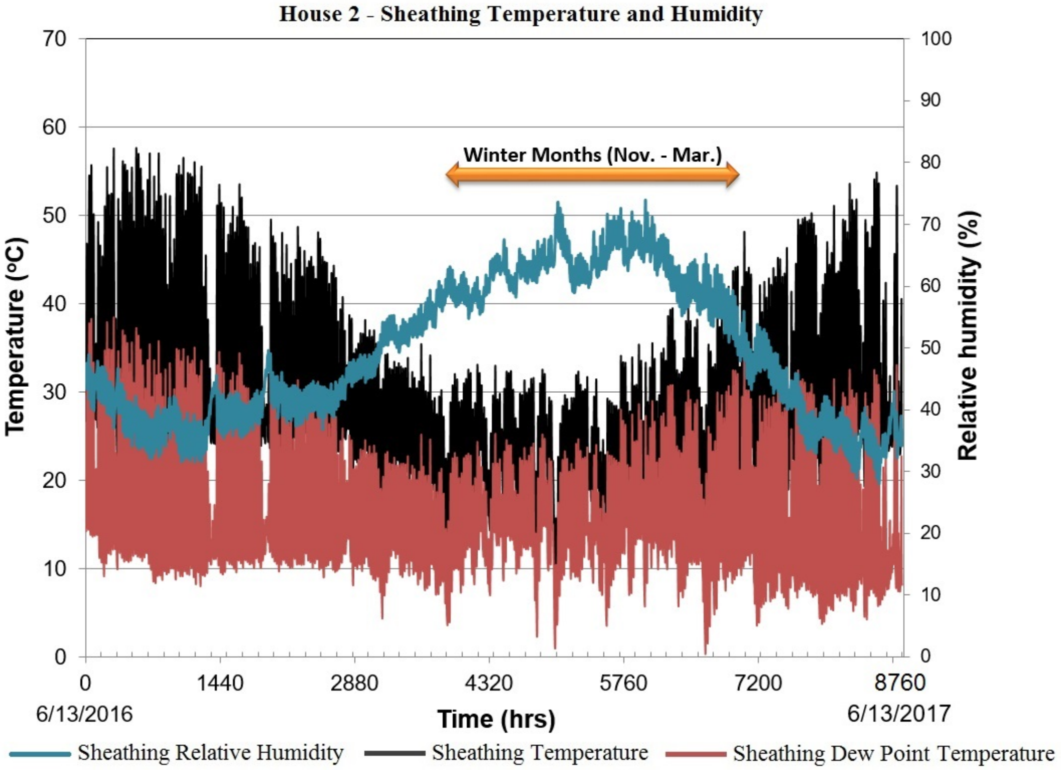

Figure 13 Measured Sheathing Temperature and Humidity for House 2. Sheathing temperatures (black) reach dew point (red) during the winter months for a small time-period.

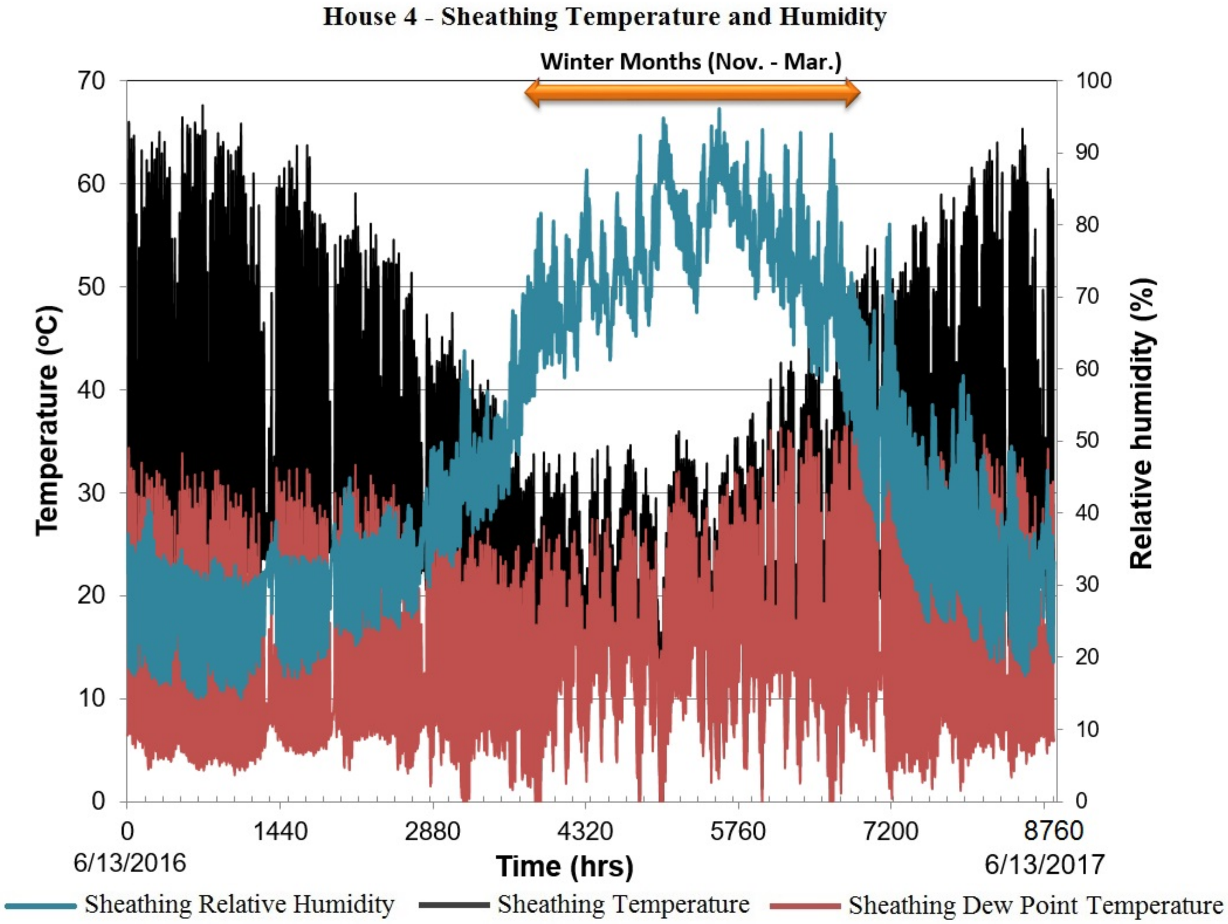

Figure 14 Measured Sheathing Temperature and Humidity for House 4. Sheathing temperatures (black) coincide with dew point (red) during the winter months. This allows favorable conditions for moisture accumulation.

4.7 HURRICANE MATTHEW EFFECT ON 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 15. 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.

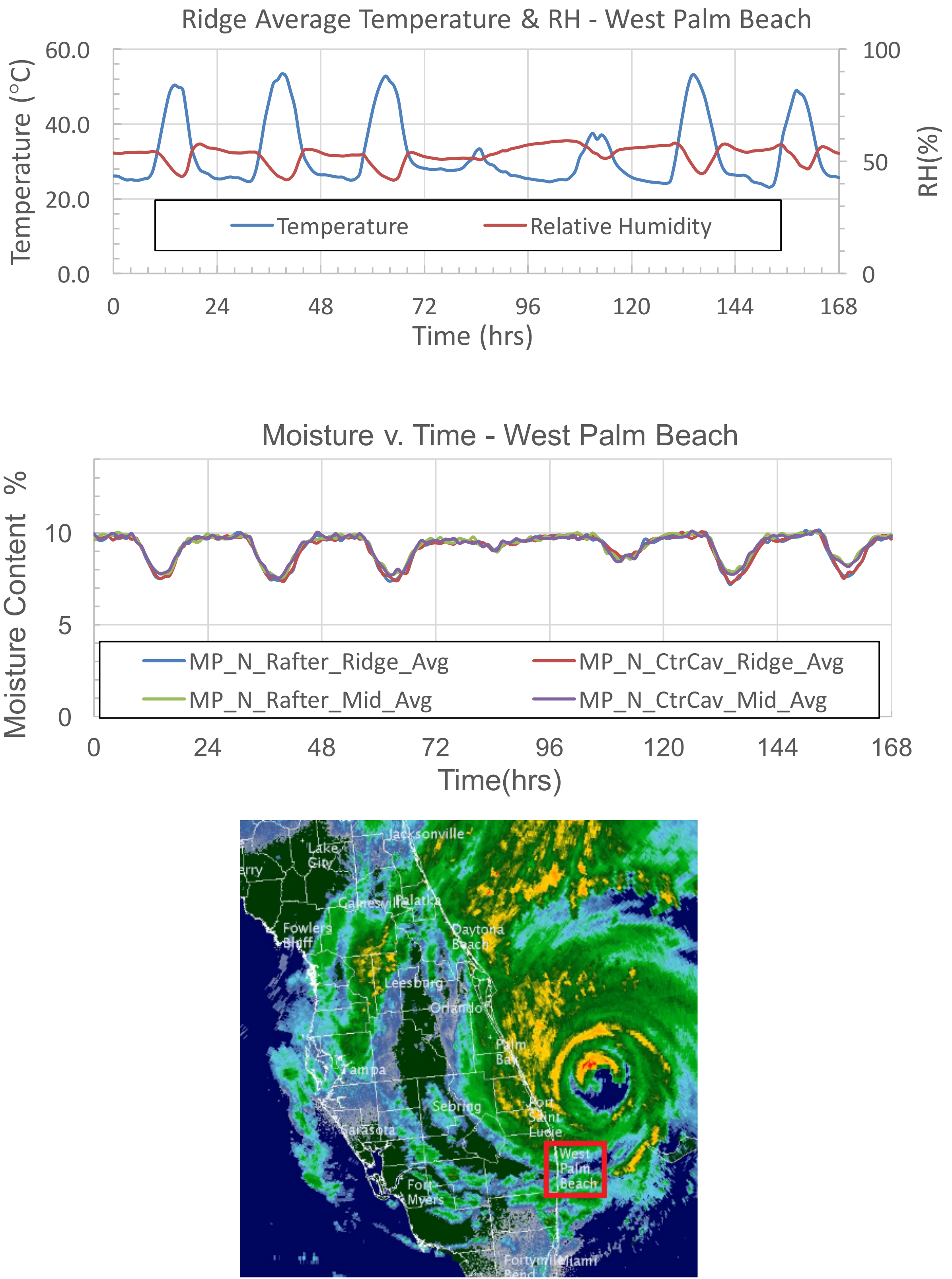

Figure 15 Effect of Hurricane Matthew on Measured Climate of House 1, October 3rd – 10th, 2016. Moisture and Temperature diurnal fluctuations absent due to cloud cover. High humidity during hurricane attack. Cloud cover image source: National Weather Service.

4.8 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 16 represents this comfort zone. We compare field-measured indoor climates with ASHRAE comfort zone to determine the occupant comfort levels in the sealed attic houses. 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.

Table 10 Percentage Time House Conditions were Outside of ASHRAE Comfort Zone

House	House 1 West Palm Beach	House 2 Venice	House 3 Orlando	House 4 Gainesville
House Retrofit with Spray Foam?	YES	NO	NO	NO
% of Hours Outside Comfort Zone	36%	3.9%	13.6%	11.1%

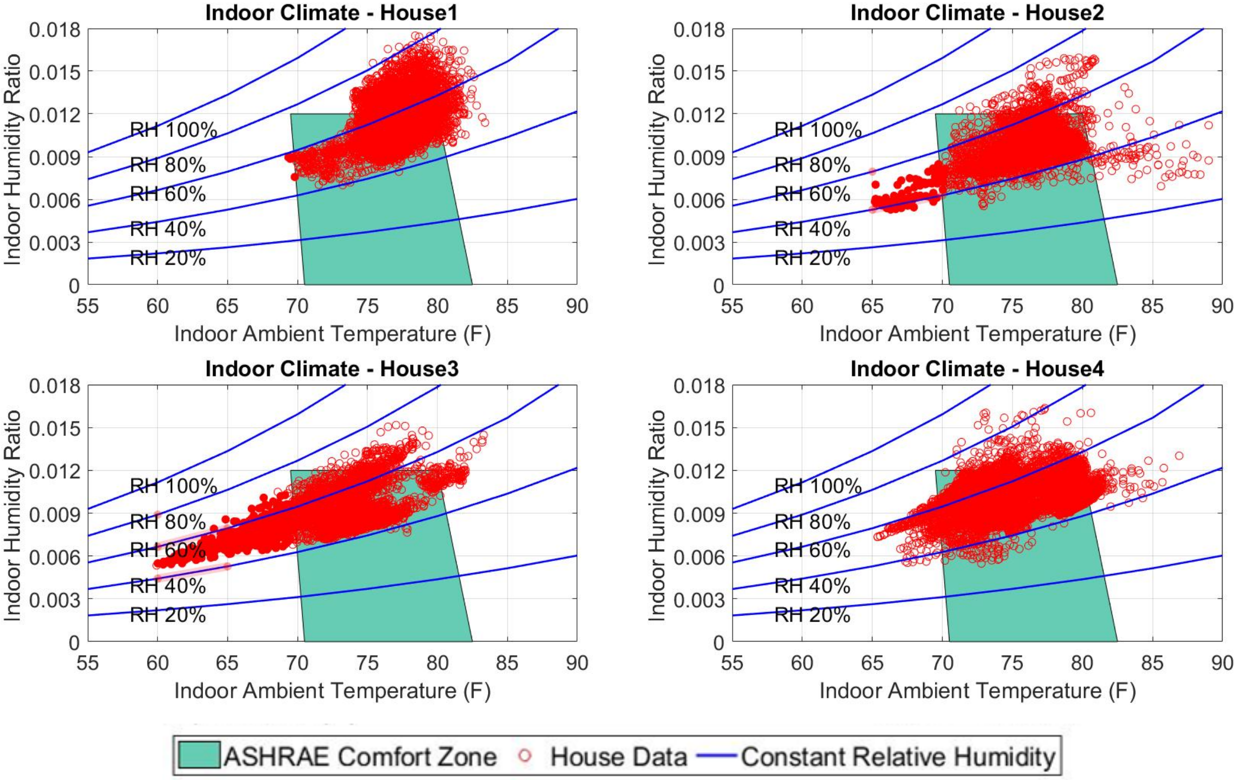

Figure 16 Comparison of Measured Indoor Climate vs ASHRAE Comfort Zone. Red circles indicate measured hourly data. The blue lines represent the humidity levels in the indoor conditioned space of all four houses. The indoor air comfort is quantified by the percentage of red dots within the green shaded area.

5. 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 11 tabulates the inputs required by each software of the toolkit.

Table 11 PRAT Inputs

Building Energy Optimization BEopt	Energy Plus ENERGY PLUS	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 ENERGY PLUS • Outdoor Climate

5.1 DESCRIPTION OF PRAT SOFTWARE PACKAGES

5.1.1 Building Energy Optimization Software (BEopt)

For our research project, the sealed attic behavior of four single family residential homes are studied. The Building Energy Optimization (BEopt) code was used to account for the numerous construction materials. BEopt was also developed by the DOE to serve as a front-end graphical user interface (GUI) for Energy Plus. The inputs in Table 11 are specific to each house and characterize the sealed attic behavior in climate zones 1 and 2. When defining the house geometry, the materials are defined as surfaces of two types, heat storage surfaces and heat transfer surfaces. Ceilings, floors, exterior walls and roofs separate two zones of varying temperatures. Hence these members are defined as heat transfer surfaces. Partition walls are within the same zone having constant temperatures and are defined as heat storage walls. To accommodate for the air leakage through the building envelope, holes are drilled which have the sizes as the ELA's for the three building air leakages. A duct leakage is introduced at the supply duct in the attic. This information along with the occupancy conditions are key in determining the indoor moisture generation and latent heat generation rates. As per the inputs specified, BEopt generates a visual representation of the whole building envelope.

5.1.2 Energy Plus Simulation Software

Once the .idf file is fed into ENERGY PLUS, we must identify and specify the key variables for which ENERGY PLUS would create simulated results. These input variables are defined in Table 11.ENERGY PLUS utilizes two modules – the Air Flow network (AFN) and the Effective Moisture Penetration Depth (EMPD) to incorporate the interzonal air flow and moisture movement. Gu, 2007 discusses the AFN module. It simulates air, heat and moisture movement between zones caused due to interzonal pressure difference. Holes are defined at each outward facing wall to account for living space to attic leakage. The attic roofs and walls also have holes to represent the attic to outside leakage. A hole in the attic floor characterizes the living space to attic leakage. Duct leakage in the attic is modelled as a forced air system with supply and return leakages. EMPD module is used to induce moisture buffering properties of construction materials. Moisture penetrates the building envelope materials due to short term humidity fluctuations and long term humidity fluctuations. The indoor humidity is affected by five factors:

1. Interior moisture generation
2. House ventilation
3. Air infiltration
4. HVAC scheduling
5. Moisture sorption or desorption in materials

Christensen et al. 2013 A non-isothermal behavior of the materials is considered. As water vapor is absorbed into the material, the heat of sorption reduces and the surface temperature increases. This in turn lowers the relative humidity, which decreases the equilibrium moisture content in the wood. Hence the wood can absorb only less moisture from the attic air. This means that the moisture buffering capacity of the materials is reduced due to the inverse relationship between temperature and equilibrium moisture content.

ENERGY PLUS simulations will be performed by varying the key input variables. A test matrix is created which contains minimum, maximum and average values of the key input variables used for simulating temperature and relative humidity. The field measured variables for the four houses will fall within this range. ENERGY PLUS simulations produce air flow rates between zones and temperature and RH values for each zone. By comparing the indoor climate with the comfort zone defined in ASHRAE Standard 55, the range of variables which satisfy the comfort zone can be formulated. Boudreaux et al. 2014 found out that the key variables affecting indoor comfort zone are leakage from attic to outside, living space to outside and duct leakage. Simulations closely matching the behavior of the four field houses will be analyzed to produce air leakage rates from the attic to the outside environment. This is used as an input for the WUFI 1D model.

5.1.3 WUFI 1D

WUFI 1D is a hygrothemal modelling software which is used to simulate the moisture content in wood roofing materials. A roof section will be designed for each house, giving all dimensions and material properties. An air leakage path will be developed to model the air leakage between the attic and the outside environment. A direct leakage path can be defined to model the energy losses. This leakage will be throughout the section of the roof. For the effect of moisture accumulation, the air leakage path is more of an indirect path, at the interface of the insulation and the wood sheathing. The air leakage is introduced as a point source leak in WUFI 1D. This minute leakage path has the potential to induce condensation effect which in turn might cause moisture to accumulate the interface. Critical moisture contents of more than 20% are considered to cause molds, fungi and decay or wood. Moisture contents greater than 30% can cause structural failure of building members (ASHRAE *Fundamentals* 2013). The air flow rates play an important role in the accumulation of moisture. High air flow rates cause the temperature and moisture to be like the outside air producing lesser condensation effect. Very low air flow rates will not have sufficient vapor pressure to allow the moisture to condense. Boudreaux et al. 2014 concluded that medium air flow rates between the attic and the outside environment causes more condensation effect leading to moisture contents greater than 20% for a period of three months in a year (January – March 2011).

WUFI simulations are performed for all four houses by varying the internal moisture generation rates, the attic to outside leakage, and the living space to outside leakage and the duct leakage. Sensitivity analysis will be performed to determine the effect of the input variables. A range of these input variables which produce safe moisture contents in the wood roof sheathing will be formulated to produce moisture durable sealed attic constructions.

5.2 PROBABILISTIC AND DETERMINISTIC SIMULATIONS

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 17. The analytical models include the house physical characteristics of mechanical ventilation, space conditioning and associated conditioning schedules, lighting, water heating and appliances. The spray foam insulation was installed during initial construction in three of the four houses, 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 17 are used to generate input files for Energy Plus, which, in turn will be used in the PRAT software package.

Table 12 Simulated and Field House Characteristics

House	Generic House Model	House 2 – Venice	House 4 – Gainesville
Story	2 – story	2 – story	1 – story
Plan Area	2,400 sq.ft.	3,592 sq.ft.	3,055 sq.ft.
Roof Structure	Hip	Hip	Hip
Roof Cover	Asphalt Shingle	Concrete S-tile	Asphalt Shingle
Roof Sheathing	Plywood (5/8 in)	OSB (5/8 in)	Plywood (5/8 in)
Roof Deck Insulation	R-38 10in. ocSPF	R-21 5.5in. ocSPF	R-27 7in. ocSPF
Conditioned Volume	19000 ft^3	42,183 ft^3	29,022 ft^3
Attic Volume	4000 ft^3	7,692 ft^3	14,002 ft^3
# of Occupants	1 - 6	2	2

Table 13 Type of Inputs used for PRAT Simulations

Inputs	Simulation 1	Simulation 2	Simulation 3
	Probabilistic Inputs	Probabilistic + Deterministic	Probabilistic + Deterministic
House Model	Generic model	Generic model	Specific House Model
Exterior Temperature	Texas (climate zone 2A)	Florida (climate zone 2A)	Florida (climate zone 2A)
Indoor Moisture and Heat	Probabilistic data	Probabilistic data	Probabilistic data
Attic Duct Leakage Area	Generic house leakage	Field-measured leakage	Probabilistic data
Attic-to-Outside Leakage Area	Generic House Leakage	Field-measured leakage	Field-measured leakage
Interior-to-Outside Leakage Area	Generic House Leakage	Field-measured leakage	Field-measured leakage
Attic-to-Interior Leakage Area	ORNL measured leakage from 12 houses	ORNL measured leakage from 12 houses	ORNL measured leakage from 12 houses
Thermostat Set Point	Climate zone 2A	Homeowner Survey	Homeowner Survey
Mechanical Ventilation	ASHRAE Standard 62.2	ASHRAE Standard 62.2	ASHRAE Standard 62.2
Simulation Set 3 same as set 2, except for specific house models			

Figure 17 Generic House Model (top). House 2 model (left bottom) and House 4 model (right bottom)

5.3 GENERATION OF INDOOR HEAT AND MOISTURE (GIHM) TOOL

ORNL has developed a sophisticated tool known as the Generation of Indoor Heat and Moisture (GIHM) tool to simulate residential generation of moisture and heat. The GIHM tool uses statistical data for residential user behaviors together with moisture and heat production rates from occupant activities and appliances inside homes to predict the indoor heat and moisture rates. Since the amount of moisture generated in homes is building and climate-dependent, the tool also uses the type of building (multi- or single-family) and location as inputs. The tool is a probabilistic instrument that simulates hourly variations of moisture and heat generation in homes using a stochastic approach. So, for each climate zone, an output set of hourly profiles captures the range and distribution of moisture and heat generation in real homes. shows the probability distribution of average daily moisture production simulated by the tool for House 2 and House 4 as a function of occupants compared with the deterministic ASHRAE 160 standard. The indoor sensible heat generation was based directly on the indoor latent heat (moisture) generation. To estimate the sensible heat generation a multiplier of 2.7 was used with the simulated latent load. This is based on an estimation of the latent/sensible total load split from the appliances, miscellaneous electric loads, and occupants from the Building America research benchmark. (Boudreaux et al. 2016).

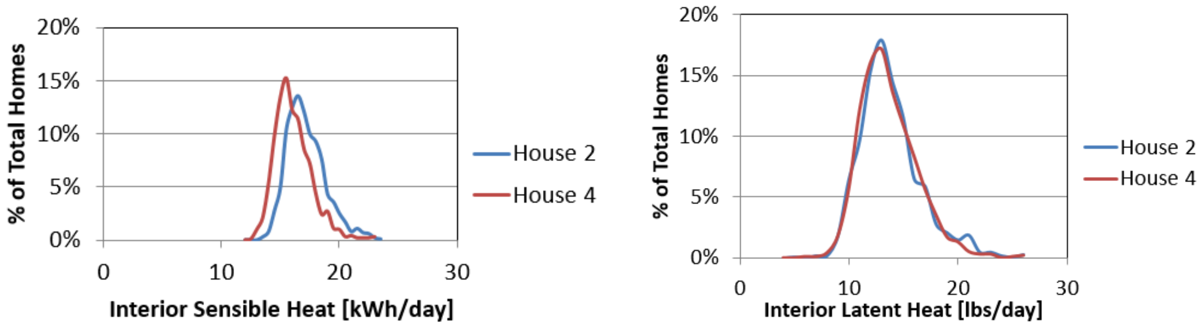

Figure 18 Interior Heat and Moisture Generation from ORNL's Generation of Indoor Heat and Moisture Tool. From LBNL Database, the mean values representing houses with 2 occupants were selected

5.4 PROBABILISTIC ASSESSMENT OF PROTOTYPE HOUSE MODEL AND SPECIFIC HOUSE MODEL

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. The key input variables used in the simulations and the test matrix follow in Table 14. LBNL[3] database is used to determine the air leakage areas for a generic house in climate zone 2A. The indoor moisture is developed from ORNL's Generation of Indoor Heat and Moisture tool. Another important parameter affecting the PRAT outputs is thermostat set points. The thermostat set points for both heating and cooling seasons are obtained from the 2009 Residential Energy Conservation Survey[4].

Table 14 Matrix of Key Input Variables Defined for Climate Zone 2A

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
Indoor Heat Generation Rate (kWh/day)	11.94	20.55	28.58
Temperature Heating Set Point (°C)	14.4	20.26	26.7
Temperature Cooling Set Point (°C)	15.6	22.50	29.4

The outputs from ENERGY PLUS 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.

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[3] **LBNL** - LBNL (2015). "Lawrence Berkeley National Laboratory - Residential Diagnostics Database." from **http://resdb.lbl.gov/**. The LBNL database contains whole-house air leakage data from 147,000 houses. Climate zone specific data is available for building envelope as well as duct leakage results.

[4] **Residential Energy Conservation Survey** - RECS (2015). "Residential Energy Consumption Survey ". from **http://www.eia.gov/consumption/residential/**. The RECS Household Survey is a U.S. Department of Energy, Energy Information Administration, research program that collects information from households regarding uses of energy, behaviors and housing characteristics that affect present and long-term uses of energy, and the size of household energy bills.

Table 15 Details of Probabilistic and Deterministic Inputs for PRAT Simulations

Parameter	**Simulation 1**	**Simulation 2 & Simulation 3**	
	All Houses	**House 2 - Venice**	**House 4 - Gainesville**
House Model	Generic - 2400 sq.ft., 2-story, box house, gable roof	Generic - 2400 sq.ft., 2-story, box house, gable roof Specific – 3592 sq.ft., 2-story, hip roof	Generic - 2400 sq.ft., 2-story, box house, gable roof Specific – 3055 sq.ft., 2-story, hip roof
# of Occupants	1 – 6	2	2
Indoor Heat & Moisture	GIHM Tool (varied FFA, # occupants)	GIHM Tool (3592 sq.ft. FFA, 2 occupants)	GIHM Tool (3055 sq.ft. FFA, 2 occupants)
Attic Duct Leakage Area	LBNL Residential Diagnostics Database - Duct Leakage	0.002 [kg/s] balanced supply and return leakage	LBNL Residential Diagnostics Database - Duct Leakage
Attic-to-Outside Leakage Area	LBNL Table 5 in.A Literature Review of Sealed and Insulated Atticsin.	0.0058 [m^2] x 4 for each face (2 gable + 2 roof)	0.0017 [m^2] x 4 for each face (2 gable + 2 roof)
Interior-to-Outside Leakage Area	LBNL Residential Diagnostics Database - Duct Leakage	0.0052 [m^2] x 8 for each face (N,S,E,W walls for each story)	0.0158 [m^2] x 8 for each face (N,S,E,W walls for each story)
Attic-to-Interior Leakage Area	ORNL Measured Data from Field Sites	ORNL Measured Data from Field Sites	ORNL Measured Data from Field Sites
Thermostat Set Point	2009 Residential Energy Conservation Survey (RECS) microdata	76°F during day 75°F during night Homeowner Survey	75°F during heating season 80°F during cooling season Homeowner Survey
Mechanical Ventilation	0 if ACH@50 is above IECC 2015 Code, calculated using ASHRAE 62.2 if ACH@50 is below Code	0.037 [m^3/s] Based on ASHRAE 62.2 and that homes ACH@50 = 2.2 < 5	0 [m^3/s] Based on ASHRAE 62.2 and that homes ACH@50 = 5.2 > 5
Simulation Set 3 same as set 2, except for specific house models			

5.5 PRAT SIMULATED ATTIC TEMPERATURE AND RELATIVE HUMIDITY

This section presents the PRAT simulations of attic temperature and relative humidity. The results are based on BEopt models and Energy Plus energy simulations. The three simulation sets are compared to analyze the sensitivity of air leakage rates, building geometry and number of occupants.

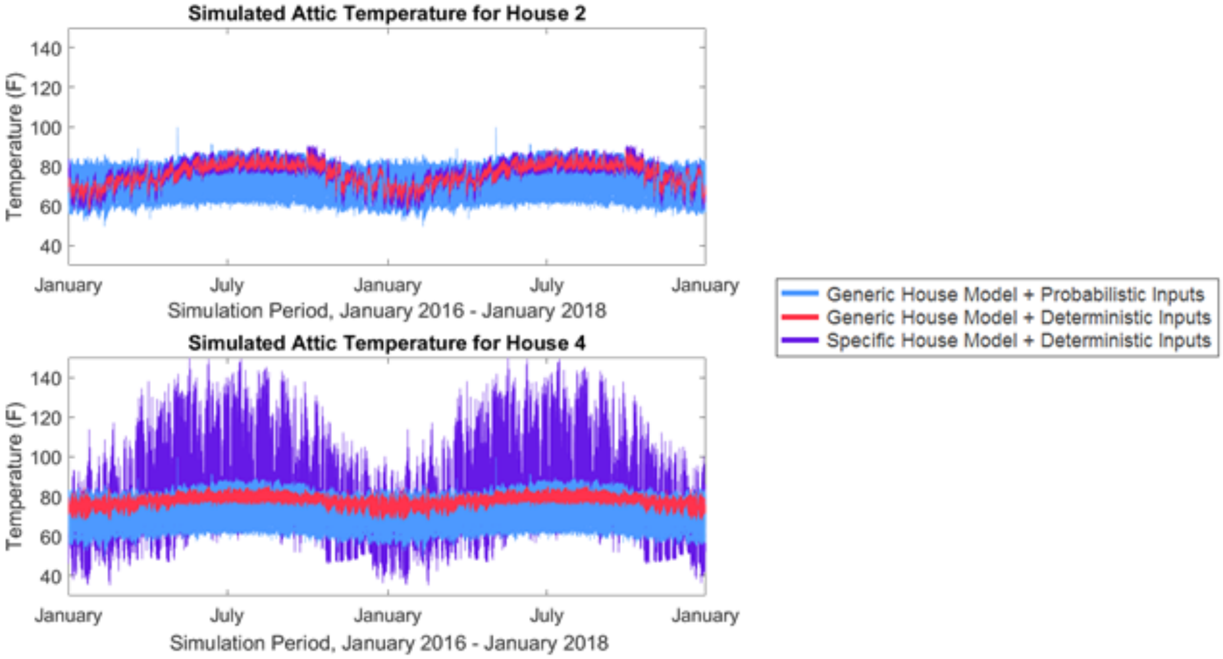

Figure 19 Comparison of three PRAT Simulations of Attic Air Temperature.

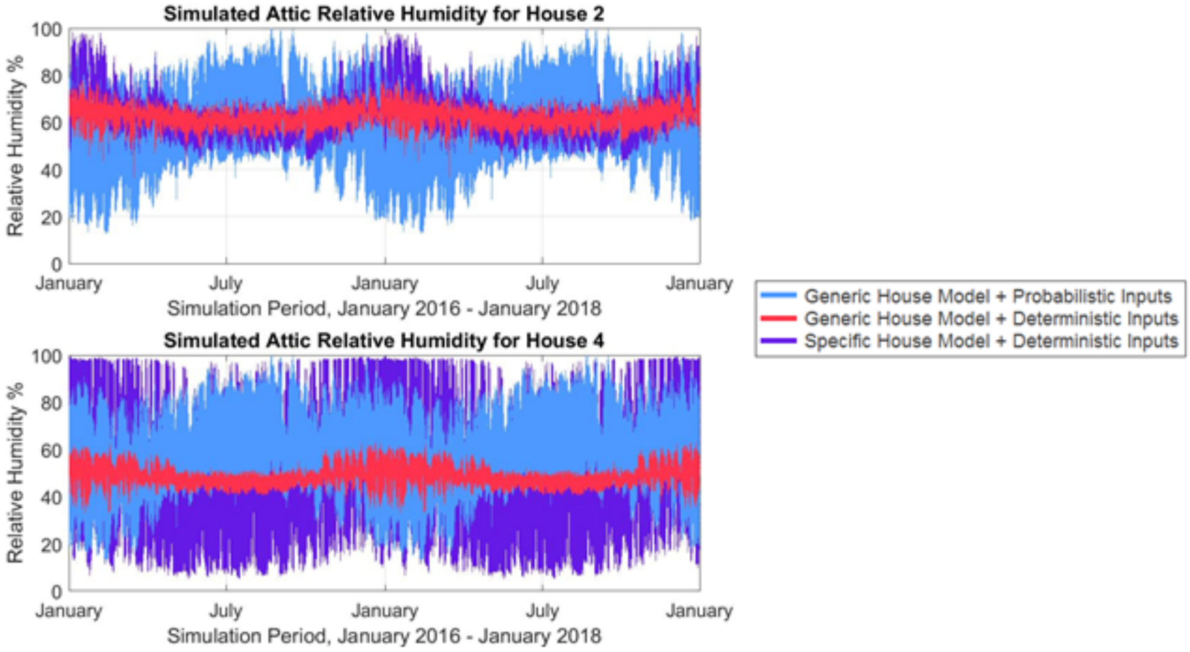

Figure 20 Comparison of three PRAT Simulations of Attic Air Relative Humidity.

Figure 19 and Figure 20 presents the PRAT simulations of attic temperature and relative humidity. Three variations of PRAT simulations are presented for both the parameters. The differences between the three sets of PRAT simulations are tabulated in Table 13 and Table 15. The implications of the three simulation sets and how they are used to predict the roof sheathing moisture content is discussed in the upcoming sections.

5.5.1 Simulation 1 – Generic House Model with Probabilistic Inputs

The blue band in Figure 19 shows 1000 PRAT simulations made with a generic house model and all probabilistic inputs. This blue band is the same band as shown below. The 1000 variations can be seen clearly.

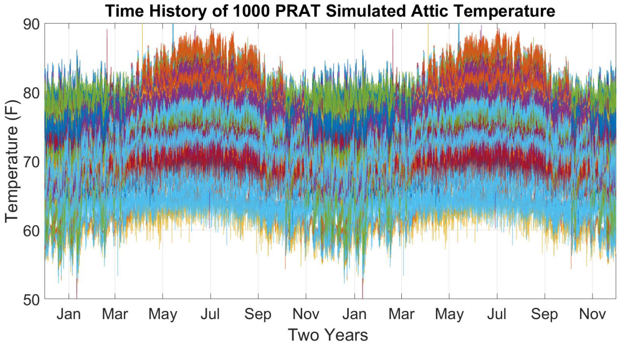

Figure 21 1000 PRAT Simulated Attic Temperature

This simulation set is representative of Florida's hot and humid climate zone 2A. The measured attic temperature and relative humidity of every Florida house is expected to fall within this blue band. This trend is satisfied when the PRAT simulated attic temperature and humidity is compared with the field-measured attic temperature and humidity. The comparison is presented in Figure 24 and **Error! Reference source not found.**. The field-measured attic temperatures fall near the upper limit of the PRAT simulated bandwidth.

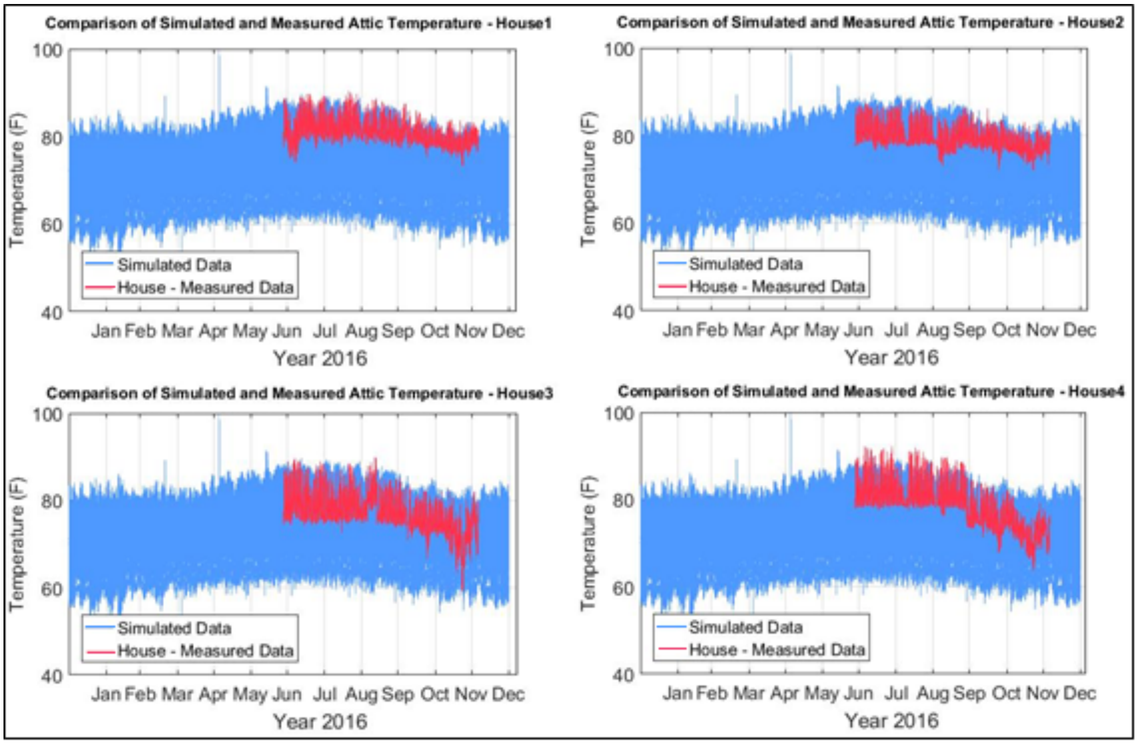

Figure 22 PRAT simulated attic temperatures (blue band) compared to field-measured attic temperatures (red trace). 1000 PRAT simulations are performed with a generic house model and probabilistic inputs

The blue band in Figure 20 shows 1000PRAT simulated values of attic relative humidity with a generic house model and probabilistic inputs. These 1000 variations of attic relative humidity are depicted below. The field-measured attic relative humidity fall all along the PRAT simulated bandwidth as shown in Figure 24.

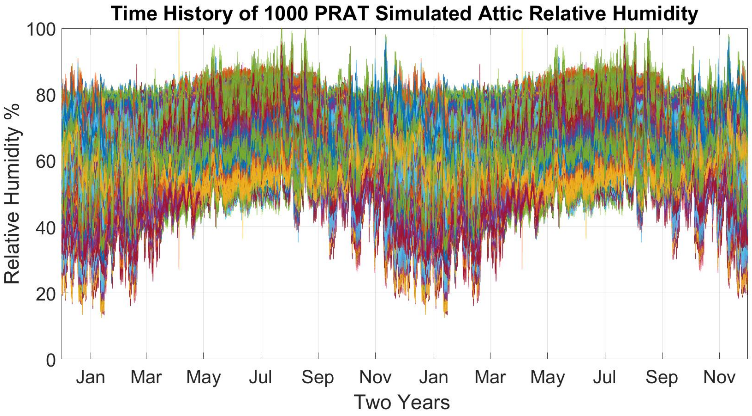

Figure 23 1000 PRAT Simulated Attic Relative Humidity

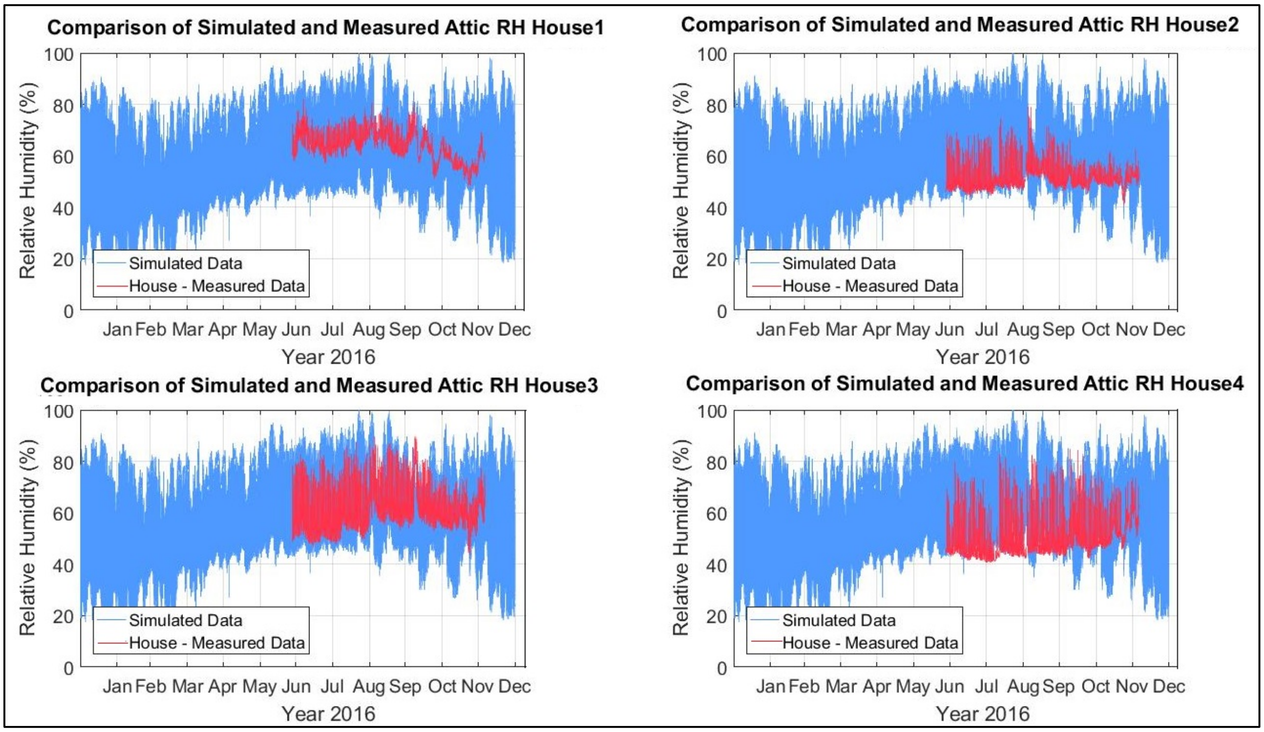

Figure 24 PRAT simulated attic relative humidity (blue band) compared to field-measured attic relative humidity (red trace). 1000 PRAT simulations are performed with a generic house model and probabilistic inputs

5.5.2 Simulation 2 & Simulation 3 – House Models with Deterministic Inputs

In Phase 1 work, air leakage parameters and temperature set points were recorded by the research team. These deterministic values are used in PRAT simulations to predict the attic temperature, humidity and moisture content. This section presents the simulated attic humidity and temperature for Simulation 2 and Simulation 3 as defined in Table 15.

The deterministic simulations performed with a specific house model (purple trace) has variations in attic temperature and humidity when compared to the field-measured data, presented in Figure 25 and Figure 26. The blue trace shown in these figures better match with the field-measured data especially for House 4. The difficulty in modelling comes into picture when deterministic inputs are set into place. When varying all inputs probabilistically, the range of inputs cover any shortcomings of modelling the actual behavior of houses; while the deterministic inputs magnify the errors in modelling. The moisture buffering capacity of the materials used in the specific house models better match House 2 than House 4. Hence it is prudent to use a generic house model while simulating deterministic inputs.

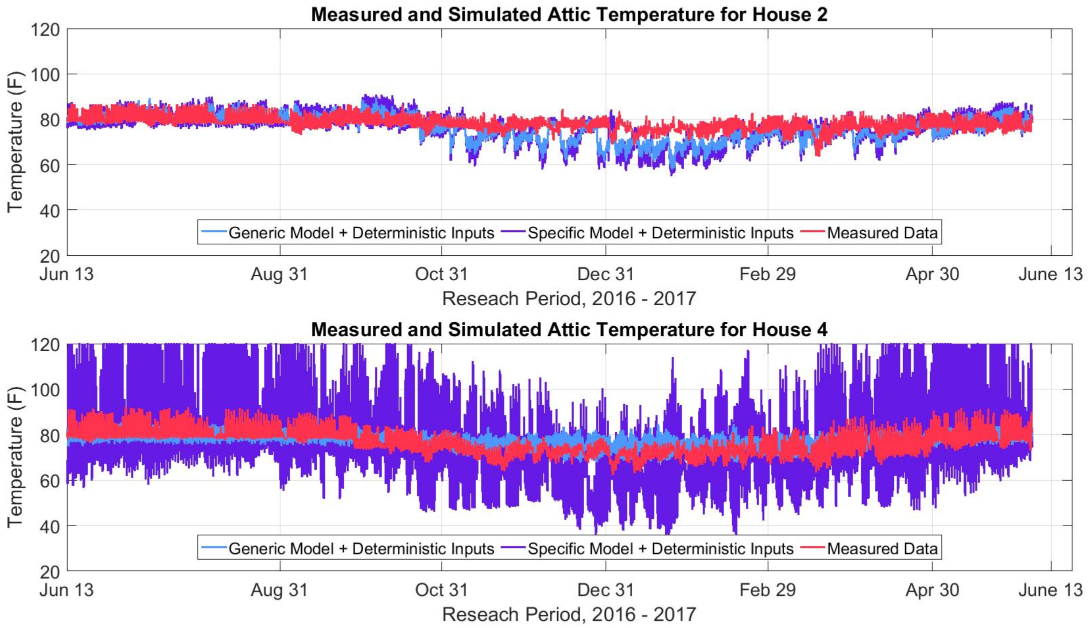

Figure 25 Comparison of Measured Attic Temperature with Deterministic Simulations of Attic Temperature

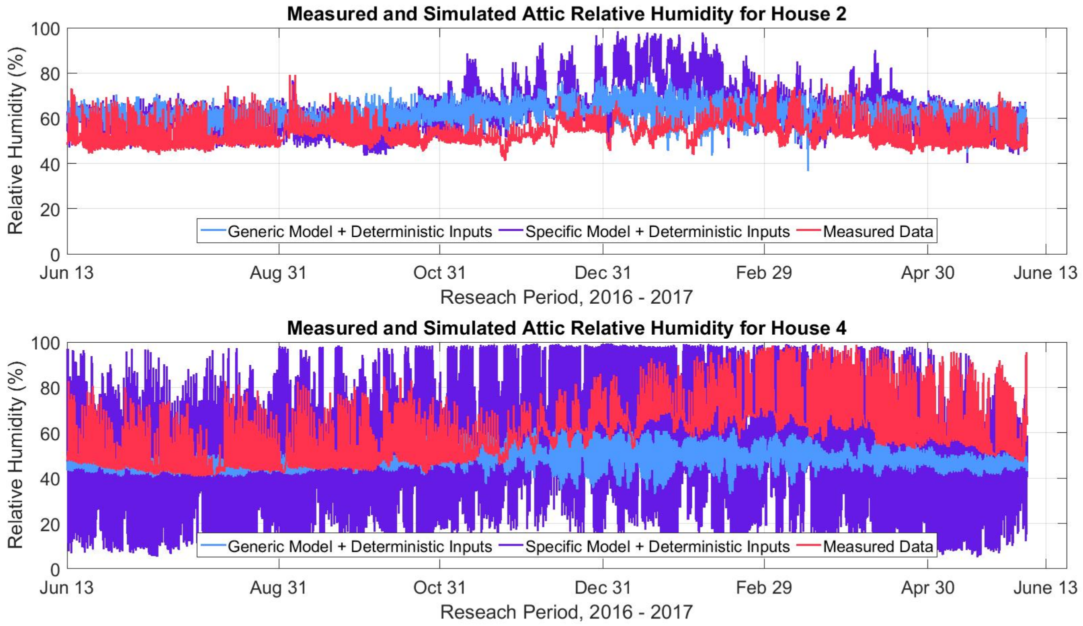

Figure 26 Comparison of Measured Attic Humidity with Deterministic Simulations of Attic Humidity

5.6 PRAT SIMULATED ROOF SHEATHING MOISTURE CONTENTS

It has been established in the previous section that the specific house models cannot accurately predict the temperature and humidity in the attic of the Florida field-homes. Hence, for predicting the roof sheathing moisture contents the following inputs are used:

- Attic temperature and humidity from a generic house model with probabilistic inputs
- Attic temperature and humidity from a generic house model with deterministic inputs

5.6.1 Generic House Model with Probabilistic Inputs

To compare the actual field-measured moisture contents to the simulated moisture contents, the parameters affecting the moisture movement in the field should be considered in the WUFI 1D model roof section. Several parameters like outside temperature, attic temperature, wind speed, radiation of the roof, air leakage paths and material properties affect the moisture movement.

The generic models have a concrete tile roof, a weathering membrane, OSB wood sheathing and 5.5in. of open-cell spray polyurethane foam insulation. A small air layer separates the concrete tile and the weathering membrane.

The generic house models do not consider any roof leak, air leakage paths from the attics or varying insulation thickness. The sections are modelled to represent a generic climate zone 2A house having hot and humid Texas climate, with attic temperature simulated from Energy Plus and generic rainfall patterns. However, two models are developed to account for the airflow occurring at the sheathing-to-insulation interface. Air flow can occur at the sheathing-to-insulation interface if the thickness of the insulation layer is less and the joists and rafters are not completely covered by the insulation. If the insulation layer is thick enough, no air can pass through the interface.

Two cases of air flow within the roof section was considered to determine the actual behavior of the roof section in the field.

- Air flow at the interface between the sheathing and spray foam insulation
- No Air flow at the interface between the sheathing and spray foam insulation

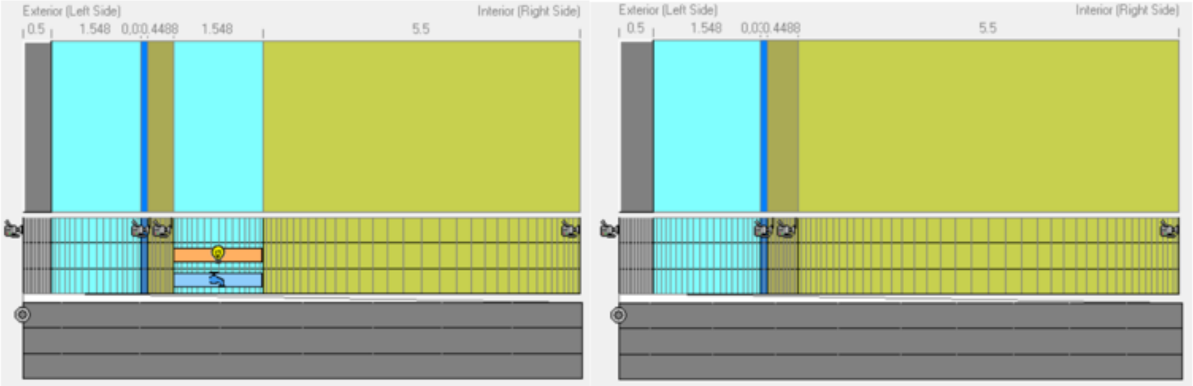

Figure 27 Generic Roof Section Model in WUFI. Air flow between the sheathing and the insulation is considered (left) and no air flow between the sheathing and the insulation is considered (right)

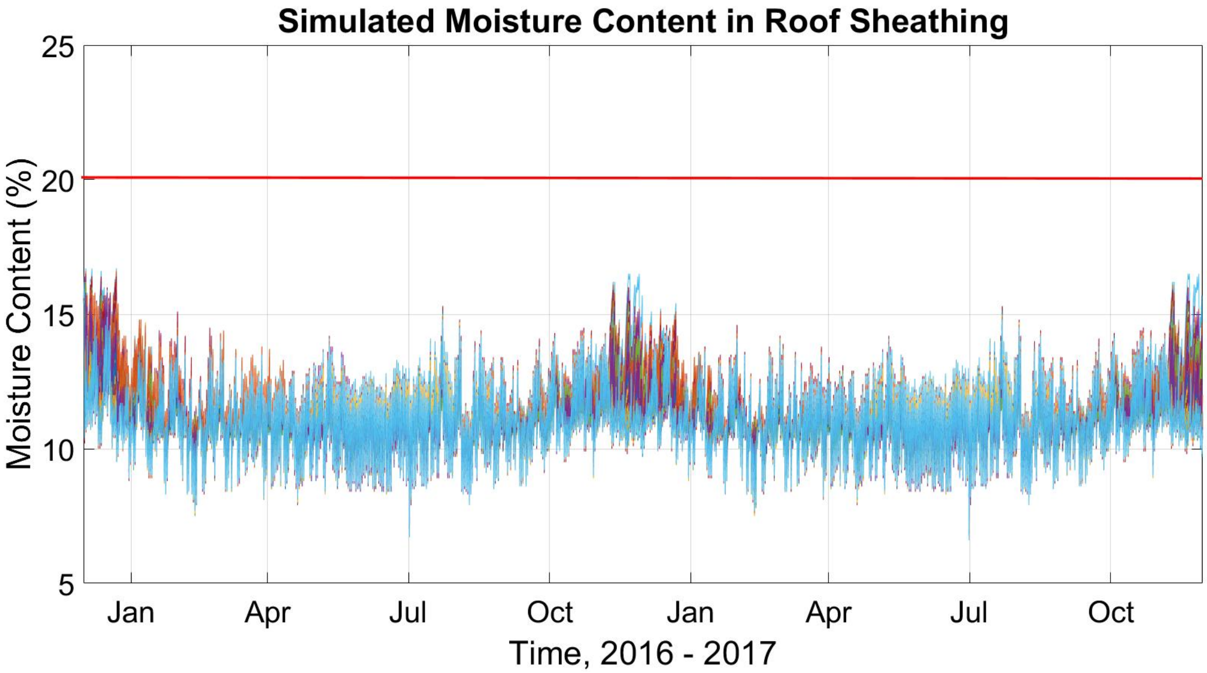

Figure 28 1000 PRAT Simulated Moisture Contents at Roof Sheathing considering Air flow at the sheathing-to-insulation interface. Air flow at the interface allows less moisture to condense.

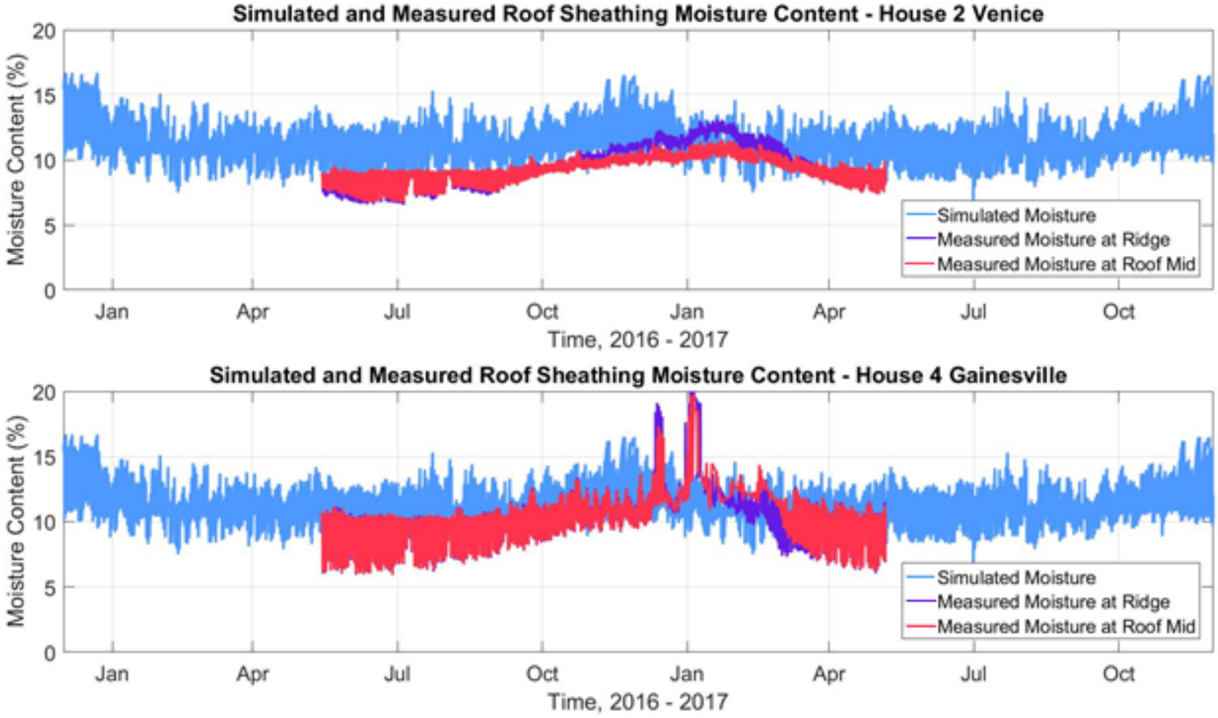

Figure 29 Simulated and Measured Moisture Contents. 1000 probabilistic PRAT simulations (blue band) consider air flow at the sheathing-to-insulation interface. House 2 matches with this case better than House 4.

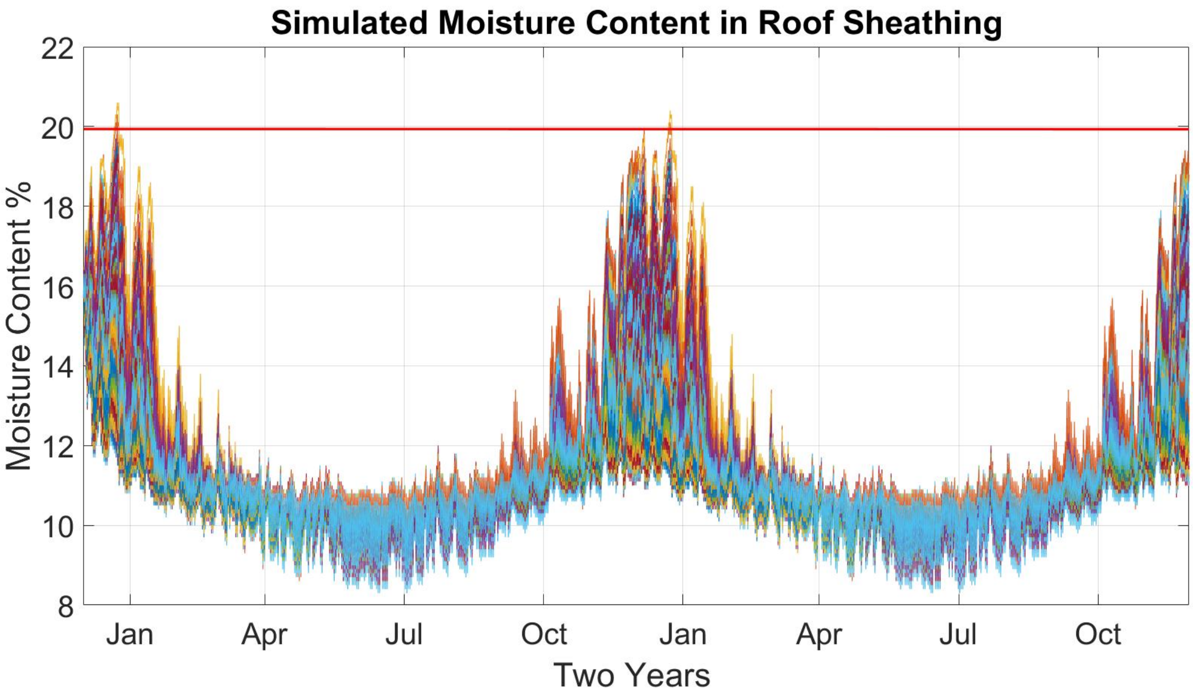

Figure 30 1000 PRAT Simulated Moisture Contents at Roof Sheathing considering no air flow at the sheathing-to-insulation interface. Lack of air flow allows more moisture to condense at the wood sheathing.

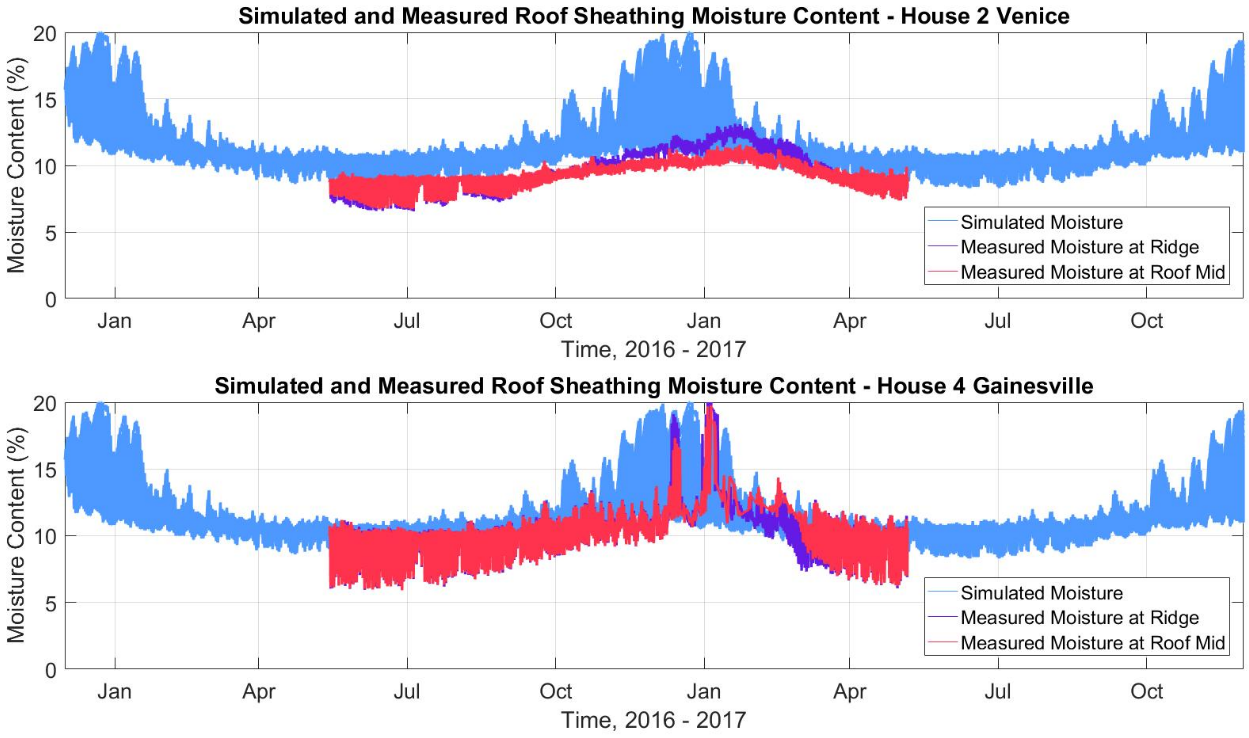

Figure 31 Simulated and Measured Moisture Contents. 1000 probabilistic PRAT simulations (blue band) do not consider air flow at the sheathing-to-insulation interface. House 4 matches with this case better than House 2.

The PRAT simulations performed with a generic house model can predict the roof sheathing moisture content with some extent of accuracy. The peak moisture content of 20% occurring in House 4 is well predicted by this model. However, these models do not consider any variation of insulation thickness, air leaks from the attic to the outside or rain water intrusion. A better analysis is required to determine the effect of these parameters.

5.6.2 Specific House WUFI Model with Deterministic Inputs

To accurately model the moisture diffusion and permeance through the foam layer, it is important to induce an air change between the attic and the outside environment. The field measured air changes from the attic-to-outside environment values cannot be used as it is because, most of the air leaks in the field occur near the ridge and the eaves and not through a generic roof section. Hence a parametric analysis is performed by varying the air change rate from the attic to the outside environment. Specific house WUFI models were developed for the simulations with inputs from **Error! Reference source not found.**.

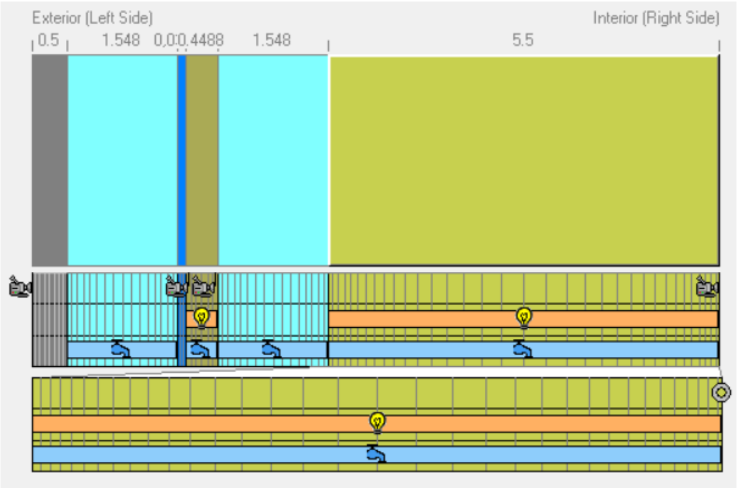

Figure 32 WUFI Roof Section Model for House 2 – Concrete Roof with Air Layer between Sheathing and Insulation

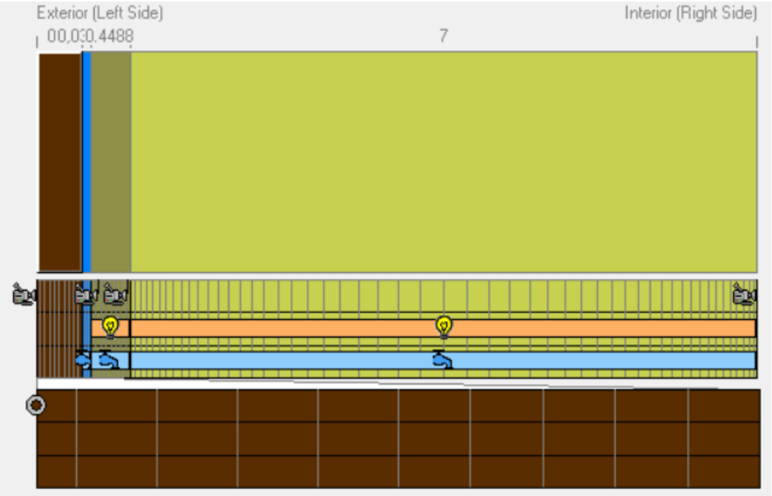

Figure 33 WUFI Roof Section Model for House 4 – Asphalt Shingle Roof without Air Layer between Sheathing and Insulation

WUFI considers several input parameters like outside temperature, attic temperature, air leakage rates to simulate the moisture content in the roof sheathing. While modelling the roof section, the team did not have enough information such as wind speed and radiating properties of roof as well as hourly changes in internal pressure due to temperature and stack effects. Hence, an accurate replication of the field-measured moisture contents was not possible. To closely match the field-measured data, air leakage parameters highly influenced the simulations. Hence several simulations were performed by varying the air leakage input at the roof section in the WUFI 1D model. The outdoor and indoor temperatures can either be defined by the user for a location or can be selected from the available climate data built into the WUFI database. The differences in simulations are tabulated in Table 16 and plotted along with measured data in Figure 34.

Table 16 WUFI Parametric Simulation Inputs

Case Number	Outdoor Temperature	Attic Temperature	Air Leakage
1	WUFI inbuilt	Energy Plus probabilistic Simulations	LBNL Probabilistic Data
2	WUFI inbuilt	Energy Plus deterministic simulations	No air leakage
3	Field-measured	Field-measured	No air leakage
4	Field-measured	Field-measured	1 ACH mixing with attic air
5	Field-measured	Field-measured	1 ACH mixing with outside air

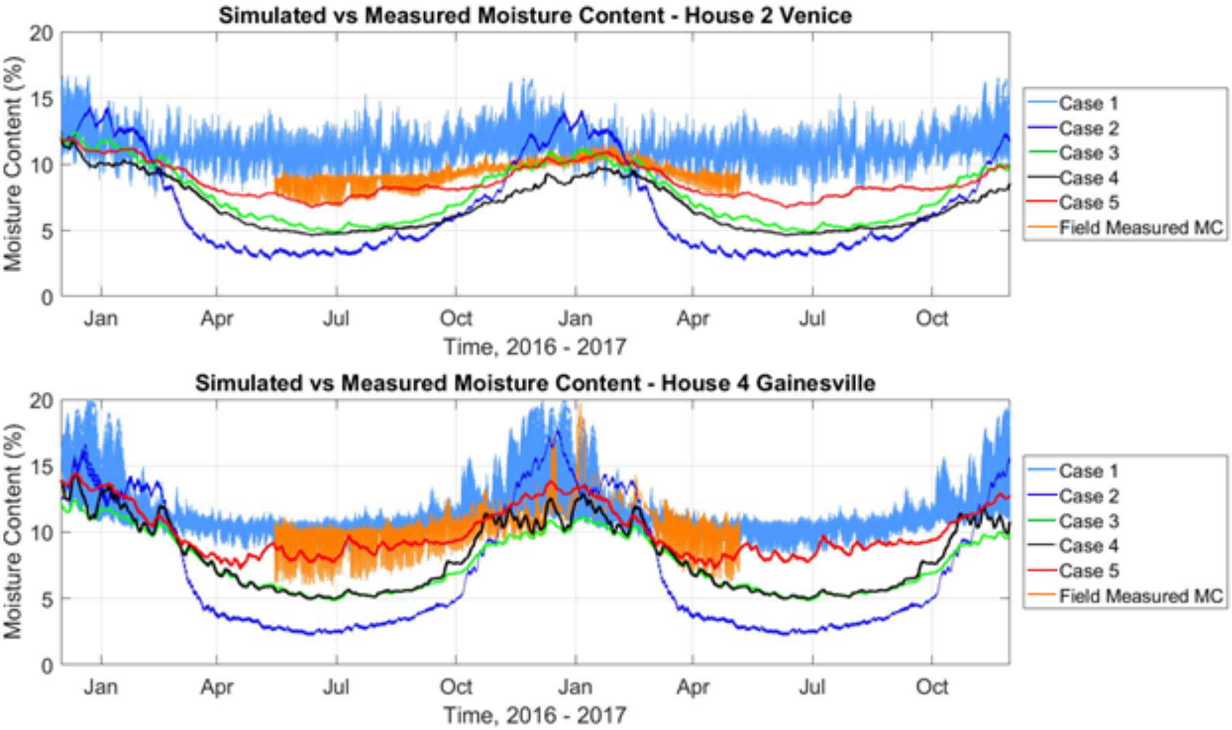

Figure 34 WUFI Probabilistic Simulations for House 2 and House 4. The red trace which has field-measured outdoor and attic temperatures plus an air leak matched well with the field-measured moisture contents.

WUFI simulations performed using field-measured outdoor temperature and attic temperature along with an air leak into the outside environment matched well with the field-measured data.

This shows that in the sealed attics of House 2 and House 4, the air leakage in the attic allows outside air to leak into the attic space rather than have the attic air leak outside into the environment. It is understandable because, both attics do not have a supply vent pumping air into the attic and typically the attic hatch is closed. So due to the wind blowing onto to the roof system, the leaks allow air to flow into the attic. During the winter, when cold air passes through the sheathing onto the foam, the resistance to air permeance inhibits air flow into the attic and thereby can cause condensation at the sheathing-to-insulation interface.

The condensation effects can be increased if the colder air from the outside reaches a thick insulation layer. Thicker insulation layers combined with high attic humidity could cause more condensation at the wood sheathing as evidenced in House 4. However, further detailed analysis is required to solidify this statement.

5.6.3 Parametric WUFI Simulations with Varying Insulation R-Values

A parametric analysis was performed by keeping all input parameters to the WUFI model constant and by varying the R-value of the spray foam insulation layer. For this analysis, field-measured outdoor temperature and attic temperature are used as inputs to the WUFI model along with an air leakage rate of 1ACH from the outside to the attic. The results of this WUFI analysis is presented below.

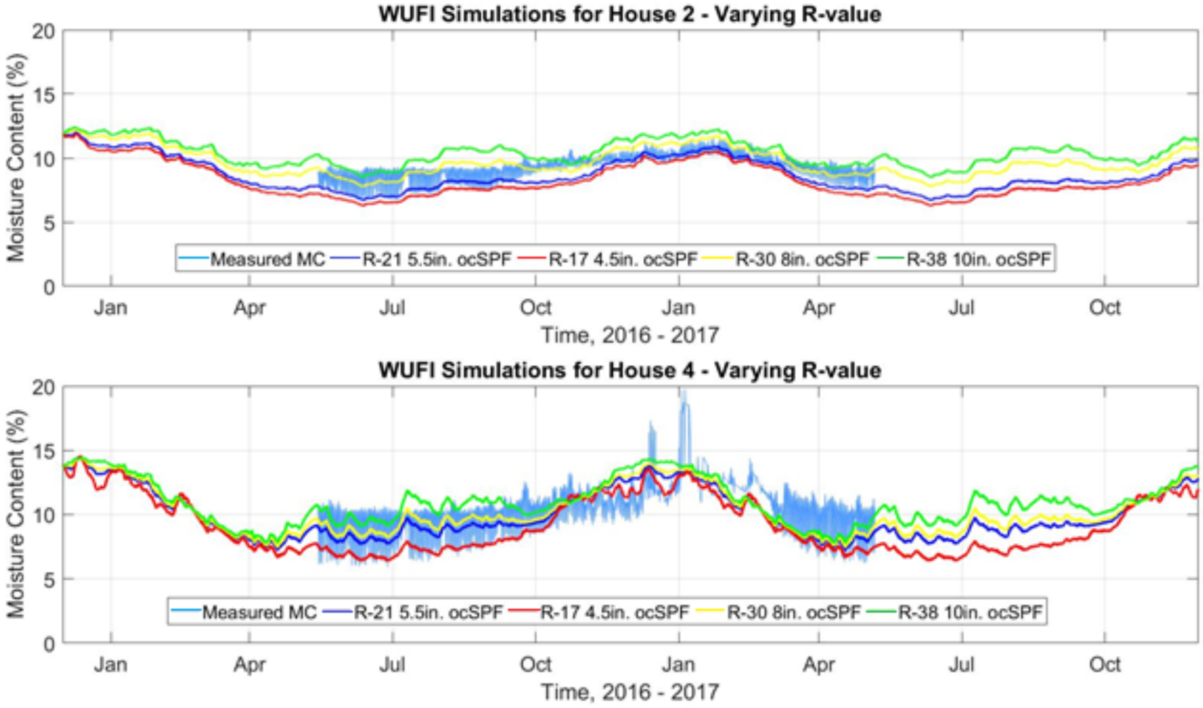

Figure 35 WUFI Simulations performed with varying R-values. R-38 insulation has higher moisture contents during winter while R-17 has the lowest. However, R-17 might increase indoor temperatures due to lack of thermal resistance

The analysis shows that R-38 insulation having more resistance to vapor flow, inhibits cold air movement into the attic thereby allowing moisture to condense at the sheathing-to-insulation interface. However, none of the levels of insulations produce dangerous moisture contents closer to 20% in a normal working condition.

6. SENSITIVITY ANALYSIS OF INPUT PARAMETERS

For the PRAT simulations performed using a generic house model and probabilistic inputs, a sensitivity analysis was performed to determine the effect of input parameters on the peak simulated moisture contents. This simulation set has 1000 variations of all input variables to produce 1000 time-histories of moisture contents for a 24-month period. The results of the sensitivity analysis are shown below.

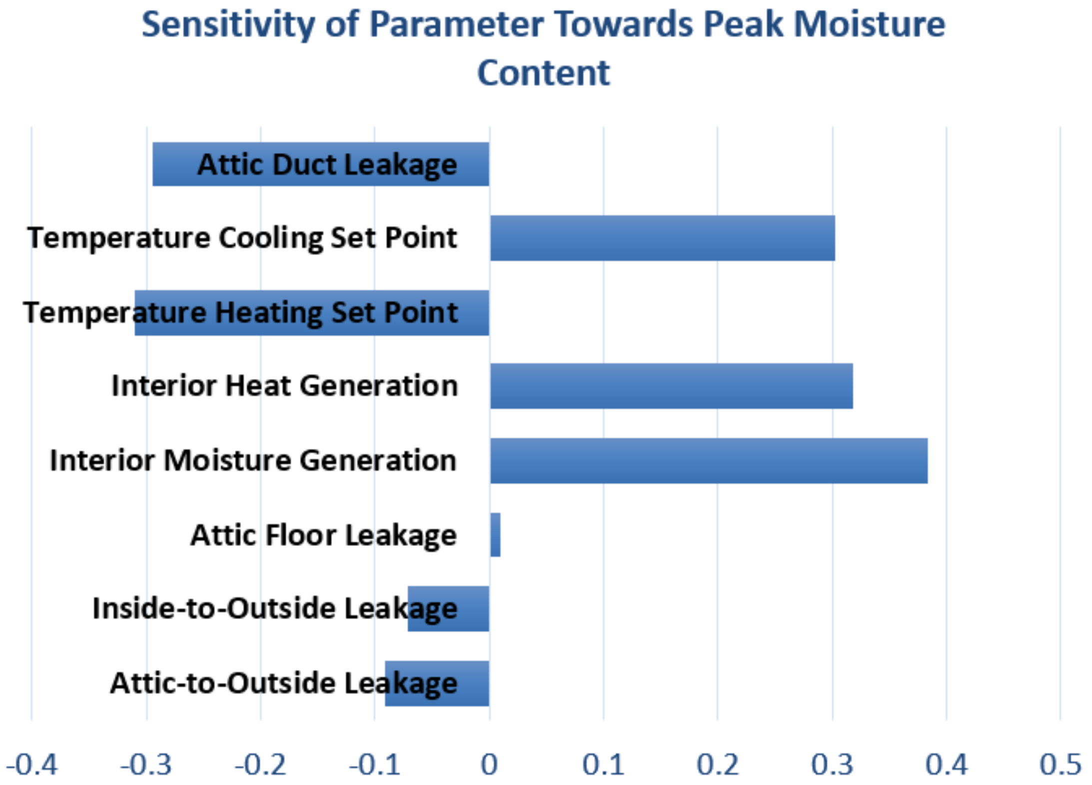

Figure 36 Sensitivity of input parameters towards simulated peak moisture contents in the roof sheathing. Positive values have a direct relationship with the moisture content and negative values have an inverse relationship over the moisture content

The results of the sensitivity analysis show that the interior heat and moisture generation as well as the thermostat cooling set points have a positive influence over the roof sheathing moisture contents. These values are indicative that for a generic house model, the occupancy conditions influence the moisture movement in the attic when compared to the building geometry. The duct leakage and thermostat heating set points have a greater negative influence over the roof sheathing moisture content. The duct leakage into the attic actively serves as a dehumidifier and removes the excess moisture from the attic thereby inhibiting the moisture movement from the attic into the wood roof deck.

7. CONCLUSIONS

A combined analytical and field study was conducted to collect field data, benchmark the data against analytical tools and document the effects of air convection and the diffusion of water vapor on the heat and moisture transfer occurring in sealed-semi conditioned attics. Field site selections were based on homes 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.

Analysis of field data showed that all the four homes with sealed attics had measured moisture accumulations in the roof sheathing that yielded less than 20% moisture content over the duration of the one-year field study. House 4 located in Gainesville had a spike in moisture content during January 2017 that reached levels of about 20% for a two-week period. The reason for this spike is unknown but presumed due to some occupancy habit because the house is occupied only during the winter months. However, the moisture content did drop to safer levels by the start of February 2017.

The moisture in the attic originates primarily from inside the house, due to occupant activities but can also emanate from air leakage crossing the outdoor to attic boundary. During evening hours, the night-sky radiation cools the roof deck below the outdoor ambient temperature and unwanted moisture in the attic diffuses by the gradient in vapor pressure through the spray foam and enters the wood sheathing. Hence, the moisture content in the wood deck is higher at night. During daytime, the solar radiation drives the moisture from the wood sheathing back into the attic air, which causes a rise in attic relative humidity. The sheathing's moisture content drops around solar noon and the attic humidity reaches peak values. The effect of the solar driven moisture diffusion was clearly documented during sunny days and the phenomenon was absent during rainy days or when thick cloud cover blocked the irradiance. The weather effect of Hurricane Matthew on House 1 caused less moisture from the sheathing to be driven into the attic air as compared to days having solar irradiance bearing down on the roof.

The measured attic leakage rates for House 1 located in West Palm Beach were excessively high which essentially made the attic perform as a conventionally ventilated attic. Therefore attic ventilation removed any excessive moisture. However, the air leakage caused the indoor climate to fall outside the comfort zone prescribed by ASHRAE 55. About 36% of the time the indoor temperature and relative humidity was outside the thermal comfort zone. The other three houses had lower levels of attic leakage and better maintained comfort conditions.

The PRAT toolkit was further formulated and benchmarked against the year of measured field data. Initial efforts using fixed rates of air leakage crossing the boundary of the conditioned space and using the actual house geometry yielded poor agreement with the field measurements. Assessments showed that air leakage was a predominant parameter in better predicting the temperature and humidity of the conditioned space and the attic space. The team opted to use a more generic model based on a more robust set of empirical data (RECS 2015) for a multiplicity of homes representing climate zone CZ-2A. As a result, the generic model successfully benchmarked the field data and was therefore used to predict the moisture content of the sheathing in the Probabilistic Risk Assessment Toolkit (PRAT). The toolkit varied seven input parameters to predict the moisture content in the roof sheathing; 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 was performed to quantify the effect of each of the seven parameters on the peak moisture content in the roof sheathing.

The indoor heat and moisture generation rates along with the duct leakage into the attic play a major role in affecting the moisture flows in a sealed attic. The duct leakage brings in conditioned air into the attic and helps mitigate the high humidity in hot and humid climates. Other parameters affecting the moisture movement involve occupant's setting of the thermostat temperature. House 4 in Gainesville is unoccupied during the summer and the homeowner sets the thermostat to 80°F. High indoor temperature coupled with high outdoor temperatures causes near saturated levels of humidity in the attic air. However, the 7-in. of ocSPF (R-27) insulation drops the partial pressure gradient for attic air to the foam and impedes moisture from condensing on the sheathing.

From the combined analytical and field study, the following recommendations are made to the Florida Building Commission for sealed attics with open-cell spray polyurethane foam applied to the underside of the wood roof deck:

- The field data and analysis showed that section R806.4 of the Florida Building Code provides adequate protection against moisture affecting the durability of roof sheathing.
- Inclusion of a dehumidifier in the sealed attics would keep attic air moisture levels at a safer level; however, it use is not necessary.
- If the attic-to-outside air leakage is not well controlled in a sealed attic, then the energy conservation of the home is compromised.

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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 houses 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 houses 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 in.ain. and in.din.. 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 17 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 houses in the respective climate zones.

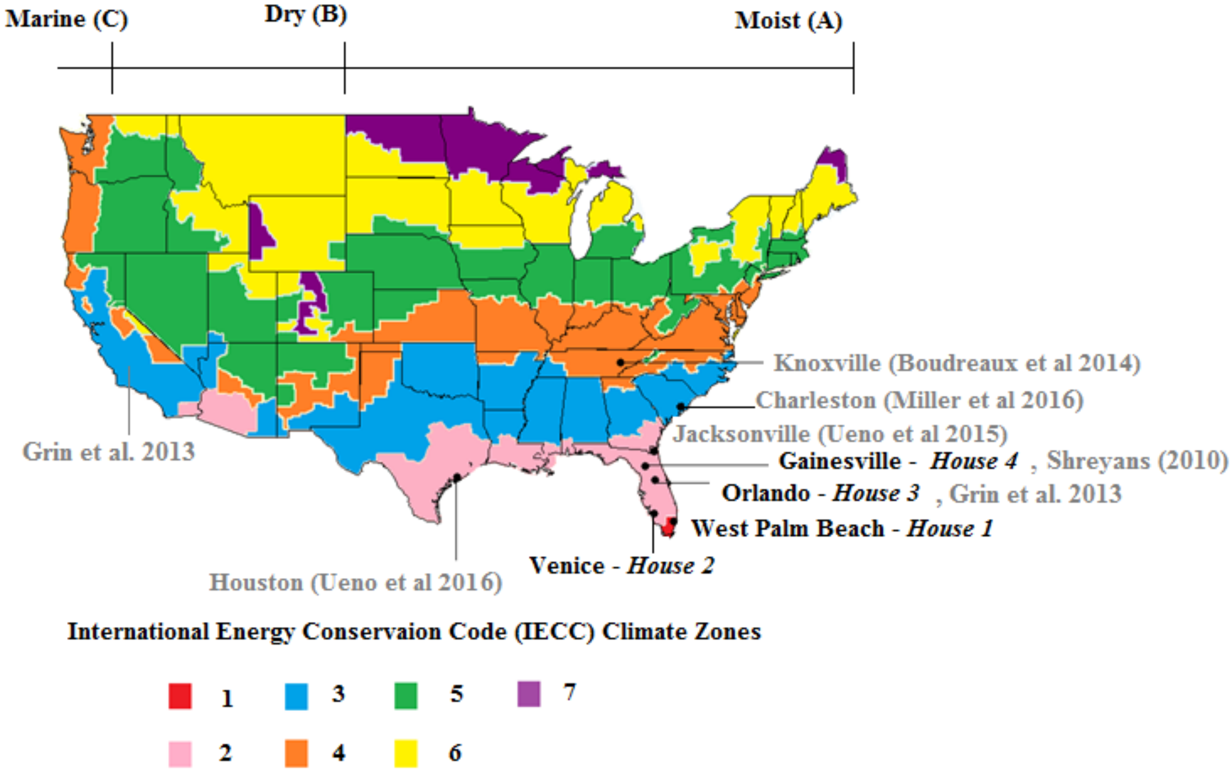

Figure 37 Climate zone map based on IECC 2012. Bold black text indicates the field house locations used in this study. Grey text indicates the field house locations from the literature review.

APPENDIX C: WORKING OF PRAT

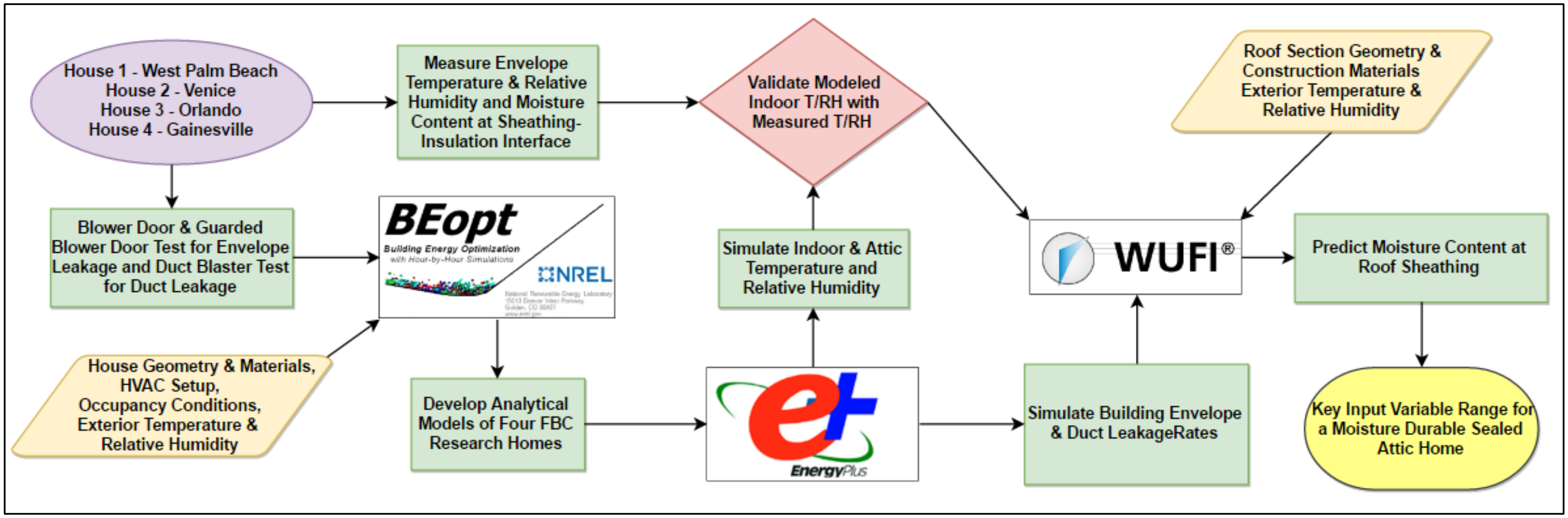

Figure 38 Working of the Probabilistic Risk Assessment Toolkit