Survey of Unvented Attics in Climate Zone 2A

FSEC-CR-2106-21

Final Report
March 17, 2021

Submitted to
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American Chemistry Council

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Acknowledgements

This research was sponsored by the American Chemistry Council. The authors gratefully acknowledge Stephen Weironiey, Director of the Center for the Polyurethanes Industry, and Richard Duncan, Executive Director of the Spray Polyurethane Foam Alliance, for initiating and supporting the research.
Executive Summary

Introduction

Unvented attics are becoming more commonplace in new residential construction. Construction of unvented attics involves eliminating all attic venting to the outdoors. Insulation is typically applied on the underside (and sometimes on top) of the roof sheathing, enclosing the attic inside the home’s air and thermal boundary. Benefits of the approach include reduction of the thermal penalties for locating ducts and air handlers inside the attic, improvements in building air tightness, and a reduction of the influence of duct leakage on building pressure and uncontrolled infiltration.

Because of the lack of venting to the outdoors, moisture risk must be managed in unvented attics to ensure durability of components and longevity of the system. Managing risks from elevated moisture in unvented attics can be accomplished through a variety of means including controlling the temperature of the roof deck, inhibiting the ability of moisture to come in contact with the deck, and conditioning the attic either directly (via attic located supply vents) or indirectly (by promoting air exchange between the attic space and the conditioned living space).

The FSEC Energy Research Center (FSEC), at the University of Central Florida tested and collected data in six homes in the northern Florida portion of IECC Climate Zone 2 built after 2015 with insulated, unvented (semi-conditioned) attics to add to the body of knowledge on the accumulation of moisture in the attic and its effects on roof moisture that may impact durability. All homes utilized open cell, low density spray polyurethane foam (LDSPF) to create the air and thermal control layers. Data was initially collected during a period spanning December 2017 to early summer of 2018. After analysis of year one data (2017-2018) two additional data collection periods were added. The primary research focus was to monitor the wood moisture content (WMC) of the roof deck, and identify any period of time when WMC values of 20% or greater could be detected in any of the homes. The LDSPF is impermeable to air, but is vapor permeable, and it will allow moisture in the attic to pass through it and migrate to the underside of the roof sheathing. Likewise, it allows moisture to pass back through into the attic. In general, prolonged WMC values exceeding 20% indicate an elevated level of wood moisture and can result in development of surface molds. WMC values exceeding 28-30% indicate potential for decay fungi growth to occur that could damage the structural integrity of the wood deck if occurring over prolonged periods without adequate drying cycles.
Year One Methods and Results
To collect data on conditions at the roof deck including WMC, temperature and relative humidity, researchers carefully cut-out and temporarily removed a plug of foam to enable installation of roof deck sensors. Each test plug was approximately one square foot. After sensor installation, foam plugs were re-installed to cover the sensors and the thin cut seam was plugged with existing foam insulation. In addition to roof deck WMC, data was collected on temperature and relative humidity at the roof deck, in the attic air volume, in the indoor living environment, and outdoors. Whole home, attic, and forced air ductwork air tightness was also characterized.

In year one, roof deck sensors were installed in two locations: at the attic peak, and at a location approximately mid-way up the north roof slope. As seen in Figure ES-1, two homes experienced high roof deck WMC values during the months of January and February of year one with a significant number of days having daily average roof deck WMC exceeding 30%.

Data showed that elevated roof deck WMC values dissipated after exposure to sufficiently warm outdoor temperatures that occurred along with increasing solar insolation moving from winter into summer. This wetting/drying effect can even be seen on a diurnal basis, and on a seasonal basis with all roof decks returning to a dry condition by springtime.
Year Two Methods and Results
To investigate whether roof deck WMC would again become elevated upon the return of prolonged low outdoor temperatures, data was collected over a second period spanning December 2018 to early summer 2019 (year two). During this data collection period, data was not collected from the homes’ north facing roof deck, and instead data was collected from two locations at the peak of the roof deck. While the north slope roof deck was typically colder than the peak, relative humidity was higher at the peak. For one peak location, the foam plug removed for roof deck sensor installation was re-installed in the same manner it was reinstalled during year one data collection: by sealing the minute gap between the edges of the foam plug and the surrounding roof deck insulation with the pieces of loose foam that flaked off when plugs were cut out (loose foam). For the second peak location, the foam plug was reinstalled by injecting single component, minimal expansion and low-pressure polyurethane foam packaged in a pressurized metal container (can foam) which was purchased at a home improvement store. The closed-cell product used is intended for “window and door” applications and remains flexible when cured. During year two, comparative data was collected with these two methods of foam plug re-installation to investigate whether elevated WMC was influenced by moisture passing through the loose foam gap at a higher rate, either from air transport or diffusion mechanisms.

Figure ES-2 shows data collected under loose foam seal plugs for all houses during year two. As seen in the figure, the overall trend is similar to year one with WMC reaching an elevated state in homes 1, 2, 4, and 5, although not as high as in year one. Data collection in house 6 was not continued in year two and instead began in two homes with conventional vented attics with ceiling insulation to serve as experimental controls. One of the homes had roof decking with an integrated radiant barrier, and the other did not. As expected, both control homes show consistently low roof deck WMC values. Figure ES-3 shows data collected under can foam plugs for year two.

Year two results showed:
• The method used to re-seal foam plugs removed for instrumentation purposes influenced the amount of moisture the roof deck was exposed to.
• Roof deck WMC measured under can foam plugs was much lower than loose foam plugs.
Figure ES-2. Roof deck wood moisture content recorded for loose foam plugs for all homes during year two.

Figure ES-3. Roof deck wood moisture content recorded for can foam plugs for all homes during year two. The sensor in this location in House 2 stopped recording data on January 14, 2019.

As seen in Figure ES-3, WMC recorded under the can foam plugs was considerably lower, with less diurnal variation. As this finding indicated some influence of the foam plug sealing method on the conditions experienced by the roof deck underneath, a third data collection period spanning October 2019 to early summer 2020 (year three) was added to investigate whether this influence would persist over time.

**Year Three Methods and Results**

No changes were made to instrumentation, homes, or foam plugs between years two and three. Figures ES-4 and ES-5 show data collected under loose foam and can foam plugs respectively during year three.
Figure ES-4. Roof deck wood moisture content recorded for loose foam plugs for all homes during year three. Data from the House 7 Control/radiant barrier is not available in year three due to problems encountered with the data logger.

As seen in figures, the overall trend is similar to year two with WMC exceeding 20% in homes 2, 4, and 5 under loose foam plugs, but remaining under 20% in all homes under can foam plugs, with most homes remaining under 15%. Can foam plugs may be more representative of actual conditions experienced by a roof deck insulated with open cell polyurethane foam, however, it is not known whether the can foam, being closed cell and less permeable than the surrounding roof deck open cell foam, instituted its own bias.
This project analyzed collected data to search for indications of significant variables contributing to high WMC. It appeared that internal moisture did not satisfactorily explain the highest roof WMC in the homes of this study, nor did the airtightness of the house, attic or ducts. Outdoor temperature, roof deck relative humidity, and roof deck condensation potential, expressed as a difference between roof deck dry bulb and dew point temperature, showed better correlation to WMC. Homes experiencing the coldest outdoor weather, which occurred at the very beginning of year one, also experienced the greatest magnitude and longest duration of roof deck WMC. Can foam plugs were not utilized during this coldest period, and it is not known how elevated roof deck WMC might have become under those conditions.

The 2018 IRC provides prescriptive means for unvented attic design according to climate, and all homes in this study met that prescriptive requirement. It also allows somewhat of a performance approach that involves a target to keep the underside of the roof deck above a monthly average temperature of 45F. The coldest monthly average roof deck temperature measured in this project was approximately 50F. While some elevated roof deck WMC values were recorded, roof deck WMC values dissipated after exposure to sufficiently warm outdoor temperatures that occur with increasing solar insolation upon the roof deck moving from winter into summer. No evidence of lasting durability effects has been obtained, but a thorough disassembly of the roof would need to be conducted to collect definitive data. Given the results obtained, and considering the data under can foam plugs may be more representative of whole roof deck performance than data under loose foam plugs, these homes located towards the northern portion of climate zone 2A seem adequately protected from attic moisture related roof deck durability risk.

The applicability of these results are restricted to the homes that were tested, and more research would need to be conducted before extending this recommendation broadly:

- High mass roofs (tile) and high reflectivity roofs (white metal) were not part of the study and may behave differently as these roofs may experience delayed drying during morning hours.
- The climatic conditions were rather mild. The highest moisture content were found under the coldest conditions tested. The authors recommend additional

### Year three results confirmed:
- **Roof deck WMC under can foam plugs remained below 20% in all homes.**
- **Similar future research should utilize methods that maintain the properties of undisturbed roof deck insulation.**
- **Unvented attics in climate zone 2A insulated with open cell LDSPF at the roof deck are adequately protected from attic moisture related durability risk.**
measurements under can foam plugs in homes in climate zone 3A that are likely to experience prolonged periods of outdoor temperatures below 30F.
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1.0 Introduction

Sealed or unvented attics are becoming more commonplace in new residential construction. Construction of unvented attics involves eliminating all attic venting to the outdoors. Insulation is typically applied on the underside (and sometimes on top) of the roof sheathing, enclosing the attic inside the home’s air and thermal boundary. Benefits of the approach include reduction of the thermal penalties for ducts and air handlers located inside the attic, improved building air tightness, and reduced influence of duct leakage on building pressure and uncontrolled infiltration.

Because of the lack of venting to the outdoors, moisture risk must be managed in unvented attics to ensure durability of components and longevity of the system. One source of moisture inside an unvented attic includes air transported moisture from the outdoors due to an imperfect air seal. Moisture may also originate as a result of generation within the living space and subsequent transport into the attic. Managing risks from elevated moisture in unvented attics can be accomplished by controlling the temperature of the roof deck, inhibiting the ability of moisture to come in contact with the deck, and conditioning the attic either directly (via attic located supply vents) or indirectly (by promoting air exchange between the attic space and the conditioned living space). The 2018 International Residential Code (ICC, 2018) includes provisions for managing moisture risk according to house location and associated climate, and whether air permeable or air impermeable insulation is utilized. When air impermeable insulation is used in climate zones 1-3, no other prescriptive means for controlling moisture risk are required. In climate zones 5-8, a class II vapor retarder is required to be used in conjunction with the air impermeable insulation. Where air permeable insulation is used, a layer of air impermeable insulation on the outside of the roof deck is required in nearly every climate to control temperature of the condensing surface. A new addition to the 2018 code permits air permeable insulation to be used in climate zones 1, 2, and 3, without the air impermeable insulation layer, if both a vapor diffusion port is installed and conditioned air is supplied to the attic at a rate of 50 cubic feet per minute (cfm) per 1,000 square feet of ceiling.

A typical design for insulating unvented attics in Florida, and most of climate zones 1-3, is to use low-density spray polyurethane foam (LDSPF). The LDSPF is impermeable to air, but is vapor permeable, and it will allow moisture in the attic to pass through it and migrate to the underside of the roof sheathing. The vapor permeability of one specific brand of LDSPF with 5 ½ inch thick application and a core density of 0.5 lb/ft³ is stated by the manufacturer to be about 11 perms. The oriented strand board (OSB) roof deck has a lower permeability that may vary from about 1 perm at low relative humidity (RH) up to about 12 perms at high sustained RH (APA 2009). On average it would be expected that most water vapor transfer occurs between the attic space and foam. Presumably the relatively warmer outdoor temperatures throughout climate zones 1-3 combined with minimizing air transported moisture through the use of air impermeable insulation are enough to minimize moisture risk. Moisture can travel through the vapor permeable insulation to the roof deck, but sufficient conductive and radiative heat gains on
the roof drive the moisture back down through the foam into the attic, resulting in repeated wetting and drying. Little data is available on resulting roof deck wood moisture content (WMC). A previous investigation (Prevatt, 2017) based on limited field study and simulation concluded that the current IRC provides adequate protection against moisture affecting the durability of roof sheathing in warm humid climates. It is desired to collect data in additional homes with characteristics that may increase risk, including tighter ducts, which minimize direct and indirect air exchange between the attic and the conditioned living space, tighter attics, which minimize air exchange between the attic and the outdoors, and exposure to colder outdoor temperatures. Beginning in December 2017, the FSEC Energy Research Center (FSEC), at the University of Central Florida tested and collected data in six homes in the northern Florida portion of IECC Climate Zone 2A built after 2015 with insulated, unvented (semi-conditioned) attics to add to the body of knowledge on the accumulation of moisture in the attic and its effects on roof durability. After analysis of year one data (2017-2018) two additional data collection periods were added (year two and year three).

2.0 Year One (2017-2018) Methods and Results

2.1 Participant Recruitment
FSEC developed a postcard and website\(^1\) to use as recruitment tools. To obtain addresses of candidate homes, the FSEC Energy Rated Homes Database was queried. The database contains detailed information on homes that have undergone an energy audit for which FSEC has performed quality control and archived the results. The database includes the address of each home, year of construction, and detailed information on physical characteristics of the home, including attic and insulation details. The database does not contain any homeowner contact information or other personally identifiable information. A total of 6,067 Florida homes were identified in the database as having unvented attics. Due to the small number of homes targeted for the study, researchers desired to recruit homes with characteristics that would provide the largest attic/roof deck moisture signal. This included colder attic temperatures, most likely found in homes in northern Florida (Marion County and north), tight ducts, and lighter colored, reflective roofs. In general, homes east of Leon County were targeted for ease of access, but postcards were sent as far west as Pensacola for homes with lighter colored, non-shingle roofs in an attempt to obtain a mix of roof coverings. A total of 310 postcards were sent in order to yield six confirmed participants. A monetary stipend was offered to participating homeowners. While it was also desirable to recruit homes with high occupancy in order to increase the moisture signal, ultimately all homes recruited were 2-3 person households. Spending additional time on recruitment would have caused additional delays to instrumentation and loss of critical winter data. The location of the homes is depicted in Figure 1, and a summary of home characteristics is included in Table 1. The energy audit conducted on each home prior to occupancy shows that each home was constructed to be more energy efficient.

\(^1\) [http://www.fsec.ucf.edu/go/atticstudy](http://www.fsec.ucf.edu/go/atticstudy)
than minimum Florida building code. This is evidenced by the homes’ Home Energy Rating System (HERS) Index\(^2\). For reference, a home of this vintage built to minimum Florida code has a HERS Index of approximately 70, and each HERS Index point lower than 70 represents an energy savings of approximately 0.7\%. Photos of each home are included in Appendix A.

![Figure 1. Study house locations.](image)

Table 1. Summary of house and occupancy characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>House 1</th>
<th>House 2</th>
<th>House 3</th>
<th>House 4</th>
<th>House 5</th>
<th>House 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Jacksonville</td>
<td>Jacksonville Beach</td>
<td>Umatilla</td>
<td>Fernandina Beach</td>
<td>Ponte Vedra Beach</td>
<td>Ponte Vedra Beach</td>
</tr>
<tr>
<td>Initial visit date</td>
<td>12/20/2017</td>
<td>1/16/2018</td>
<td>1/22/2018</td>
<td>2/1/2018</td>
<td>2/2/2018</td>
<td>2/2/2018</td>
</tr>
<tr>
<td>Builder</td>
<td>Terrawise Builders</td>
<td>Custom Home</td>
<td>Owner Builder</td>
<td>Riverside Builders</td>
<td>Providence Builders</td>
<td>Providence Builders</td>
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<tr>
<td>Occupants</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
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<tr>
<td>Conditioned Area</td>
<td>1822</td>
<td>3129</td>
<td>3541</td>
<td>2695</td>
<td>2208</td>
<td>2168</td>
</tr>
<tr>
<td># stories</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Roof type</td>
<td>Light composite shingle</td>
<td>Light composite shingle/metal</td>
<td>Dark Metal</td>
<td>Medium composite shingle</td>
<td>Medium composite shingle</td>
<td>Medium composite shingle</td>
</tr>
<tr>
<td>Underlayment</td>
<td>OSB</td>
<td>OSB</td>
<td>Huber Zip</td>
<td>OSB</td>
<td>OSB</td>
<td>OSB</td>
</tr>
<tr>
<td>Roof deck R-value(^1)</td>
<td>22</td>
<td>21</td>
<td>20</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Duct / Air handler location</td>
<td>Attic / 1(^{st}) floor</td>
<td>Attic / 2(^{nd}) floor</td>
<td>Attic / Garage Closet</td>
<td>Attic / 1(^{st}) floor</td>
<td>Attic/attic</td>
<td>Attic/attic</td>
</tr>
<tr>
<td>Wall Construction</td>
<td>Concrete Block</td>
<td>Wood Frame</td>
<td>Insulating Concrete Form</td>
<td>Wood Frame</td>
<td>Wood Frame</td>
<td>Wood Frame</td>
</tr>
<tr>
<td>HERS Index</td>
<td>29</td>
<td>58</td>
<td>14</td>
<td>62</td>
<td>52</td>
<td>54</td>
</tr>
</tbody>
</table>

2.2 House Characterization and One Time Tests

\(^2\) https://www.hersindex.com/hers-index/what-is-the-hers-index/
During the visits researchers carried out a series of one-time tests to characterize the fundamental aspects of each house. Much of this information was already captured by the home’s energy auditor immediately prior to occupancy and entered into the FSEC database. However, for consistency, researchers performed the following during the site visits at each home:

- Visual inspection to note HVAC layout and any pertinent home features that could contribute to attic moisture.
- House air tightness measured by fan depressurization multi-point test method.
- House pressure difference between house and attic when house with reference to outdoors was at -50 Pascals (Pa) (0.20 in wc).
- Guarded air tightness test (by fan depressurization) with house and attic at -50 Pa with reference to outdoors enabling separate quantification of leakage from attic to outdoors and from house to outdoors.
- Central heating and cooling system duct leakage by DuctBlaster method: Total leakage within the pressure boundary and leakage to outside the pressure boundary.
- Thermographic infra-red scan of attic and visual inspection to identify moisture and / or air leaks as conditions permitted.

Select infra-red images are included in Appendix B. Standard house multi-point air tightness testing was conducted according to ASTM standard E779. The home air leakage flow rate was measured in cubic feet per minute (cfm) at specific house with reference to outdoor pressures measured in Pa. The multipoint test reduces uncertainty that may occur during windy periods. The Energy Conservatory Tectite program was used to calculate the house leakage at the standard test pressure of 50 Pa, known as CFM50. This value was normalized by house conditioned volume and at an hourly rate of leakage this value is known as air changes per hour at 50 Pa or ACH50. Air tightness can also be measured according to conditioned space floor area and building total envelope surface area.

The goal of the tightness testing was to evaluate if homes and attics were reasonably tight or leaky. The house CFM50 was normalized by total house conditioned floor area and attic CFM50 was normalized by attic floor area. The guarded air tightness test enabled the attic air tightness to be measured independently from the conditioned house tightness. This test was conducted by simultaneous use of two separate calibrated fans with one placed in an exterior doorway to outdoors and the other installed at an attic hatch. While many homes had attic access in the garage, in all cases the garage attic had been separated from the main house attic with an air and thermal barrier. In all houses unvented access was only through access hatches from within conditioned spaces.

Figure 2 shows an illustration of the guarded test concept, and Figure 3 shows photos of the testing. A standard Blower door fan was installed in the front entry doorway of the home and a DuctBlaster fan was used in the attic hatch located inside the home. The speed of the fan in the front door was adjusted until the house with reference to outdoors was -50 Pa. The DuctBlaster fan in the attic hatch was adjusted until the attic with reference to outdoors was -50 Pa. At this
condition there is no pressure differential between the conditioned space indoors and the attic space above. With no pressure differential, no airflow moves through air pathways across the ceiling plane, including duct leakage.

The attic fan pulled air from the attic and pushed it into the house. The front door fan not only pulled the attic air leakage portion out, but also the additional amount required to depressurize to -50 Pa. With this method, the front door fan measured the sum of attic leakage to out and the house leakage to out. The house leakage to outdoors not including leakage across the ceiling plane is obtained from the difference between the house + attic combined leakage and the attic leakage to out measurement.

![Guarded Tightness Test Using Two Calibrated Fans](image)

Figure 2. Illustration of guarded house and air tightness test.
2.2.1 House Tightness Test Results

While there is no official national standard threshold for whether a building is substantially air tight, the authors have assessed that each home in this study was reasonably airtight according to ACH50 and CFM/ft² values. We have used 0.5 CFM50/ft² or less as a level to be considered reasonably airtight for house and attic leakage. A rationale for this assertion follows.

House tightness testing is measured based on airflow with interior space maintained at 50 Pa with reference to (wrt) outside. The airflow rate is directly proportional to the accumulative leak pathway to outdoors. This leakage can be normalized by volume or area. We have used both methods of normalization in the past, but prefer the method based upon area for ease of use, particularly by others outside of the research practice. Once the leakage is normalized, the question remains:

“What should the threshold air leakage limit be for an attic to be considered moderately tight?”

The authors are not aware of a publicly available published study of unvented attic airtightness consisting of a statistically significant number of homes to base this upon. In absence of this, we make a provisional assertion that attic leakage less than 0.50 CFM50/ft² of area under tested attic be considered until a more suitable number may become available. A home with 3.0 ACH50 is considered reasonably tight by most in the building industry. While this is debatable and homes can be made tighter than this, they are already tight enough at 5 ACH50, that the 2012 IECC building code began requiring whole-house mechanical ventilation. Furthermore, another point of reference that may be considered is the ENERGY STAR Certified Homes, Version 3.1 tightness requirements (US EPA, 2015). This beyond code program requires the
reference design home (baseline home) to be modeled with 5 ACH50 in Florida, 4 ACH50 in Climate Zones 1, 2, and 3 ACH50 in Climate Zones 3-8. An example home at 3 ACH50, with 2,000 ft² of conditioned floor area and 20,000 ft³ of conditioned volume, would have a measured tightness of 1000 CFM50. This would be 1000 CFM50/2000 ft² = 0.50 CFM50/ft². We have used 0.50 CFM50/ft² as a level to be considered reasonably airtight for house and attic leakage.

Results from the air tightness test of the six homes are first presented as the house unguarded test with the attic hatch closed in Table 2. This is the simpler of the two tests that are completed by professional home energy raters. Also shown is the house wrt attic differential pressure (dp) when the house is at -50 Pa wrt outdoors and the attic wrt out pressure. These two values can be used to determine the relative leakage between the house wrt attic and attic wrt out. In other words, how much leakier or tighter is the ceiling plane compared to attic wrt out? This has been represented as the house to attic leak factor. It does not indicate if the ceiling or attic is “tight”, but if it can be determined that the attic is fairly tight or leaky, then you have an idea if the ceiling plane is tight or not. Usually the ceiling plane is not very tight. A house dP wrt attic of 25 Pa would result in a value of 1. This would indicate that the ceiling plane had the same accumulative area of leak pathway as the attic to outdoors. The tightest house (#3, 0.86 ACH50) had the lowest house to attic leak factor that was 1.7 times larger than the attic to outdoor leakage. This leakage is associated with unsealed ceiling penetrations (including through wall up through top wall plate) as well as duct leakage and duct register boot penetrations through ceiling. Figures 4 and 5 shows some examples of typical ceiling leak pathways.

Houses 1 and 2 had the highest house to attic leak factor. This might indicate a greater potential for internally generated moisture to make its way into the attic from indoors. This is not conclusive and the reader is reminded that this factor is relative to the attic leakage which cannot be measured in a standard unguarded tightness test. If one doesn’t know if the attic is tight or leaky, this may lead to wrong conclusions.

Table 2. Standard Multi-Point House Air Tightness Leakage Test

<table>
<thead>
<tr>
<th>House ID</th>
<th>House CFM50</th>
<th>House ACH50</th>
<th>House wrt Attic dP (Pa)*</th>
<th>Attic wrt Out dP (Pa)*</th>
<th>House to attic leak factor</th>
<th>House CFM50/ft² **</th>
<th>House conditioned floor area ft²</th>
<th>House CFM50/ft³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>657</td>
<td>2.40</td>
<td>-3.0</td>
<td>-47.0</td>
<td>6.0</td>
<td>0.361</td>
<td>1822</td>
<td>16398</td>
</tr>
<tr>
<td>2</td>
<td>1473</td>
<td>2.82</td>
<td>-4.0</td>
<td>-46.0</td>
<td>4.9</td>
<td>0.456</td>
<td>3232</td>
<td>31350</td>
</tr>
<tr>
<td>3</td>
<td>545</td>
<td>0.86</td>
<td>-15.4</td>
<td>-34.6</td>
<td>1.7</td>
<td>0.154</td>
<td>3541</td>
<td>38243</td>
</tr>
<tr>
<td>4</td>
<td>1123</td>
<td>2.31</td>
<td>-9.9</td>
<td>-40.1</td>
<td>2.5</td>
<td>0.417</td>
<td>2695</td>
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<td>0.247</td>
<td>2208</td>
<td>22080</td>
</tr>
<tr>
<td>6</td>
<td>894</td>
<td>2.55</td>
<td>-7.5</td>
<td>-42.5</td>
<td>3.1</td>
<td>0.412</td>
<td>2168</td>
<td>21030</td>
</tr>
<tr>
<td>Average</td>
<td>873</td>
<td>2.07</td>
<td>-7.5</td>
<td>-42.5</td>
<td>3.7</td>
<td>0.341</td>
<td>2611</td>
<td>26368</td>
</tr>
</tbody>
</table>

* When house wrt out = -50 Pa
** Leakage per conditioned floor area ft²
Table 3 shows the guarded test results where more detail about how much attic leakage to outdoors occurs. It also distinguishes how much the attic to outdoor leakage represents the total leakage to outdoors (house + attic combined). Since the greatest leakage potential from the attic is most likely to occur where the roof deck meets the exterior walls, the attic leakage is normalized by attic floor area instead of attic volume. The attic volume can also be time consuming to calculate, particularly in those with more complicated geometries. The house + attic leakage was also normalized by conditioned area. The attic CFM50 leakage divided by house + attic CFM50 was used to determine the attic leak ratio.

The quick take-away from this data is that the attic and house leakage to outdoors is reasonably tight. It is a small test sample, all but two homes stood out compared to the average tightness of all six. House 3 had the leakiest attic (CFM50/ft²), but tightest house to out leakage (CFM50/ft²). House 5 had the second tightest house to out leakage (CFM50/ft²) and the tightest attic to out leakage (CFM50/ft²). The guarded tests show that the average attic leakage to out represented a little over half (54%) of the combined house + attic leakage total. The attic leakage of House 3 represented the highest proportion of total leakage (69%). House 3 also had the leakiest attic measurement of 0.338 CFM50/ft². This attic leakage (CFM50/ft²) was 45% greater (leakerier)
than the six-house average, but was still considered reasonably tight. There were no observable outside pathways in attic sections inspected so it is not known why this attic was leakier than the others. House 3 house to out leakage (CFM50/ft\(^2\)) was about 36% lower (tighter) than the six-house average. House 5 stood out from the average by having the lowest total CFM50/ft\(^2\) and lowest attic CFM50/ft\(^2\). The house + attic CFM50/ft\(^2\) was 33% tighter and attic CFM50/ft\(^2\) was 47% tighter than the six-house average.

Table 3. Guarded Air Tightness Test for House and Attic

<table>
<thead>
<tr>
<th>House ID</th>
<th>House + Attic CFM50</th>
<th>Attic to Out CFM50</th>
<th>House to Out CFM50</th>
<th>House to Out CFM50/ft(^2)*</th>
<th>Attic to Out CFM50/ft(^2)***</th>
<th>Attic Leak Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>768</td>
<td>388</td>
<td>380</td>
<td>0.209</td>
<td>0.213</td>
<td>50.5%</td>
</tr>
<tr>
<td>2</td>
<td>1450</td>
<td>324</td>
<td>1126</td>
<td>0.348</td>
<td>0.232</td>
<td>51.7%</td>
</tr>
<tr>
<td>3</td>
<td>1730</td>
<td>1198</td>
<td>532</td>
<td>0.150</td>
<td>0.338</td>
<td>69.2%</td>
</tr>
<tr>
<td>4</td>
<td>1297</td>
<td>686</td>
<td>611</td>
<td>0.227</td>
<td>0.255</td>
<td>52.9%</td>
</tr>
<tr>
<td>5</td>
<td>623</td>
<td>271</td>
<td>352</td>
<td>0.159</td>
<td>0.123</td>
<td>43.5%</td>
</tr>
<tr>
<td>6</td>
<td>920</td>
<td>259</td>
<td>661</td>
<td>0.305</td>
<td>0.239</td>
<td>56.3%</td>
</tr>
<tr>
<td>Average</td>
<td>1131</td>
<td>521</td>
<td>610</td>
<td>0.233</td>
<td>0.233</td>
<td>54.0%</td>
</tr>
</tbody>
</table>

** Leakage per conditioned floor area ft\(^2\)  
*** Leakage per tested attic floor area ft\(^2\)

Figures 6 and 7 show some examples of how small attic leakage to outside was, if found at all. Figure 6 shows images from the same location. It is difficult to seal between two closely spaced framing members. Figure 7 also shows images from the same location. The image at left shows that it is difficult to see lower leaks with good interior lighting. The leaks are not visible when standing up in attic looking downward. They were only noticeable when viewing from a low angle to the attic floor. The right image is with minimal lighting with daylight coming from a vented soffit.

Figure 6. Examples of small leak pathways from attic to outdoors. Note specs of daylight visible in the right photo where a good seal was not attainable between the two closely spaced framing members.
2.2.2 Duct Tightness Test Results

Ducts were visually inspected with no observable significant leakage. All six homes had mastic applied at duct connections in the attic spaces. Ducts were also tested for air tightness. A calibrated duct test fan was installed on the central duct system located in the unvented attic and other return and supply registers temporarily sealed. The fan was used to depressurize the duct to -25 Pa with reference to indoors during the total leakage test. The total leakage represents total duct system leakage that occurs both within and outside of the primary air barrier. The test was repeated so that the conditioned space was depressurized to 25 Pa wrt outside using a blower door fan. At the same time the duct was depressurized to -25 Pa wrt outside using the duct test fan. This resulted in no pressure differential from duct to conditioned space so that the duct leak would only measure leakage occurring to outside. In these cases, leakage to out is essentially leakage into the attic. Table 4 shows the summary of test results for all six homes. The leakage is normalized by conditioned floor area served by the system tested and is represented as CFM25/ft². The total leakage is a little high, however much of this can be due to leaks right at where the grill meets the drywall at the ceiling which is of no consequence. This happens because the temporary seal created for testing purposes only covers the grill and is not continued over onto the drywall. Because the leakage to out was very low and the duct connections in attic were observed to be constructed tightly with mastic, we do not believe there was a significant amount of duct leakage into the attic space in these homes.

Table 4. Duct test results for all six homes.

<table>
<thead>
<tr>
<th>House ID</th>
<th>CFM25 Total</th>
<th>CFM25 Out</th>
<th>CFM25/ft² Total</th>
<th>CFM25/ft² Out</th>
<th>Attic Leak Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>208</td>
<td>18</td>
<td>0.114</td>
<td>0.010</td>
<td>50.5%</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>28</td>
<td>0.086</td>
<td>0.020</td>
<td>51.7%</td>
</tr>
<tr>
<td>3</td>
<td>214</td>
<td>68</td>
<td>0.086</td>
<td>0.027</td>
<td>69.2%</td>
</tr>
<tr>
<td>4</td>
<td>338</td>
<td>35</td>
<td>0.125</td>
<td>0.013</td>
<td>52.9%</td>
</tr>
<tr>
<td>5</td>
<td>274</td>
<td>16</td>
<td>0.124</td>
<td>0.007</td>
<td>43.5%</td>
</tr>
<tr>
<td>6</td>
<td>227</td>
<td>11</td>
<td>0.105</td>
<td>0.005</td>
<td>56.3%</td>
</tr>
<tr>
<td>Average</td>
<td>230</td>
<td>29</td>
<td>0.107</td>
<td>0.014</td>
<td>54.0%</td>
</tr>
</tbody>
</table>
2.3 Year One Instrumentation

Initial visits to all six homes to install instrumentation began late December 2017 and were completed by early February 2018. Prior to installation, each sensor was tested in an FSEC laboratory home attic and compared to existing lab instrumentation. Instrumentation was installed in each home to record data at 1 hour intervals. Table 5 details the instrumentation installed in each home.

Table 5. Installed instrumentation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Location</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor temperature and relative humidity</td>
<td>Central living area, each floor</td>
<td>Onset HOBO U-12</td>
</tr>
<tr>
<td>Outdoor temperature and relative humidity</td>
<td>Back porch</td>
<td>Onset HOBO U-23</td>
</tr>
<tr>
<td>Roof deck moisture content</td>
<td>North side of peak and midway up north facing slope</td>
<td>Omnisense S-2</td>
</tr>
<tr>
<td>Roof deck temperature and relative humidity</td>
<td>North side of peak and midway up north facing slope</td>
<td>Omnisense S-2</td>
</tr>
<tr>
<td>Attic air temperature and relative humidity</td>
<td>Peak and mid-attic height</td>
<td>Omnisense S-2 and HOBO U-12</td>
</tr>
</tbody>
</table>

To install roof deck instrumentation, a small plug of foam was removed and sensors were attached to the roof deck before re-installing the foam plug. In addition to temperature and relative humidity at the interface of the insulation and the roof deck, wood moisture content was determined via electrical resistance measurements between stainless steel screws installed in the roof deck. Figure 8 shows a photo of the roof deck instrumentation arrangement.

Figure 8. Left Photo - T/RH sensor (gold cylinder) and wood moisture content sensor (adjacent screws) before re-installing foam plug. Right Photo - data logger recording sensor data and finished installation of roof deck sensors seen at right of image where two wires enter foam after plug re-installed.

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3 [https://www.fpl.fs.fed.us/documents/fplgtr/fplgtr06.pdf](https://www.fpl.fs.fed.us/documents/fplgtr/fplgtr06.pdf)
During installation a hand-held Delmhorst moisture content sensor was used to check roof deck moisture content. The readings from the hand-held instrument were compared to the first few readings available from the long term moisture content monitoring sensor prior to leaving the site. We found the readings to be in acceptable agreement within manufacturer accuracy. Upon re-insertion of the foam plug, the minute gap between the edges of the foam plug and the surrounding roof deck insulation was sealed with the pieces of loose foam that flaked off when plugs were cut out. Every attempt was made to create a tight seal using the same roof deck insulation material, and prevent air transfer through this minute gap between the sides of the plug and the surrounding roof deck insulation. The foam plugs generally fit tightly back into their holes upon re-installation, but gap width was variable around the perimeter of each plug, and ranged from 0” (tight fit with plug in contact with surrounding roof deck insulation) to 1/2” (with pieces of loose foam stuffed in the gap). Data was collected in each home through June 2018, at which time instrumentation was removed. The hand-held instrument measurements were repeated during removal and also found to correlate with the long term monitoring sensor readings. After removal of instrumentation, foam plugs were re-installed, and gaps sealed with a single component, minimal expansion and low-pressure polyurethane foam packaged in a pressurized metal container and purchased at a home improvement store. The closed-cell product is intended for “window and door” applications and remains flexible when cured.

Figure 9 shows the general location of the monitoring sensors for the one-story homes. Figure 10 shows how the locations differed for the two-story homes. The peak sensors for House 4 were placed in the attic of the second-floor bonus room. The sensors for the midpoint north slope were placed in the attic over the first floor. The upper and lower attics are intentionally well connected by design. For House 6, both the peak and the north slope sensors were placed in the second-floor attic. In this case the attics are separate spaces by design, although the necessity to run ducts from the upper attic (where the air handler resides) down into lower attic permitted air leakage between the two spaces since the duct penetration was not well sealed.

![Figure 9. Location of monitoring sensors for one story homes, year one.](image)
2.4 Year One Monitored Data Results

Data collected from December 2017-June 2018 shows a range of peak wood moisture content readings among the houses. Hourly WMC values collected from the roof deck at about the midpoint on the north facing slope for all 6 houses are plotted in Figure 11, and WMC values collected from the roof deck at the north side of the peak for all 6 houses are plotted in Figure 12. The table in each figure tabulates the number of days each roof deck experienced an average daily WMC within certain ranges. In general, prolonged wood moisture content (WMC) values exceeding 20% indicate an elevated level of wood moisture, and can result in development of surface molds. WMC values exceeding 28-30% indicate potential for decay fungi growth to occur (APA 1999).
Figure 12. Roof deck wood moisture content recorded for north facing roof at peak for all homes during year one.

As can be seen in the year one data, House 1 and 2 experienced high WMC values during the months of January and February 2018. Most other homes experience moderately high WMC in March 2018. The exceptions are House 6 and House 3. House 3 is geographically further south than the rest of the homes, experiences slightly warmer outdoor weather, is the only home with a weather barrier integrated into the roof deck (Huber Zip) and is the only home with 100% metal roofing. Figures 13-16 show hourly roof deck moisture content from the north facing midpoint slope and peak for House 1 and 2, along with other monitored parameters for the entire year one monitoring period. Similar figures with associated details for the other homes can be found in Appendix C. The environmental parameters most closely correlated with WMC are roof deck relative humidity, and outdoor temperature. More details on these correlations are presented in the Discussion section of the report.
Figure 13. Roof deck moisture content, temperature and RH from House 1 north facing roof slope, and indoor and outdoor conditions during year one.

Figure 14. Roof deck moisture content, temperature and RH from House 1 roof peak, and indoor and outdoor conditions during year one.
Figure 15. Roof deck moisture content, temperature and RH from House 2 north facing roof slope, and indoor and outdoor conditions during year one.

Figure 16. Roof deck moisture content, temperature and RH from House 2 roof peak, and indoor and outdoor conditions during year one.
3.0 Year Two (2018-2019) Methods and Results

Data from year one showed that elevated roof deck WMC values dissipated after exposure to sufficiently warm outdoor temperatures that occurred along with increasing solar insolation moving from winter into summer. This wetting/drying effect can even be seen on a diurnal basis, and on a seasonal basis with all roof decks returning to a dry condition by springtime. To investigate whether roof deck WMC would again become elevated upon the return of prolonged low outdoor temperatures, data was collected over a second period spanning December 2018 to early summer 2019 (year two).

3.1 Year Two Instrumentation

During year two, data was not collected from the homes’ north facing roof deck, and instead data was collected from two locations at the peak of the roof deck. While the north slope roof deck was typically colder than the peak, attic relative humidity was higher at the peak, and considered a worst-case location. The peak location from year one was reused, and a new plug of foam was cut out from a second peak location. For one peak location, the foam plug removed for roof deck sensor installation was re-installed in the same manner it was reinstalled during year one data collection: by sealing the gap between the edges of the foam plug and the surrounding roof deck insulation with the pieces of loose foam that flaked off when plugs were cut out (loose foam). As in year one, every attempt was made to create a tight seal using the same roof deck insulation material, and prevent air transfer through this minute gap between the sides of the plug and the surrounding roof deck insulation. For the second peak location, the foam plug was reinstalled by injecting a single component, minimal expansion and low-pressure polyurethane foam packaged in a pressurized metal container and purchased at a home improvement store (can foam). The closed-cell product used was for “window and door” applications and remains flexible when cured. During plug re-installation, the straw that connects to the foam can’s nozzle was inserted into the gap between the plug and the surrounding roof deck, and foam injected until it expanded out of the gap. Example photos of the “loose foam” plug and “can foam” plug are shown in Figure 17. These two methods of foam plug re-installation were used to investigate whether elevated WMC and roof deck relative humidity were at all influenced by moisture passing through the loose foam gap at a higher rate than the surrounding roof deck foam, either from air transport or diffusion mechanisms.
As it was one of the homes with the lowest WMC in year one and geographically close to some of the other homes, data collection in house 6 was not continued in year two and instead began in two homes with conventional vented attics with ceiling insulation to serve as experimental controls. One of the homes had roof decking with an integrated radiant barrier, and the other did not. Control home characteristics are described in Table 6 and representative photos shown in Figure 18. Both control homes were located in the same geographic area as Homes 1, 2, 4, and 5.

Table 6. Summary of control house and occupancy characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>House 7 Control / Radiant Barrier</th>
<th>House 8 Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Fernandina Beach</td>
<td>Ponte Vedra Beach</td>
</tr>
<tr>
<td>Initial visit date</td>
<td>12/07/2018</td>
<td>12/18/2018</td>
</tr>
<tr>
<td>Builder</td>
<td>D.S. Ware</td>
<td>Providence Builders</td>
</tr>
<tr>
<td>Occupants</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Year Built</td>
<td>2016</td>
<td>2013</td>
</tr>
<tr>
<td>Conditioned Area</td>
<td>3150</td>
<td>2222</td>
</tr>
<tr>
<td># stories</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Roof type</td>
<td>Light composite shingle</td>
<td>Light composite shingle</td>
</tr>
<tr>
<td>Underlayment</td>
<td>OSB w/ radiant barrier</td>
<td>OSB</td>
</tr>
<tr>
<td>Ceiling Insulation</td>
<td>Blown Fiberglass</td>
<td>Blown Fiberglass</td>
</tr>
<tr>
<td>Duct / Air handler location</td>
<td>Attic / 2nd floor</td>
<td>Attic / 2nd floor</td>
</tr>
<tr>
<td>Wall Construction</td>
<td>Wood Frame</td>
<td>Wood Frame</td>
</tr>
</tbody>
</table>
Figure 18. Instrumentation installed in control homes with vented attics. Left photo: House 7 Control with radiant barrier. Right photo: House 8 Control.

3.2 Year Two Monitored Data Results
Year two data was collected from December 2018 – May 2019. Figure 19 shows data collected under loose foam sealed plugs for all houses during year two, along with data from the two control homes. As seen in the figure, the overall trend is similar to year one with WMC reaching an elevated state in homes 1, 2, 4, and 5, although not as high as what homes 1 and 2 experienced in January/February of year one. As expected, both control homes show consistently low roof deck WMC values.

Figure 19. Roof deck wood moisture content recorded for loose foam plugs for all homes during year two.

Figure 20 shows data collected under can foam sealed plugs for all houses during year two, along with the data from the two control homes.
Figure 20. Roof deck wood moisture content recorded for can foam plugs for all homes during year two. The sensor in this location in House 2 stopped recording data on January 14, 2019.

As seen in the figure, WMC recorded under the can foam plugs was considerably lower, with less diurnal variation. One exception is House 3, for which data under both peak deck plugs is similar. As previously mentioned, this home is geographically further south than the rest of the homes, experiences slightly warmer outdoor weather, is the only home with a weather barrier integrated into the roof deck (Huber Zip), and is the only home with 100% metal roofing. Figures 21-24 show hourly roof deck moisture content from the loose foam and can foam plugs for House 4 and 5, along with other monitored parameters for the entire year two monitoring period. Similar figures with associated details for the other homes can be found in Appendix C.
Figure 21. Roof deck moisture content, temperature and RH from House 4 loose foam plug, and indoor and outdoor conditions during year two.

Figure 22. Roof deck moisture content, temperature and RH from House 4 can foam plug, and indoor and outdoor conditions during year two.
Figure 23. Roof deck moisture content, temperature and RH from House 5 loose foam plug, and indoor and outdoor conditions during year two.

Figure 24. Roof deck moisture content, temperature and RH from House 5 can foam plug, and indoor and outdoor conditions during year two.
4.0 Year Three (2019-2020) Methods and Results

Data from year two indicated some influence of the foam plug sealing method on the conditions experienced by the roof deck underneath. To investigate whether this influence would persist over time data was collected over a third period spanning October 2019 to early summer 2020 (year three).

4.1 Year Three Instrumentation

No adjustments were made to the homes or the instrumentation in year three. The foam plugs were not removed and reinstalled between years two and three.

4.2 Year Three Monitored Data Results

Year three data was collected from October 2019 – May 2020. Figure 25 shows data collected under loose foam sealed plugs for all houses during year three, along with data from the two control homes. As seen in the figure, the overall trend is similar to year two with WMC reaching an elevated state in homes 2, 4, and 5. Data from the House 7 Control/radiant barrier is not available in year three due to problems encountered with the data logger.

Figure 25. Roof deck wood moisture content recorded for loose foam plugs for all homes during year three.

Figure 26 shows data collected under can foam sealed plugs for all houses during year three. Data from Homes 1 and 2, along with data from the House 7 Control/Radiant barrier is not available due to problems encountered with the data loggers.
Figure 26. Roof deck wood moisture content recorded for can foam plugs for all homes during year three.

As seen in the figure, WMC recorded in year three under the can foam plugs was again considerably lower in most homes, and with less diurnal variation, than WMC under the loose foam plugs. Figures 27-30 show hourly roof deck moisture content from the loose foam and can foam plugs for House 4 and 5, along with other monitored parameters for the entire year three monitoring period. Periodic values for Peak Deck RH of zero seen in House 5 are unexplained, and thought to be related to problems with this sensor. Similar figures with associated details for the other homes can be found in Appendix C.
Figure 27. Roof deck moisture content, temperature and RH from House 4 loose foam plug, and indoor and outdoor conditions during year three.

Figure 28. Roof deck moisture content, temperature and RH from House 4 can foam plug, and indoor and outdoor conditions during year three.
Figure 29. Roof deck moisture content, temperature and RH from House 5 loose foam plug, and indoor and outdoor conditions during year three.

Figure 30. Roof deck moisture content, temperature and RH from House 5 can foam plug, and indoor and outdoor conditions during year three.
5.0 Discussion

As can be seen in the monitored data plots for each home in the previous sections, roof deck moisture content values and associated roof deck relative humidity values are consistent with the standard relationship between equilibrium wood moisture content and relative humidity. The left-hand plot shown in Figure 31 illustrates this standard relationship, showing that at their highest levels, WMC values exceeding 28-30% coincide with 100% relative humidity at the roof deck. At their lowest, WMC values of approximately 8% coincide with relative humidity values of approximately 20-40% (Forest Products Laboratory, 2010). The right-hand plot in Figure 31 shows data from House 1 for the loose foam sealed plug at the peak during year one, and the loose and can foam sealed plugs at the peak during year two, illustrating the standard relationship.

![Figure 31. Left plot: Relationship between equilibrium moisture content of wood and relative humidity (Forest Products Laboratory, 2010). Right plot: Daily average data from House 1 during years one and two.](image)

As seen in the monitored data shown in Figure 31, higher roof deck WMC values under loose foam plugs in House 1 result from the deck being exposed to higher relative humidity values. During year one, the deck under the loose foam plug experienced significantly higher WMC values than in year two. To understand this, it is helpful to understand the relationship among roof deck relative humidity, and roof deck temperature on both a diurnal and seasonal basis. In general, roof deck temperatures often drop below the outside air temperature overnight due to additional heat loss through radiation to the night sky as specific conditions permit, and low temperatures cause relative humidity at the roof deck to increase. As the sun rises, roof deck temperatures quickly increase above the outdoor air temperature, and drive some moisture out of the roof deck. The diurnal cycle of wetting and drying, or the “ping pong water effect” (Lstiburek, 2016), is illustrated in Figure 32.
Figure 3.2. “Ping pong water effect” illustrates diurnal adsorption and desorption of water from the roof deck contingent with diurnal temperature swings. Water migrates towards the peak. (Lstiburek, 2016).

Figure 3 shows how the “ping pong water effect” is reflected in the data for House 1, under the loose foam plug at the roof peak during year one. Before describing more about the patterns in the data it helps to understand a little more about air dew point measurements. Dew point temperature is the temperature at which water condenses from vapor to liquid. This is of course relevant if building surfaces reach or become cooler than the surrounding air dew point. Dew point temperature can also be used for a relative comparison among different locations to determine which location has a greater amount of absolute moisture in the air.

Figure 3. One week of cool weather data from House 1 during year one showing how deck moisture increases with colder deck temperature and the pattern of moisture (Tdp) movement between the roof deck and the attic air.

As seen in Figure 3, solar radiation and warming outdoor daytime temperatures cause the roof deck to heat up, and some drying to occur. Decreases in roof deck WMC correspond with increases in dew point of air adjacent to the roof deck, and an increase in dew point of air on the attic side of the foam at the peak lags behind slightly. The moisture subsequently migrates through the foam and back into the roof deck as temperatures drop overnight. For the first two
days shown in the figure, daily high roof deck temperatures only reach about 80F, and the rate of drying does not exceed the subsequent night’s rate of wetting, and a relatively flat WMC of about 35% is maintained. The maximum daily roof deck temperature over the next three days declines to just over 60F, and the gradual increase in roof deck WMC shows the rate of wetting exceeds the rate of drying. Also evident is how the roof deck dry bulb temperature regularly drops to the dew point temperature at the roof deck, and below the dew point of the air at the attic peak. Notice that there is little difference between Peak Deck Temp and Peak Deck DP because the Peak Deck RH is at about 100%, and there is an increasing trend in roof deck MC when the deck dry bulb temperature is much lower than the attic air dew point. Similar trends can be seen in the data from year two, with Figures 34 and 35 showing data from House 1 for the loose foam and can foam plugs respectively for the same week. Figure 34 shows roof deck relative humidity near 100% results in wetting of the roof deck overnight, but sufficiently warm daytime temperatures moderate the WMC values below 20%. Figure 35 shows a similar trend, but the can foam seal results in lower roof deck relative humidity, and subsequently lower magnitude and variation of roof deck WMC. It is likely that the can foam seal resulted in lower rates of moisture transport between the attic air and the roof deck by air transport and diffusion mechanisms. This is evident by observing the slightly lower dew point temperature at the deck, and how the deck dry bulb temperature remains slightly above the dew point temperature at the deck.

![Figure 34. One week of data from House 1 under the loose foam plug during year two showing the diurnal pattern.](image-url)
In general, data from all homes during all years show that during winter, prolonged periods with overnight roof deck temperatures dipping below 40°F, without sufficient warming occurring the next day, result in prolonged elevated relative humidity at the roof deck. Sustained high levels of RH can result in increasing roof deck moisture content above 15%. While data from sensors under loose foam plugs show roof deck WMC values reaching an elevated state above 20% for prolonged periods of time, which may be cause for concern, data from sensors under the plugs sealed with can foam in years two and three show roof deck WMC values maintained below 20%, and may be more representative of actual conditions experienced by a roof deck insulated with open cell polyurethane foam. However, it is not known whether the can foam, being closed cell and less permeable than the surrounding roof deck open cell foam, instituted its own bias. Upon removal of the can foam plugs, some spread of the can foam under the plug and across the deck was evident in some homes. Some examples of this is shown in Figure 36. It is possible that this foam spread contributed to sensor failures experienced in some homes in year three.

Figure 35. The same week data from House 1 under the can foam plug during year two. Note how roof deck dry bulb temperature (dotted orange) remains above dew point temperature (dotted purple).

Figure 36. Can foam seen covering the deck after removal of the can foam sealed plug at the end of data collection.  Left photo: House 2.  Right photo: House 3.
5.1 Influence of Outdoor Temperature on Roof Deck WMC

It is important to note that recorded roof deck WMC values are dependent on the severity and duration of low outdoor temperatures the homes were exposed to during data collection, and could increase upon exposure to lower outdoor temperatures. As seen in the data under loose foam plugs, once saturation conditions were reached at the roof decks, the rate of daytime drying does not exceed the rate of nighttime wetting until a daily maximum roof deck temperature threshold can be sustained. The onset of saturation conditions is highly dependent on outdoor temperature, and the magnitude of the drying threshold depends on the relative severity of the wetting cycle. It appears that the severity of the wetting cycle was also affected by the plug sealing method, with more roof deck wetting seen under loose foam plugs. The coldest temperatures that the homes experienced during the entire three year study was at the very beginning of year one, when only Houses 1 and 2 had been instrumented, and only loose foam plugs were used. This cold weather period resulted in severe wetting cycles for House 1 and 2, with roof deck WMC values increasing above 30%. For House 1, significant drying did not occur until the middle of February, when daytime high roof deck temperatures regularly exceed 100F. House 2 is a little further south and closer to the coast than House 1, and did not experience outdoor temperatures quite as cold as House 1 through the period when both homes were being monitored during same time. As a result, roof deck WMC was not quite as high, and significant drying occurred near the beginning of February when daytime high roof deck temperatures regularly exceeded 80F. We do not know what the data would have looked like in these homes had can foam plugs also been used during this cold period.

Referring back to Figures 11 and 12, one can see that data available for House 5 during year one shows a similar WMC trend to House 2. If House 5 had been instrumented in time to capture data earlier in the winter when it was likely subjected to colder outdoor temperatures, it is plausible to believe similarly high values of roof deck WMC would be been recorded. Also referring back to Figures 11 and 12, note that nearly all homes experienced three similar episodes of increased roof deck WMC between February 27 and March 22. In all homes, data from years one, two, and three show that relatively short term increases in roof deck WMC correspond with relatively short term periods of cold outdoor temperatures. However, roof deck WMC does not approach levels as high as seen in House 1 and 2 early in year one because 1) outdoor temperatures did not get as cold and 2) outdoor temperatures did not stay cold for an extended amount of time. Also note how the roof deck WMC for House 3 remained the lowest throughout the three year monitoring period. House 3 was located further south than all other homes, and hence experienced warmer outdoor temperatures.

To this point in the report, hourly interval data has been shown. Daily average data was also evaluated to evaluate relationships among temperature, and roof deck moisture content. Figure 37 shows that in addition to relative humidity, another way to think about the relationship between wood moisture content and moisture content of the surrounding air is in terms of a condensation potential, expressed in terms of a difference between the roof deck dry bulb temperature and the dew point temperature of the air at the roof deck.
As seen in Figure 37, the closer the difference between roof deck dry bulb and dew point temperatures gets to zero, the higher the condensation potential and the higher the resulting roof deck WMC. As previously discussed, year two data shows that the can foam plug seal moderates the amount of moisture the roof deck is exposed to compared to the loose foam plug, lowering the condensation potential. Year one data shows the roof deck under loose foam plug experiencing much higher WMC than in year two, and as previously discussed, is related to lower and more prolonged outdoor temperatures. Notice however that year one data also shows elevated values for roof deck WMC, exceeding 20%, even during periods of lower condensation potential. The following plots illustrate how this can occur, and shed light on how WMC values reached such high values during year one.

Figure 38 shows the daily average roof deck WMC at the corresponding daily average difference between peak roof deck temperature and peak attic air dew point temperature during year one for House 2 as orange data points. Similar to the condensation potential displayed in Figure 37, the deck temperature minus the attic air dew point temperature also indicates a condensation potential, when less than zero. The blue points in Figure 38 show daily average roof deck WMC at the corresponding outdoor temperature for House 2 during year one. For these figures and subsequent discussion, the attic air and outdoor air data are used rather than data at the roof deck since the attic air and outdoor air data are easier to measure and monitor by homeowners and contractors without the need to remove foam plugs for sensor installation. Similar plots for other homes are shown in Appendix D with some additional commentary.
Figure 38. Daily average temperature vs. peak deck WMC for House 2 during year one. Temperature for orange data points is the difference between peak deck temperature and dew point temperature of attic air at the peak. Temperature for blue data points is the outdoor air temperature.

An interesting feature in Figure 38 is that the data looks somewhat like a footprint. To investigate this trend, Figure 39 focuses on the daily average outdoor temperature versus daily average roof deck WMC for House 2 during year one, and illustrates the order of a sequence of consecutive days. As seen in the figure, a cold trend begins on 1/16/18, shortly after installation of monitoring equipment. As previously discussed, the cold roof deck temperatures and high prolonged relative humidity at the roof deck result in increasing roof deck WMC. A warming trend began on 1/19/18, however a sufficient maximum temperature threshold is not reached to enable noticeable drying of the roof deck to occur and the deck WMC remained high for a few days even though the daily average temperature increased about 30 degrees F from the coldest day. Therefore it is important to note that while in years two and three roof deck WMC values did not reach levels as high as in year one, and remained below 20% under can foam sealed plugs, outdoor temperature did not get as cold in years two and three as it did in year one.
Figure 39. Daily average outdoor temperature vs. peak deck WMC for House 2 during year one. Arrows indicate sequence of consecutive days. The cold trend initiates wetting of the roof deck that takes time to dry despite a warming trend that increases daily average outdoor temperature by 30 degrees.

5.2 Influence of the Magnitude of the Moisture Source on Roof Deck WMC
Data was analyzed to determine if the magnitude of the moisture source was correlated to elevated roof deck WMC values, and found to have much less of an impact than outdoor temperature. During the winter, when roof deck condensation potential is high due to cold outdoor temperatures, the primary source of moisture inside a sealed attic is moisture that originates as a result of generation within the living space and subsequent transport into the attic. Thermal and moisture stratification was of particular interest in House 1 and 2 during year one since they exhibited the higher WMC. These qualities are shown in Figures 40 and 41 for House 1. Figure 40 shows the relative humidity measure in air for indoors, mid attic height and at peak attic height. The lowest indoor RH is seen during the coldest (dry) weather and during regular space cooling once outdoors is consistently warm. The attic shows a consistent pattern with attic air RH spikes at the peak coinciding with mid attic air RH spikes. Figure 41 shows dry bulb and dew point temperatures. The attic RH spikes of Figure 40 also coincide with attic dry bulb and dew point spikes that are most prevalent during warmer weather.
Figure 40. Relative humidity recorded indoors and at various heights in the attic at House 1 during year one; hourly intervals.

Figure 41. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 1 during year one; hourly intervals.
In general, the peak attic location had higher dew point and therefore a greater amount of moisture at that location than at mid attic. This demonstrated that there was measurable moisture stratification in the attic. From Figure 41, the mid attic air dew point (solid green) is lower than the peak attic air dew point (dotted gold) during peaks. Both closely track the same diurnal pattern up and down together, but the peak air dew point is noticeably higher at its maximum than mid attic. There was not much difference during the low periods.

The highest roof deck WMC occurred during the coldest weather in House 1 (December 2017-January 2018). The measured data show low indoor dew point around mid 40sF with the attic dew points also low and reasonably low RH. During the coldest parts of the cold period the deck temperatures were low, deck RH high and wood deck in process of taking up moisture as seen in WMC values. During this period, there is the least amount of moisture stratification in the attic air. It is not until warmer deck temperatures later on that the moisture begins being driven out at a higher rate into attic air.

Overnight when the attic deck was coolest, there was not much difference between mid and peak dew point. The attic air dew point spikes occurred during the time when the attic air was warmest. This was also about when the attic roof deck was warmest (deck temperatures not shown in Figure 41). This can be explained by high deck temperature driving stored moisture out of wood material during the day into attic. The higher peak temperature has greater potential to drive moisture out. During overnight periods, the roof deck cooled, RH at deck increased and moisture began moving back into wood. With a relatively tight attic to outdoors and leaky attic to indoors, the attic air RH began to decrease.

Figure 42 and 43 show the same measurements for House 2 as Figure 40 and 41 did for House 1. Similar plots of dry bulb temperature, dew point temperature, and relative humidity for all homes for years one and two can be found in Appendix C. Figures 42 and 43 show the same attic RH and dew point pattern in House 2 as was observed in House 1. The peak attic air RH and dew point are higher than the mid attic air during spikes. However, House 2 attic RH and dew point spikes did not get as high as House 1 even though the attic air temperatures are similar. Each had similar color composite shingles over the attic deck areas measured. One small difference can be seen in the interior dew points. House 2 indoor dew point was lower indicating a lower indoor moisture level.
Figure 42. Relative humidity recorded indoors and at various heights in the attic at House 2 during year one; hourly intervals.

Figure 43. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 2 during year one; hourly intervals.
Table 7 shows monthly average dew point temperatures, along with outdoor dry bulb temperature during year one for all homes. In general greater attic moisture stratification is evident during warmer months as shown by peak attic air dew point being greater than midpoint attic air dew point. Data shows that the highest roof deck WMC was during the colder months for all homes, with the coldest period of year one resulting in the highest roof deck WMC. February is the first-coolest month in year one that all homes can be compared. Interestingly in February, House 3 had the second highest amount of moisture in indoor and attic air and still had the lowest roof deck moisture content. As seen in the temperature data plots, it was the warmest of all attics. This points to outdoor temperature influencing roof deck WMC to a greater degree than magnitude of the moisture source. Similar trends are seen in year two data shown in Table 8.

Table 7. Monthly average dew point temperatures (F) at various locations and outdoor temperature (F); year one.

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<td>Data for only half of January is available for House 2.</td>
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Table 8. Monthly average dew point temperatures (F) at various locations and outdoor temperature (F); year two.

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<td>Data for only half of January is available for House 2, and Attic midpoint data is not available after January.</td>
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### 6.0 Summary and Conclusions

FSEC tested and collected data in six homes in the northern Florida portion of IECC Climate Zone 2 built after 2015 with insulated, unvented (semi-conditioned) attics to add to the body of knowledge on the accumulation of moisture in the attic and its effects on roof durability. All homes utilized LDSPF to create the air and thermal barrier. Because of the lack of venting to the outdoors, moisture risk must be managed in unvented attics to ensure durability of components and longevity of the system, and building codes have evolved to contain such provisions. After analysis of one year of data, two additional data collection periods were added. Of primary interest was the wood moisture content (WMC) of the roof deck, and if elevated WMC values of 20% or greater could be detected in any of the homes. Key findings of the research include:

- There is a strong correlation between roof deck WMC and outdoor temperature.
- Elevated roof deck WMC exceeding 30% was monitored in some homes during year one when the homes experienced the coldest outdoor temperatures of the entire study.
- The method used to reseal foam plugs removed for instrumentation purposes influenced the amount of moisture the roof deck was exposed to. Roof deck WMC measured under can foam plugs was much lower than loose foam plugs.
- Roof deck WMC recorded using can foam methods, considered most representative of undisturbed roof deck insulation, remained below 20% in all homes.
- Unvented attics in climate zone 2A insulated with open cell LDSPF at the roof deck are adequately protected from attic moisture related durability risk.
- Similar future research should take caution to ensure data collection methods do not increase moisture transfer from the attic to the roof deck.

A previous investigation (Prevatt, 2017) based on limited field study and simulation had also concluded that the current IRC provides adequate protection against moisture affecting the durability of roof sheathing in warm humid climates. It was desired to collect data in additional homes with characteristics that may increase risk, including tighter ducts, which minimize direct and indirect air exchange between the attic and the conditioned living space, tighter attics, which minimize air exchange between the attic and the outdoors, and exposure to colder outdoor temperatures. A detailed comparison of homes in both studies is included in Appendix E.
Of primary interest was the wood moisture content (WMC) of the roof deck, and if elevated WMC values of 20% or greater could be detected in any of the homes. The LDSPF is impermeable to air, but is vapor permeable, and it will allow moisture in the attic to pass through it and migrate to the underside of the roof sheathing. Likewise, it allows moisture to pass back through into the attic. Two homes experienced high roof deck WMC values at the very beginning of the monitoring period with a significant number of days having daily average roof deck WMC exceeding 28%. While elevated roof deck WMC values dissipated after exposure to sufficiently warm outdoor temperatures that occurred along with increasing solar insolation moving from winter into summer, and no visible signs of decay were noted on the roof decks at the end of the first monitoring period (year one), the initial monitoring period was extended (years two and three) to see if elevated WMC would return with cold, wintertime outdoor temperatures.

**Sensitivity of results to plug sealing method:** In year one, data was collected at the roof peak and at a location half way up the north slope of the roof. Foam plugs cut out from the roof deck insulation in order to install instrumentation against the deck were reinstalled on top of the sensors with the gap between the edges of the foam plug and the surrounding roof deck insulation sealed with the pieces of loose foam that flaked off when plugs were cut out (loose foam). In years two and three, data was collected at one peak location the same way in year one, and under a second foam plug at a second peak location reinstalled by injecting single component, minimal expansion and low-pressure polyurethane foam packaged in a pressurized metal container and purchased at a home improvement store (can foam). The closed-cell SPF product used is intended for “window and door” applications and remains flexible when cured. These two methods of foam plug re-installation were used to investigate whether elevated WMC and roof deck relative humidity were at all influenced by moisture passing through the loose foam gap at a higher transfer rate, either from air transport or diffusion mechanisms.

Data collected for years two and three show daily average roof deck WMC values recorded under loose foam plugs exceeding 20% in some of the homes, but roof deck WMC values recorded under can foam plugs remained under 20% for all homes, and under 15% for most homes. This finding and subsequent analysis of relative humidity and dew point temperatures under the plugs indicates that the loose foam seal allowed a greater amount of moisture to reach the roof deck than the can foam plugs, via air transport and diffusion mechanisms. Can foam plugs may be more representative of actual conditions experienced by a roof deck insulated with open cell polyurethane foam, however, it is not known whether the can foam, being closed cell and less permeable than the surrounding roof deck open cell foam, instituted its own bias.

**Other factors influencing roof deck WMC:** This project analyzed collected data to search for indications of significant variables contributing to high WMC limited to practical measurements of indoor, attic and outdoor temperature and RH. Indoor dew point was used as an indication of internal moisture level. It appeared that internal moisture did not satisfactorily explain the highest roof WMC in the homes of this study. These homes had an average of two adult occupants and internal loads would be lower than homes with much higher occupant density.
Martin and Withers, the authors of this report, disagree that interior moisture and heat generation and thermostat cooling set point have the greatest effect on roof deck MC as was determined by the Prevatt 2017 simulation sensitivity analysis. FSEC data does show that moisture in the homes is stratified vertically, with greatest amounts of moisture accumulating near the roof peak, and while these variables certainly play some role, we believe other variables play a more significant role.

Outdoor temperature and roof deck condensation potential showed better correlation to WMC than indoor conditions in the FSEC study. Roof deck condensation potential is when the temperature of the roof deck falls below the dew point of the surrounding air, and is affected by outdoor temperature, the radiative property of the external roof material, and magnitude of the moisture source. As expected, the measurement of roof deck RH has the best correlation to WMC, however deck RH is a variable significantly impacted by deck temperature which is significantly impacted by outdoor temperature, solar insolation, and exterior roof material absorption and radiant properties. The magnitude of moisture source is difficult to practically predict. High values of roof deck WMC had been recorded in cases with modest internal moisture generation. The most practical external environmental variable to measure or predict having the most impact was outdoor temperature.

Homes experiencing the coldest outdoor weather also experienced the greatest magnitude and longest duration of roof deck WMC. The coldest weather periods also coincided with the coldest roof deck temperatures and highest deck RH (100% RH) as would be expected. Due to contract delays that ultimately delayed recruitment, a significant portion of the homes in this study were not instrumented in time to capture data during the coldest period, which occurred at the very beginning of year one. Trends in the data show that if the homes had been instrumented earlier in that winter, it is likely that higher roof deck WMC values would have been recorded under the loose foam plugs. Can foam plugs were not utilized during this coldest period, and it is not known how elevated roof deck WMC might have become under those conditions. House 3, which is located furthest south and was subjected to warmer outdoor conditions, had consistently low roof deck WMC values, despite having among the higher indoor and attic air moisture levels.

The airtightness of the house, attic and ducts were also tested to determine if leakage levels played any significant role in roof deck WMC. It has been postulated that leaks in an unvented attic due to imperfect air seal could unintentionally allow entry of cold dry air in the winter and potentially reduce moisture levels. Alternatively, these same attic leaks to outdoors during summer humid conditions increase condensation potential on cold air supply ducts and increase attic air RH. While there is no official national standard threshold for whether a building is substantially air tight, the authors have assessed that each home in this study was reasonably airtight according to ACH50 and CFM/ft² values. The authors have also looked at the data from the homes in the Prevatt 2017 study, where one home had roof deck WMC reach 20%, and
assessed that while the living space leakage was substantially larger, the attics were also substantially tight.

**Conclusions:** The 2018 IRC provides prescriptive means for unvented attic design according to climate, and all homes in this study met that prescriptive requirement. It also allows somewhat of a performance approach that involves a target to keep the underside of the roof deck above a monthly average temperature of 45F. The coldest monthly average roof deck temperature measured in this project was approximately 50F. While some elevated roof deck WMC values were recorded, roof deck WMC values dissipated after exposure to sufficiently warm outdoor temperatures that occur with increasing solar insolation upon the roof deck moving from winter into summer. No evidence of lasting durability effects has been obtained, but a thorough disassembly of the roof would need to be conducted to collect definitive data. Given the results obtained, and considering the data under can foam plugs may be more representative of whole roof deck performance than data under loose foam plugs, these homes located towards the norther portion of climate zone 2A seem adequately protected from attic moisture related durability risk.

The applicability of these results are restricted to the homes that were tested, and more research would need to be conducted before extending this recommendation broadly:

- High mass roofs (tile) and high reflectivity roofs (white metal) were not part of the study and may behave differently as these roofs may experience delayed drying during morning hours.

- The climatic conditions were rather mild. The highest moisture content were found under the coldest conditions tested. The authors recommend additional measurements under can foam plugs in homes in climate zone 3A that are likely to experience prolonged periods of outdoor temperatures below 30F.

### 7.0 References


Prevatt, D., A. Viswanathan, W. Miller, P. Boudreax, S. Pallin, and R. Jackson. “Phase II Analytical Assessment of Field Data for Sealed Attics in Florida Climate Zones 1 and 2 – Predicting Moisture Buildup in Roof Sheathing.” Submitted to Florida Building Commission, June 2017
Appendix A – House Photos

Instrumentation installed at midpoint of north facing roof deck measurement after insulation sealed back into place.

Figure A 1 House 1 photos.
Figure A 2. House 2 photos.
South facing rear side.

North facing roof deck

Roof deck sensors in place before insulation sealed back in place.

Figure A 3. House 3 photos.
Figure A 4. House 4 photos.

Insulation at deck peak.
North facing roof deck section.

Roof deck sensors installed just before sealing insulation back in place.

Figure A 5. House 5 photos.
North facing roof deck section.

Deck sensors at north peak location with insulation in place.

Figure A 6. House 6 photos.
Figure A 7. House 7 control / radiant barrier photos.
Figure A 8. House 8 control.
Appendix B – Infrared Thermography

IR thermography was used to scan for any serious anomalies in the thermal barrier inside the attic. This was done when conditions were conducive to adequate thermal differential between outdoors and indoors. Cloudy mild days are often not suitable. The figures below show examples of the types of imaging. When available, photographic images are shown to the left of the associated IR image.

IR images indicated that the insulation barrier was uniformly intact. While some small little areas of elevated temperature (during warm weather) would be found occasionally, there was no observed significant areas of inadequate attic insulation.

Figures B1-B3 are from house 1 taken during a cloudy summer afternoon that followed a sunny hot morning period. The indoor temperature was 80F, the attic floor (gypsum ceiling) was about 81F and deck insulation in attic averaged about 83F. Thermal stratification can be seen in the IR image if Figure B1.

Figure B1. Lower section of north facing roof deck in House 1.

Figure B2. Middle north roof deck height in unvented attic of House 1.
Figure B3. Peak roof deck height in unvented attic of House 1.

Figures B4-B6 are from House 3. This home had the lowest roof WMC of all homes in the study. Thermal IR imaging did not find anything unusual in this home.

Figure B4. Peak roof deck height in unvented attic of House 3. IR images taken during summer morning period before solar heating of roof began.

Figure B5. Peak roof deck of House 3 as insulation is removed to access deck sensors.
Figure B6 shows IR image during the morning when outside roof was cooler than inside and shows inner deck surface temperature a little cooler than inside attic insulation surface. The inner deck temperature was about 75F-77F and attic insulation surface temperatures were about 78F at this time. The trend would reverse as the sun heats the roof up through the day.

Figure B6. Peak roof deck House 3 just after insulation was removed. IR images taken during summer morning period before solar heating of roof began.

Figures B7-B9 are taken from House 6. This home did not have any significant periods of high WMC. Thermal IR imaging found a substantial amount of insulation intact over the roof deck. Just a couple small areas were found where the insulation was likely a little thinner along a few places where the roof deck meets the ceiling plane at exterior walls.

Figure B7. Lower attic area where north facing roof deck meets the conditioned ceiling in House 6. IR image during summer afternoon period.
Figure B8. Another area of lower attic where north facing roof deck meets the conditioned ceiling in House 6. IR image is an example where insulation may be a little thinner allowing a little more heat transfer as seen as yellow seam. This was uncommon in all homes.

Figure B9. Examples of peak roof IR images during summer afternoon period in House 6.
Appendix C – Monitored Data Plots

Figure C-1a. Roof deck moisture content, temperature and RH from House 1 north facing roof slope with indoor and outdoor conditions, year one.

Figure C-1b. Roof deck moisture content, temperature and RH from House 1 roof peak with indoor and outdoor conditions, year one.
Figure C- 1c. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 1, year one.

Figure C- 1d. Relative humidity recorded indoors and at various heights in the attic at House 1, year one.
Figure C-1e. Roof deck moisture content, temperature and RH from House 1 loose foam plug with indoor and outdoor conditions, year two.

Figure C-1f. Roof deck moisture content, temperature and RH from House 1 can foam plug with indoor and outdoor conditions, year two.
Figure C-1g. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 1, year two.

Figure C-1h. Relative humidity recorded indoors and at various heights in the attic at House 1, year two.
Figure C-1i. Roof deck moisture content, temperature and RH from House 1 loose foam plug with indoor and outdoor conditions, year three.
Figure C-2a. Roof deck moisture content, temperature and RH from House 2 north facing roof slope with indoor and outdoor conditions, year one.

Figure C-2b. Roof deck moisture content, temperature and RH from House 2 roof peak with indoor and outdoor conditions, year one.
Figure C- 2c. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 2, year one.

Figure C- 2d. Relative humidity recorded indoors and at various heights in the attic at House 2, year one.
Figure C-2e. Roof deck moisture content, temperature and RH from House 2 loose foam plug with indoor and outdoor conditions, year two.

Figure C-2f. Roof deck moisture content, temperature and RH from House 2 loose foam plug with indoor and outdoor conditions, year two.
Figure C- 2g. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 2, year two.

Figure C- 2h. Relative humidity recorded indoors and at various heights in the attic at House 2, year two.
Figure C-2i. Roof deck moisture content, temperature and RH from House 2 loose foam plug with indoor and outdoor conditions, year three.
Figure C-3a. Roof deck moisture content, temperature and RH from House 3 north facing roof slope with indoor and outdoor conditions, year one.

Figure C-3b. Roof deck moisture content, temperature and RH from House 3 roof peak with indoor and outdoor conditions, year one.
Figure C- 3c. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 3, year one.

Figure C- 3d. Relative humidity recorded indoors and at various heights in the attic at House 3, year one.
Figure C-3e. Roof deck moisture content, temperature and RH from House 3 loose foam plug with indoor and outdoor conditions, year two.

Figure C-3f. Roof deck moisture content, temperature and RH from House 3 can foam plug with indoor and outdoor conditions, year two.
Figure C-3g. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 3, year two.

Figure C-3h. Relative humidity recorded indoors and at various heights in the attic at House 3, year two.
Figure C- 3i. Roof deck moisture content, temperature and RH from House 3 loose foam plug with indoor and outdoor conditions, year three.

Figure C- 3j. Roof deck moisture content, temperature and RH from House 3 can foam plug with indoor and outdoor conditions, year three.
Figure C- 4a. Roof deck moisture content, temperature and RH from House 4 north facing roof slope with indoor and outdoor conditions, year one.

Figure C- 4b. Roof deck moisture content, temperature and RH from House 4 roof peak with indoor and outdoor conditions, year one.
Figure C-4c. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 4, year one.

Figure C-4d. Relative humidity recorded indoors and at various heights in the attic at House 4, year one.
Figure C-4e. Roof deck moisture content, temperature and RH from House 4 loose foam plug, and indoor and outdoor conditions, year two.

Figure C-4f. Roof deck moisture content, temperature and RH from House 4 can foam plug, and indoor and outdoor conditions, year two.
Figure C-4g. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 4, year two.

Figure C-4h. Relative humidity recorded indoors and at various heights in the attic at House 4, year two.
Figure C-4i. Roof deck moisture content, temperature and RH from House 4 loose foam plug, and indoor and outdoor conditions, year three.

Figure C-4j. Roof deck moisture content, temperature and RH from House 4 can foam plug, and indoor and outdoor conditions, year three.
Figure C- 5a. Roof deck moisture content, temperature and RH from House 5 north facing roof slope with indoor and outdoor conditions, year one.

Figure C- 2b. Roof deck moisture content, temperature and RH from House 5 roof peak with indoor and outdoor conditions, year one.
Figure C- 5c. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 5, year one.

Figure C- 5d. Relative humidity recorded indoors and at various heights in the attic at House 5, year one.
Figure C-5e. Roof deck moisture content, temperature and RH from House 5 loose foam plug, and indoor and outdoor conditions, year two.

Figure C-5f. Roof deck moisture content, temperature and RH from House 5 can foam plug, and indoor and outdoor conditions, year two.
Figure C- 5g. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 5, year two.

Figure C- 5h. Relative humidity recorded indoors and at various heights in the attic at House 5, year two.
Figure C-5i. Roof deck moisture content, temperature and RH from House 5 loose foam plug, and indoor and outdoor conditions, year three.

Figure C-5j. Roof deck moisture content, temperature and RH from House 5 can foam plug, and indoor and outdoor conditions, year three.
Figure C-6a. Roof deck moisture content, temperature and RH from House 6 north facing roof slope with indoor and outdoor conditions, year one.

Figure C-6b. Roof deck moisture content, temperature and RH from House 6 roof peak with indoor and outdoor conditions, year one.
Figure C- 6c. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 6, year one.

Figure C- 6d. Relative humidity recorded indoors and at various heights in the attic at House 6, year one.
Figure C- 7a. Roof deck moisture content, temperature and RH from House 7 Control/Radiant Barrier roof peak with indoor and outdoor conditions, year two.
Figure C- 7b. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 7 Control/Radiant Barrier, year two.

Figure C- 6c. Relative humidity recorded indoors and at various heights in the attic at House 7 Control/Radiant Barrier, year two.
Figure C-8a. Roof deck moisture content, temperature and RH from House 8 Control roof peak with indoor and outdoor conditions, year two.

Figure C-8b. Roof deck moisture content, temperature and RH from House 8 Control roof peak with indoor and outdoor conditions, year three.
Figure C- 8c. Dry bulb and dew point temperatures recorded indoors and at various heights in the attic at House 8 Control, year two.

Figure C- 8d. Relative humidity recorded indoors and at various heights in the attic at House 8 Control, year two.
Appendix D – Daily Average Roof Deck WMC Compared to Other Variables; Year One

This appendix compares daily average roof deck WMC to three different variables: daily average outdoor temperature, the daily average temperature difference between the roof deck temperature and the attic air dew point temperature, and the third is daily average deck relative humidity. The first two have been fit onto one figure for each home and are presented first for all six homes. The attic air dew point shown in these plots was measured near the deck just next to the inside attic face of the foam insulation. Data from each house is presented in the same order with the midpoint north facing deck location plot first followed by the north facing peak deck location.

The deck temperature minus attic dew point difference indicates how much deck condensation potential there is. A temperature difference of 0°F means that the deck has reached condensing temperature and the RH at the deck would be 100%. Temperature differences less than 0°F (negative values) indicate the roof deck was colder than the inside attic dew point temperature and would have even greater condensation potential.

This data shows that 2 out of 6 houses experienced at least several days with WMC 20% or greater. A third home, (House 5) had just a couple days of WMC at about 20%. Four homes showed a trend of having higher WMC in peak than at midpoint, although the difference was minor in three of these.

Of the three homes that had at least 20% WMC, the upper range in outdoor temperature averaged about 71.5F. This means that once the daily average outdoor temperature dropped to 71.5F, roof deck WMC could be at 20%. After looking at the plots, one will see many days where this doesn’t happen, but it becomes plausible for some homes. Of the three homes that had at least 20% WMC, the upper range in deck temperature minus attic air dew point temperature difference averaged about 10.5F.

House 1 had the most days when the daily average WMC was at least 20%. It also had been monitored the longest and experienced more cold weather than the other homes. The lowest outdoor temperature was about 35F. As seen in Figures D1 and D2 there were several days when the daily average roof deck temperature was below the daily average attic air dew point temperature.
Figure D1. House 1 midpoint attic deck WMC versus Out T and dT (deck T - attic Tdp).

Figure D2. House 1 peak attic deck WMC versus Out T and dT (deck T - attic Tdp).
House 2 had many days when the daily average WMC was at least 20% and experienced some cold weather. The lowest outdoor temperature was about 36F. As seen in Figures D3 and D4, there were also several days when the daily average roof deck temperature was below the daily average attic air dew point temperature.

Figure D3. House 2 midpoint attic deck WMC versus Out T and dT (deck T- attic Tdp).

Figure D4. House 2 peak attic deck WMC versus Out T and dT (deck T- attic Tdp).
House 3 had significantly lower daily average WMC than all other homes. Data in Figures D5 and D6 shows that daily average WMC never reached 15%. The lowest outdoor temperature was about 53°F. There were no days when the daily average roof deck temperature was below the daily average attic air dew point temperature. This home was located in central Florida and it was the only home of 6 that had a metal roof over the entire roof. It also had the leakiest attic, although the attic was still considered reasonably tight.

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**Figure D5.** House 3 midpoint attic deck WMC versus Out T and dT (deck T - attic Tdp).

**Figure D6.** House 3 peak attic deck WMC versus Out T and dT (deck T - attic Tdp).
Data in Figures D7 and D8 shows that daily average WMC for House 4 never reached 20%. The lowest outdoor temperature experienced was about 50°F. There were only a few days when the daily average roof deck temperature was below the daily average attic air dew point temperature. The peak roof deck location had a little higher WMC and a few more days when the peak deck temperature was below the peak attic air temperature.

Figure D7. House 4 midpoint attic deck WMC versus Out T and dT (deck T- attic Tdp).

Figure D8. House 4 peak attic deck WMC versus Out T and dT (deck T- attic Tdp).
For House 5, data in Figures D9 and D10 shows that daily average WMC reached 20% just twice. Outdoor temperatures did not fall below 55°F. There were only a few days when the daily average roof deck temperature was below the daily average attic air dew point temperature.

Figure D9. House 5 midpoint attic deck WMC versus Out T and dT (deck T- attic Tdp).

Figure D10. House 5 peak attic deck WMC versus Out T and dT (deck T- attic Tdp).
For House 6, data in Figures D11 and D12 shows that the daily average WMC never reached 20%, but outdoor temperatures did not fall below 55°F. There were only a few days when the daily average roof deck temperature was below the daily average attic air dew point temperature.

Figure D11. House 6 midpoint attic deck WMC versus Out T and dT (deck T- attic Tdp).

Figure D12. House 6 peak attic deck WMC versus Out T and dT (deck T- attic Tdp).
The next series of plots (Figures D13-D24) show the daily average roof deck WMC compared to daily average RH at the roof deck. The RH measurement was taken against the underside of roof deck between the deck and foam insulation. These plots generally show expected trends of WMC increasing as the RH increases. Keep in mind that this is not a steady-state condition and will vary from a lab-controlled test conditions of uncovered wood. It represents an average of a diurnal process of warming and cooling, wetting and drying, of one side of oriented strand board (OSB) roof deck covered by LDSPF. The wider band of WMC at RH >80% in House 1 and 2 is likely due to periods of wetting and drying.

Figure D13. House 1 midpoint attic deck WMC versus deck RH.

Figure D14. House 1 peak attic deck WMC versus deck RH.
Figure D15. House 2 midpoint attic deck WMC versus deck RH.

Figure D16. House 2 peak attic deck WMC versus deck RH.
Figure D17. House 3 midpoint attic deck WMC versus deck RH.

Figure D18. House 3 peak attic deck WMC versus deck RH.
Figure D19. House 4 midpoint attic deck WMC versus deck RH.

Figure D20. House 4 peak attic deck WMC versus deck RH.
Figure D21. House 5 midpoint attic deck WMC versus deck RH.

Figure D22. House 5 peak attic deck WMC versus deck RH.
Figure D23. House 6 midpoint attic deck WMC versus deck RH.

Figure D24. House 6 peak attic deck WMC versus deck RH.
Appendix E – Comparison of Select Characteristics of Homes in the FSEC Study to those in Prevatt 2017

The six homes of this (FSEC) study consisted of a small sample. This section of report is to provide a convenient summary of this study and another recent similar study conducted by Prevatt et al. 2017 in an effort to consider more homes. Prevatt 2017 studied roof deck WMC in a sample of four unvented attic homes sealed with LDSPF. Two of these homes were located in south Florida and two were in central Florida. The FSEC study used a similar approach of measuring WMC, deck temperature and RH, and attic air temperature and RH measurements as was done in the Prevatt 2017 study. Both Studies made measurements at midpoint and peak north-facing roof decks, although it is unknown how roof deck foam was altered to collect data at the roof decks for the Prevatt 2017 study. The Prevatt monitoring period was for about one full year, whereas the FSEC study monitoring period spanned three winters.

The Prevatt 2017 study conclusions regarding roof deck WMC were essentially that no significant WMC levels were observed within their study. Data presented showed WMC below 15% for three homes all year with modest increases during winter. The Gainesville home had WMC below 15% for almost the entire year except during two separate periods during the January and February 2017 period when WMC spiked up to about 19-20%. The spikes generated limited discussion, but no conclusions were drawn about the cause, primarily since this home was occupied by seasonal residents. The occupancy status throughout the monitoring of this home was unknown. Prevatt 2017 noted within the report that the colder weather coincided with the spikes but, later concluded that the cause was unknown and presumed to be due to occupancy habits.

The Prevatt 2017 study concluded:

- “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.”
- A simulation-based evaluation indicated 7 inputs used, “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.”

Outside temperatures were only reported on the Venice (#2) and the Gainesville (#4) house. The coldest outdoor temperature measured in Venice during monitoring was about 65F (very mild). Gainesville showed the coldest temperatures around 60F (again very mild) that coincided with the moisture spikes at around 20% MC in roof deck.
The authors of this FSEC report, Martin and Withers, disagree that interior moisture and heat generation and thermostat set point have the greatest effect on roof deck MC as was determined by the Prevatt 2017 simulation sensitivity analysis. While these variables certainly play some role, we believe outdoor temperature, and the radiative property of the external roof material are variables likely to have much better correlation to roof WMC. Based on the findings of the FSEC report, we suspect that at least the tighter attics of the Prevatt 2017 study homes (except Prev. House 2 which had a dehumidifier in the attic) may have measured higher WMC if they had experienced colder sustained periods of outdoor temperatures.

A basic summary of differences between homes of each study are offered below followed by tables with measure tightness data.

- Prevatt homes total (house + attic) CFM50/ft² floor area 3.3 times > than FSEC homes.
- Prevatt homes attic CFM50/ft² floor area under attic tested twice as leaky on average, but one extremely leaky home skews that average. If that home is excluded, attic leakage values are similar.
- Prevatt ducts total duct leakage (Qn total) 1.7 times greater than FSEC homes.
- Prevatt ducts leakage to our (Qn out) 2.4 times > FSEC homes (leakage to out is essentially leakage into attic; although some homes could have had AHU in garage instead of attic)

The one Prevatt home (#4) in Gainesville that did have an episode of elevated roof deck WMC had very different tightness characteristics than other homes.

- Total CFM50/ ft² FBC4 was 2.9 times > FSEC study 6 home average.
- Attic CFM50/ ft² FBC4 was 3.8 times < FSEC study 6 home average (tightest of all 10 homes).
- Total duct CFM25/ft² was 2.0 times > FSEC study 6 home average.

Table D1. Guarded Air Tightness Testing Results of Unvented Attic Homes Completed by Two Different Research Projects

<table>
<thead>
<tr>
<th>House ID</th>
<th>House + Attic CFM50</th>
<th>Attic to out CFM50</th>
<th>House to Out CFM50</th>
<th>House to Out CFM50/ft² **</th>
<th>Attic Leak Ratio</th>
<th>House wrt Attic dP (Pa)**</th>
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</thead>
<tbody>
<tr>
<td>FSEC Study</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>N.E. Jacksonville</td>
<td>1</td>
<td>768</td>
<td>388</td>
<td>380</td>
<td>0.209</td>
<td>0.213</td>
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<tr>
<td>Jacksonville Bch 2</td>
<td>1450</td>
<td>324</td>
<td>1126</td>
<td>0.348</td>
<td>0.232</td>
<td>51.7%</td>
</tr>
<tr>
<td>Umatilla 3</td>
<td>1730</td>
<td>1198</td>
<td>532</td>
<td>0.150</td>
<td>0.338</td>
<td>69.2%</td>
</tr>
<tr>
<td>Fernandina Bch 4</td>
<td>1297</td>
<td>686</td>
<td>611</td>
<td>0.227</td>
<td>0.255</td>
<td>52.9%</td>
</tr>
<tr>
<td>Pontre Vedra Bch 5</td>
<td>623</td>
<td>271</td>
<td>352</td>
<td>0.159</td>
<td>0.123</td>
<td>43.5%</td>
</tr>
<tr>
<td>Pontre Vedra Bch 6</td>
<td>920</td>
<td>259</td>
<td>661</td>
<td>0.305</td>
<td>0.239</td>
<td>56.3%</td>
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<tr>
<td>Average</td>
<td>1131</td>
<td>521</td>
<td>610</td>
<td>0.233</td>
<td>0.233</td>
<td>54.0%</td>
</tr>
<tr>
<td>House ID</td>
<td>House + Attic CFM50</td>
<td>Attic to out CFM50</td>
<td>House to Out CFM50</td>
<td>House to Out CFM50/ft² *</td>
<td>Attic CFM50/ft² **</td>
<td>Attic Leak Ratio</td>
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<tr>
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<tr>
<td>W.Palm 1</td>
<td>4298</td>
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<td>1788</td>
<td>2.104</td>
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<tr>
<td>Venice 2</td>
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<td>656</td>
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<td>0.507</td>
<td>0.183</td>
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<td>Orlando 3</td>
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<td>3637</td>
<td>1.764</td>
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<td>Gainesville 4</td>
<td>3718</td>
<td>187</td>
<td>3531</td>
<td>1.217</td>
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<td>Average</td>
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<td>965</td>
<td>2530</td>
<td>1.398</td>
<td>0.422</td>
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* Leakage per conditioned floor area ft²
** Leakage per tested attic floor area ft²
*** Measured dP when House wrt Out at -50 Pa; Prevatt 2017 dP data not available, but predicted based on FSEC least-squares regression analysis.

Table D2. Duct Leakage Testing Results of Unvented Attic Homes Completed by Two Different Research Projects

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<th>House ID</th>
<th>CFM25total</th>
<th>CFM25out</th>
<th>CFM25total/ft²</th>
<th>CFM25out/ft²</th>
<th>Attic leak ratio</th>
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<tbody>
<tr>
<td>FSEC Study</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>208</td>
<td>18</td>
<td>0.114</td>
<td>0.010</td>
<td>50.5%</td>
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<tr>
<td>2</td>
<td>120</td>
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<td>0.086</td>
<td>0.020</td>
<td>51.7%</td>
</tr>
<tr>
<td>3</td>
<td>214</td>
<td>68</td>
<td>0.086</td>
<td>0.027</td>
<td>69.2%</td>
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<td>338</td>
<td>35</td>
<td>0.125</td>
<td>0.013</td>
<td>52.9%</td>
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<tr>
<td>5</td>
<td>274</td>
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<td>0.124</td>
<td>0.007</td>
<td>43.5%</td>
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<tr>
<td>6</td>
<td>227</td>
<td>11</td>
<td>0.105</td>
<td>0.005</td>
<td>56.3%</td>
</tr>
<tr>
<td>Average</td>
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<td>29</td>
<td>0.107</td>
<td>0.014</td>
<td>54.0%</td>
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<tr>
<td>Prevatt et al. 2017 Study</td>
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<td></td>
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<tr>
<td>Prev. 1</td>
<td>115</td>
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<td>0.110</td>
<td>0.070</td>
<td>58.4%</td>
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<tr>
<td>Prev. 2</td>
<td>579</td>
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<td>0.161</td>
<td>0.032</td>
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<tr>
<td>Prev. 3</td>
<td>608</td>
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<td>0.259</td>
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<tr>
<td>Prev. 4</td>
<td>655</td>
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<td>0.214</td>
<td>na</td>
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<tr>
<td>Average</td>
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<td>0.034</td>
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