Seasonal Moisture Impacts on Roof Deck Moisture in Unvented Attics in North Florida

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ABSTRACT

Open cell spray polyurethane foam (ocSPF) has been used in insulating and sealing unvented attics for about 25 years. While ocSPF is impermeable to air, it is moisture permeable. Over time, occasional moisture control issues have occurred in some homes with ocSPF and codes have adjusted requirements in response. However, for homes in climate zones 1-4 that utilize air impermeable insulation at the roof deck, no other prescriptive means for controlling moisture at the roof deck is required by code. How well are the existing stock of unvented attics managing moisture? Research was conducted from 2017-2020 to study attic moisture in six newer unvented attic homes as well as two vented attic homes. All homes were located in central to north Florida and none had reports of moisture issues prior to or during study. House, attic, and duct airtightness was measured to verify acceptable performance. Temperature and relative humidity was measured in attics, indoors and outdoors. A plug of foam insulation at the roof deck was carefully removed in two locations per home to allow installation of wood moisture content sensors and then was carefully re-installed. Data was collected over about 2 ½ years to observe impacts throughout several seasons. No moisture damage was observed in any research homes. The roof deck moisture content tended to stay at 10% WMC or less during warm weather months from April – November. Moisture content increased during winter months and varied from 10% WMC to 18% WMC. Different influences on roof WMC were examined and outdoor and roof deck temperature were found to have the greatest impact. Findings here support IRC 2021 climate zones 2, 3, and 4 requirements, but warrant caution to be considered for unvented attics located in these specific zones that experience prolonged cold weather events.

INTRODUCTION

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). Section R806 of the 2021 International Residential Code (ICC, 2021) includes provisions for managing moisture risk according to house location and associated climate, and whether air-permeable or air-impermeable insulation is

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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 to minimize moisture from attic air to the roof deck, particularly during colder weather.

All homes utilized open cell spray polyurethane foam (ocSPF), also referred to as low density spray polyurethane foam to create the air and thermal control layers. The ocSPF is impermeable to air, but is vapor permeable, and it will allow water vapor 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 (APA 1999).

The vapor permeability of one specific brand of ocSPF with 5 ½ inch thick application and a core density of 0.5 lb/ft^3 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). 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 move through the vapor-permeable insulation to the roof deck, but heat gains on the roof drive the moisture back down through the foam into the attic, resulting in repeated wetting and drying. Little published data is available on roof deck wood moisture content (WMC) for attics having air-impermeable insulation at the deck. A previous investigation (Prevatt, 2017) based on limited field study of four central Florida homes and simulation, concluded that the International Residential Code requirements for unvented attic in Climate Zone 2A provided adequate protection against moisture affecting the durability of roof sheathing in warm humid climates. However, one home in North Central Florida had elevated roof deck moisture near 20% WMC during a brief cold period. All four homes in Prevatt 2017 study were newer, had composite shingle roofs, and did not experience very cool weather conditions during the study. This raised the question, might ocSPF unvented attic homes in Climate Zone 2 and 3 have vulnerable periods of roof deck water vapor issues, and does the type of roof covering have much impact?

RESEARCH METHOD

The primary research focus was to monitor the 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. An anonymous home energy rating database of Florida homes was used to identify homes that had been built within the previous two years and having unvented attics. Single-family homes in North Central and North Florida having asphalt composite shingle, metal, or tile roofs and built by different builders were sought after.

Data was initially collected from December 2017 to early summer of 2018 (year one). After analysis of the first period, sensors were re-installed and data was collected for an additional two years adding two more periods of monitoring. The second period was from December 2018 to early summer 2019 (year two) and the third period of monitoring was from October 2019 through early summer 2020 (year three). The roof deck surface at the sensor test sections was able to be visually inspected for signs of water damage during initial installation and removal during year 1 and again during re-installation year 2 and removal at the end of the third year. There was no indication of moisture damage such as mold or mildew stains, water marking, or softened wood in all study homes. More details on this research project can be found at (Martin and Withers 2021.)

Rationale for the last two periods is explained further here. The second year of monitoring was conducted to determine if a seasonal pattern of WMC would repeat to similar magnitudes as the first year. Since the homes were less than two years old , it was considered that the initial building material moisture of new materials could contribute to higher WMC in the first year than in following years. There was also speculation that the method of securing the ocSPF back in place after installing sensors, during year one, may have also impacted WMC. Therefore beginning in year two, there was a comparison made between how the ocSPF plugs were secured back in place after sensor installation on the roof deck. Year three was to further investigate whether seasonal trends would persist and to gather additional winter data, when roof deck WMC are typically highest. This seasonal trend in two Climate Zone 2A unvented attic homes has been observed by others (Ueno and Lstiburek 2016).

House Characteristics

The home energy rating database contained relatively few unvented attic homes in north Florida that had metal or concrete tile roofs, and only one non-shingle home was found that agreed to participate in the study. Two homes (House 5 and 6) were built by the same builder with one being a single-story and the other was a two-story home. House performance-related tests were completed in all homes during the first site visit. The purpose of the house tests were to help verify adequate building and duct airtightness as well as overall suitability to participate in the study. The field tests included guarded tests of house and attic airtightness to outdoors, primary air boundary location evaluation, duct leakage test, visual inspections, and infrared scans of some house attic surfaces. Table 1 shows some additional house characteristics. All homes had OSB roof decks. Homes with shingles were asphalt composite shingle. The roof exterior type indicated in Table 1 also indicates the coloring shade. The relative air leakage to outdoors of the attic was evaluated based on pressure differentials during the air tightness test of the home at – 50 Pa with reference to (wrt) outdoors and with attic hatch closed. The attic wrt outdoor pressure of the six unvented homes ranged from -34.1 Pa to -46.3 Pa, or 68% (-34.1Pa/-50 Pa) to 93% (-46.3 Pa/-50 Pa) of the total house wrt out pressure. In another study of unvented attics, the attic wrt out pressure difference ranged from 76% to 86% of the house wrt out pressure and deemed the attics relatively airtight (Ueno and Lstiburek 2016).

The house ACH50 airtightness tests show all houses were semi-airtight according to ANSI Standard 310 (1.0-3.0 ACH50). House 3 conditioned space tightness was substantially tighter than the others, but House 3 attic leakage to outdoors was 50% higher than the average of the other five homes. Attic inspection did not find any leaks large enough to be visually identified and it is likely the leakiness is attributed to a larger accumulation of very small cracks in House 3, the largest home in the study. The total duct leakage tightness was not significantly different among the six homes. The total tightness did indicate ducts leakier than typical beyond code high performance homes and all except House 2 had total duct leakage that exceeded ANSI Standard 310 requirement for designation of Grade I or Grade II.

Table 1. Summary of house and occupancy characteristics of unvented attic homes.

Parameter	House 1	House 2	House 3	House 4	House 5	House 6
Location	Jacksonville	Jacksonville Bch.	Umatilla	Amelia Isl.	Ponte Vedra Bch.	Ponte Vedra Bch.
Conditioned Area ft^2 (m^2)	1822 (169)	3129 (291)	3541 (329)	2695 (250)	2208 (205)	2168 (201)
# stories	1	2	1	2	1	2
Occupants	3	2-3	2	2	2	3
Move in date	Nov. 2016	Jul. 2016	Mar. 2017	Dec. 2016	Dec. 2016	Dec. 2016
Roof exterior type	Light shingle	Light shingle	Light metal	Medium shingle	Medium shingle	Medium shingle
Roof deck R-value	22	21	20	22	22	22
HERS Index	29	58	14	62	52	54
House ACH50*	2.40	2.91	0.86	2.31	1.48	2.55
Attic wrt Outdoor dP*** IWC (Pa)	-0.186 (-46.3)	-0.181 (-45.1)	-0.137 (-34.1)	-0.161 (-40.1)	-0.181 (-45.0)	-0.171 (-42.6)

* House total tightness with attic hatch closed; test volume based on house conditioned volume.
** Attic with reference to outdoor differential pressure with attic hatch closed while house at – 50 Pa wrt out.

Sensor Instrumentation

Moisture levels were evaluated from measurements of roof deck WMC as well as indoor, outdoor, and attic temperature and relative humidity. WMC, temperature, and RH sensors were located on the underside of north facing roof decks at the peak and at a lower, north facing deck surface elevation near middle attic height during the first year. The first year of monitoring found that the sensors located at roof peak had higher moisture levels than the roof location below it. It was also discovered that the first year method of not sealing the plug seams back into place with canned spray foam had made the test section a little more vapor permeable than undisturbed foam. Therefore, additional monitoring was conducted for two more years with test plugs sealed back in place with canned foam. Since roof peak locations had higher moisture content, the next two years continued monitoring at the roof peak at two locations, and did not continue monitoring the lower roof deck location. One of the peak locations was can foam sealed and the other was not.

Indoor temperature and RH were measured in reasonably close proximity to the thermostat on both floors if home was two-story. Outdoor conditions were measured in shaded location under a covered patio or porch. The attic air temperature and RH were measured in attic air space at about same vertical elevation as the WMC sensors: peak attic height and mid-attic height.

The accuracy of temperature was +/- 0.5°F (0.3°C), and that of relative humidity was +/- 2% RH. The manufacturer of WMC sensors made no claim of accuracy so these sensors were compared to another meter. The handheld moisture meter had a stated accuracy of 1% for moisture between 12%-20% WMC and 2% for saturated wood between 20%-30% WMC. Handheld readings of different sites were within 2% WMC agreement with installed WMC sensors.

RESULTS

Roof Deck Wood Moisture Content

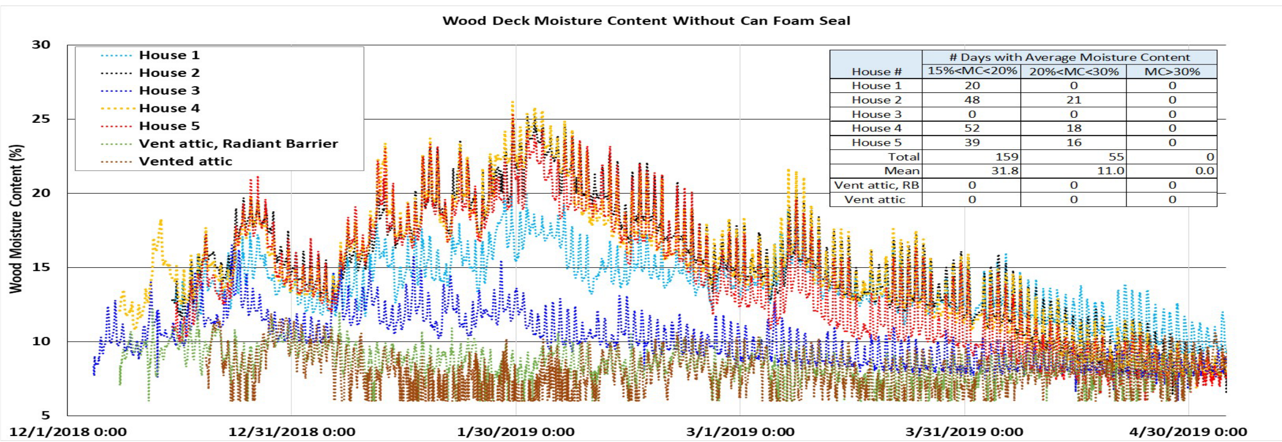
Wood moisture content data was sampled on hourly intervals in six unvented attic homes during the first year of monitoring. In subsequent years, data collection in house 6 was not continued and instead began in two homes with conventional vented attics with ceiling insulation to serve as experimental controls. House 6 had the second lowest WMC during year 1 with no days having roof moisture exceed 15% WMC. The two vented attics had light-colored composite shingle roofs. One of the vented attics had OSB roof deck and the other had an OSB deck with radiant barrier adhered to the bottom of the wood panel by the manufacturer. Both vented attic homes had three occupants, were between 2,200 ft^2 to 3,200 ft^2 (204 m^2 to 297 m^2) and had two stories.

During the first year, all foam plugs were carefully placed back over sensors, but without can foamed seam seals, which was later discovered to result in elevated roof WMC. All homes reach 20% WMC or greater during cool weather periods, however, all homes demonstrated substantial drying during the spring and summer period that followed. Roof deck moisture dropped to below 15% WMC by April and below 10% WMC by May.

Impact of Unsealed Foam Test Plug Seams

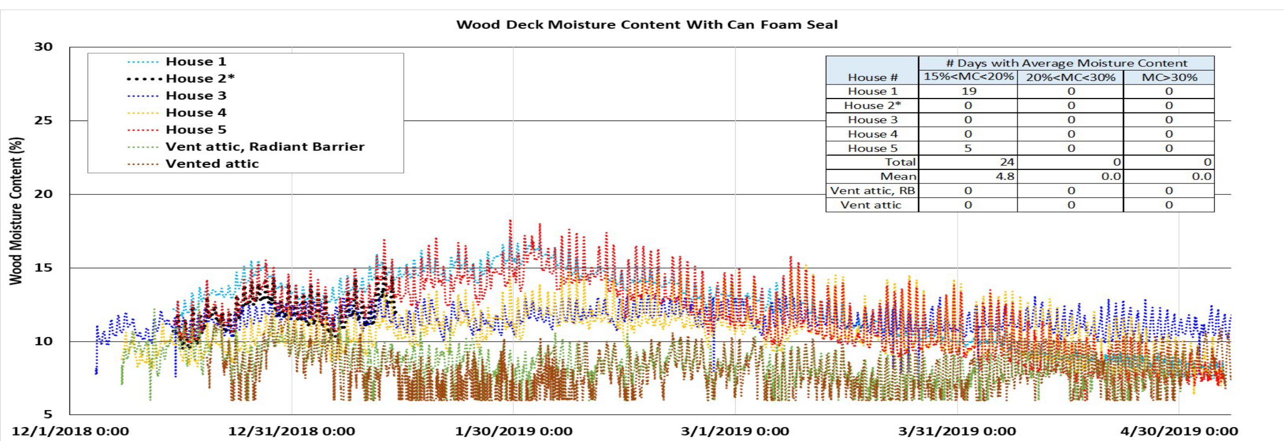
The impact of not sealing the spray foam plugs removed for monitoring of deck conditions with can foam was evaluated in years 2 and 3.Unsealed seams of the foam test sections may have increased potential for excess moisture movement by vapor diffusion and air movement. Two different test sections were monitored at the same time in each unvented attic during years 2 and 3. The test sections were located next to the peak on a north facing roof slope and were within four to six feet (1.2 m to 1.8 m) of each other. Figure 1 shows data for homes during year 2 without foam seals and Figure 2 shows data for homes during year 2 with can foam sealed plugs. The same monitoring continued through year 3.

The number of days with WMC measured within three different ranges was determined for each monitoring period. Daily average WMC was evaluated for levels between 15% to 20% WMC (elevated to high moisture), 20% to 30% WMC (high moisture), and > 30% WMC (wet). The data for year 2 are summarized in the tables within Figure 1 and Figure 2. The data demonstrated a notable increase in elevated WMC in roof deck where ocSPF plug seams were not re-sealed with spray foam after sensor installations. Due to sensor failure, data was lost for House 1 and House 2 during year 3, therefore, the mean number of days at the three levels was used to compare sealed versus unsealed test plugs. There were no days with WMC 20% or greater when foam seams were sealed with can foam during years 2 and 3. The non-sealed seam test sections over years 2 and 3 measured an average of 29 more days with WMC between 15% to 20%. The mean increase of 29 more days represented a difference of 675%. This demonstrates the importance of maintaining the integrity and continuity of the ocSPF during and long after application.



House #	# Days with Average Moisture Content 15%<MC<20%	20%<MC<30%	MC>30%
House 1	20	0	0
House 2	48	21	0
House 3	0	0	0
House 4	52	18	0
House 5	39	16	0
Total	159	55	0
Mean	31.8	11.0	0.0
Vent attic, RB	0	0	0
Vent attic	0	0	0

Figure 1 Roof deck WMC without can foam seal during year 2.



House #	# Days with Average Moisture Content 15%<MC<20%	20%<MC<30%	MC>30%
House 1	19	0	0
House 2*	0	0	0
House 3	0	0	0
House 4	0	0	0
House 5	5	0	0
Total	24	0	0
Mean	4.8	0.0	0.0
Vent attic, RB	0	0	0
Vent attic	0	0	0

Figure 2 Roof deck WMC with can foam seal during year 2.   *No data available for House 2 after mid-January.

Additional Observations of Roof Deck WMC

Since the roof test sections having foam seams sealed are better representative of undisturbed ocSPF application, only the deck data from such sections obtained during years 2 and 3 are considered for further moisture management evaluation. The hourly roof WMC of the two vented attics never exceeded 15% WMC over two years of monitoring. Roof deck WMC in both vented attics remained substantially lower than unvented attics during cool weather and demonstrated good moisture control as expected. The vented attic with radiant barrier had higher WMC than the vented attic with no barrier, but this was only a few percent WMC more during cold weather.

House 1 and House 5 demonstrated the highest roof WMC on average particularly during cold weather. There was no specific house characteristic known that explains this. House 1 had a little higher occupancy which may have contributed to greater interior moisture generation compared to other homes. Besides internal moisture generation, house mechanical ventilation may be another factor. Every home had a central fan integrated supply ventilation available, however it is not known if the systems were utilized and if so, how much. Past studies have shown that ventilation systems are often not utilized as intended for various reasons (Eklund et al. 2014), (Sonne et al. 2016), (Martin et al. 2020). House 3 had the lowest roof moisture during years 1 and 2. This house had OSB roof deck sheathing with water resistive barrier (WRB) integrated onto OSB and taped panel seams. House 3 also had a light colored metal roof, whereas all other homes had shingle roofs and typical OSB installation. House 4 had lower WMC than the other unvented attics during year 3.

Figure 3 and Figure 4 show box and whisker plots of hourly WMC of roof decks during the second year for the three cooler months and three warmer months respectively. The highlighted box denotes the upper and lower quartiles. The horizontal line between them indicates the median and "X" marks the mean. Data was not available for House 2 at the sealed foam test section after January 2019, so the distribution shown for House 2 only includes two months. Houses 1 and 5 demonstrated the highest upper levels and highest mean of WMC during the coldest three months of year 2. The vented attic WMC were clearly lower than unvented attics. Figure 4 shows the mean WMC decreased for all homes as the prevailing weather became warmer and the mean WMC of the unvented attics decreased to values closer to the WMC of the vented attics.

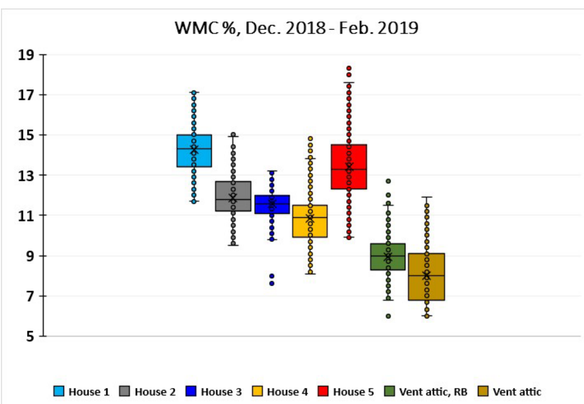


Figure 3 WMC during colder period of Year 2.

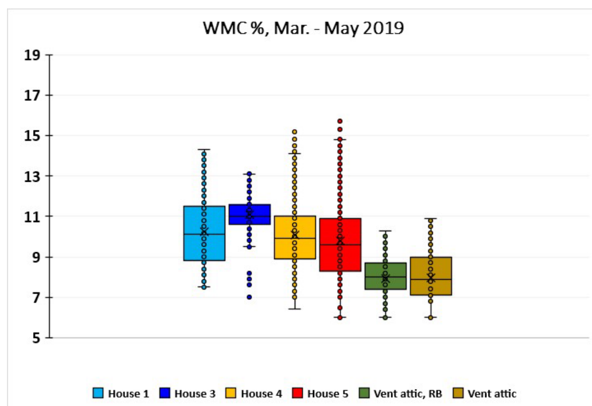


Figure 4 WMC during the warming period of Year 2.

Dewpoint temperature and relative humidity were used to evaluate air moisture levels at indoor, outdoor and attic locations. Dewpoint is a relative indicator of the absolute moisture in air with higher dewpoints having more moisture than lower dewpoints. It also indicates the surface temperature at which condensation would occur. Figure 5 shows the average dewpoint over a few cool months for five unvented attic homes during the second year of monitoring. The average dewpoint of all five is also shown. The attic air dewpoints were measured at the peak below the foam insulation (not at the roof deck) and at about mid-attic height. This data shows indoor and attic moisture levels were higher than outdoors, a condition common during winter. There was not much difference between indoor and attic dewpoints, however on average, there was a trend for dewpoint to increase with elevation from indoor, to mid attic, and to near the attic peak. House 1 and 5 had higher indoor and attic air dewpoints than the average. These two homes also tended to have higher WMC levels than the other homes during cool periods. The cause for elevated indoor moisture is not known, but may be related to differences in occupancy or mechanical ventilation rates. The average relative humidity is shown in Figure 6. This shows that indoor RH was a little elevated, but acceptable on average running near 60%. Similar to dewpoint, the RH trend increased with elevation from indoor, to mid attic, and attic peak.

The greatest WMC occurred when the daily average roof deck was coldest for sustained periods. Figure 7 shows an example of the seasonal transition of higher to lower WMC for House 5 using hourly sampled data over the course of four months. Just as the WMC decreases seasonally from winter to summer, the hourly data also shows daily trends of WMC decreasing during solar heating of the roof. The solar heating of the roof deck results in a sudden drop in deck surface RH at which point the WMC begins dropping. Once the deck begins to cool overnight the RH increases and WMC increases.

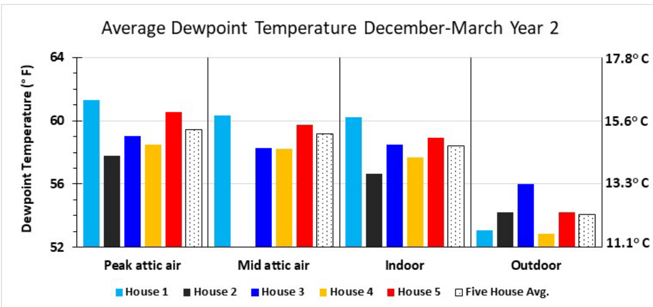


Figure 5 Dewpoint in attic, indoors and outdoors

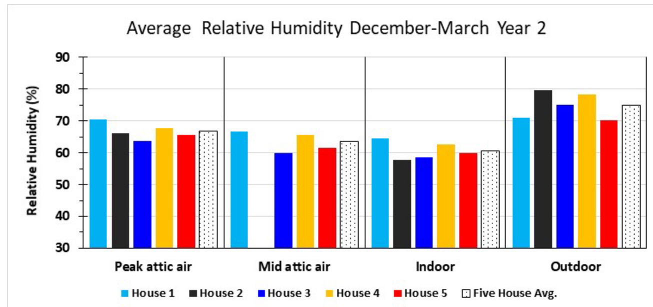


Figure 6 RH in attic, indoors and outdoors

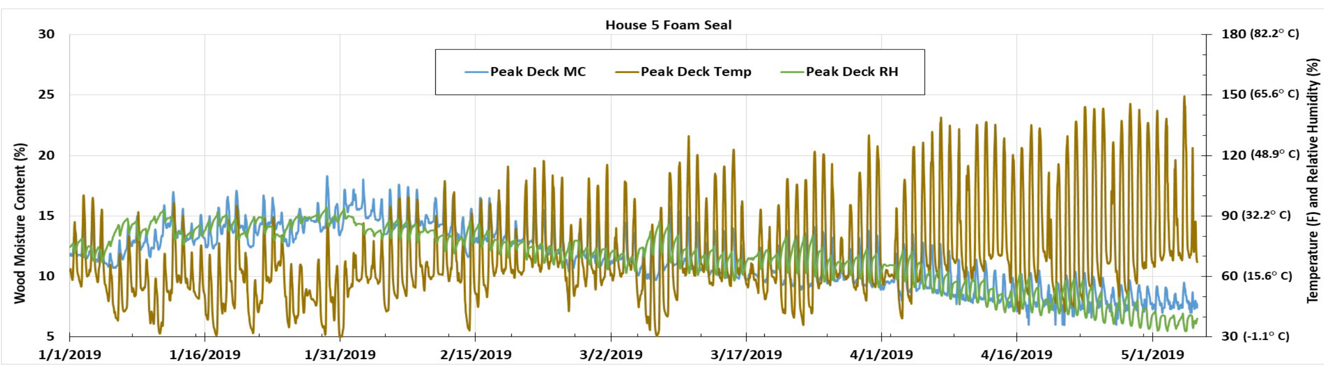


Figure 7 Roof deck conditions show WMC decreases from winter to summer as deck becomes hotter.

Implications of Roof Type and Roof Deck WMC

The metal roof of House 3 clearly demonstrated lower deck WMC during all three years of monitoring compared to the other five homes with asphalt shingles during cold weather. This light color painted metal roof had a lower solar absorbtion and emissivity than the asphalt shingles, which resulted in less deck temperature variation. Interior and outdoor moisture content differences among houses did not provide strong differences in WMC. For instance, House 3 had indoor and attic peak dewpoint higher than House 2 and House 4 (Figure 5), but lower WMC. Figure 5 also shows that House 3 outdoor dewpoint was higher than other homes by a few degrees. Higher outdoor moisture would increase potential moisture gain during summer. In the winter, indoor moisture tends to be higher than outdoors and higher indoor moisture content would increase potential moisture gain. The average interior RH shown in Figure 6 also shows very little difference among five homes.

Comparison of a home with shingle roof to a metal roof during periods of similar cold days helps to explain why the metal roof has a drier wood deck based on WMC. Figure 8 demonstrates the daily variation of deck conditions along with outdoor temperature and the attic air moisture in House 1 having an asphalt shingle. Figure 9 demonstrates the same for the metal roof of House 3. There is a similar daily trend for both homes where as the wood deck heats up, the deck surface RH drops and the WMC decreases. Then as the deck cools overnight, RH increases, and WMC increases. The WMC peak timing depends on roof composition. These processes repeat daily in unvented attics and have been previously described in greater detail provided by (Lstiburek 2016) and (Forest Products Laboratory 2010).

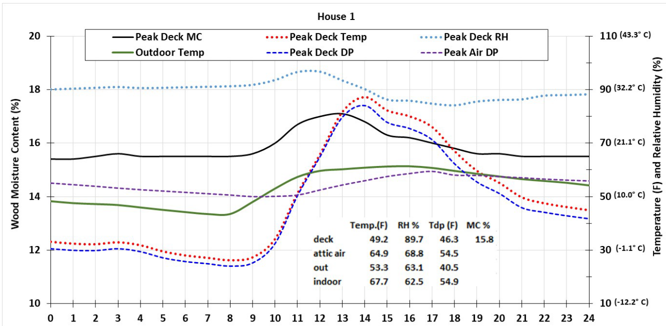


Figure 8 Attic deck, attic and outdoor air temperatures shown with deck WMC during cool period for house with asphalt shingle roof.

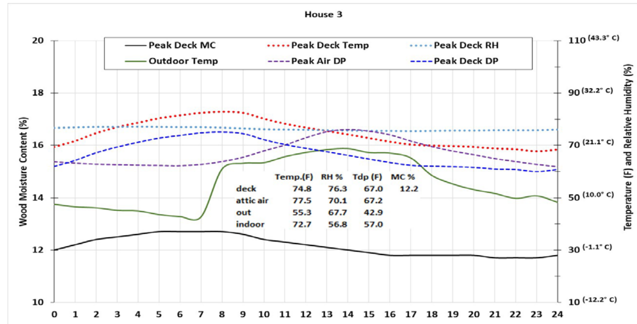


Figure 9 Attic deck, attic and outdoor air temperatures shown with deck WMC during cool period for house with metal roof.

The periods shown for each roof type have relatively similar outdoor daily low outdoor temperatures averaging near 45°F (7.2°C). While the peak deck temperatures of House 1 and House 3 were similar, it is clear that the asphalt shingle roof cooled down about 26°F (14.4°C) less than the metal roof overnight. The WMC of the shingle roof averaged 3.6% WMC greater than the metal roof. This comparison is not adequate to be representive of shingle vs metal roofs in general, but it does demonstrate the importance to consider different types of roofs in future studies since past studies largly focused on shingle roofs.

The average conditions shown in the inserted tables on Figure 8 and Figure 9 show that, although House 3 had more absolute moisture available in outdoor, indoor and attic air, the much warmer House 3 deck temperature resulted in lower deck surface RH and lower WMC compared to the shingle roof of House 1. One other factor to be considered in potential moisture impacts is that House 3 had attic leakage to outdoors (based upon leak flow to out / area attic floor) that was 50% greater than the other five unvented houses. During cold periods, the air is drier than indoors and higher ventilation rate in attic would decrease attic air moisture. Based on the average dewpoint temperatures observed, it does not appear that attic ventilation due to leakage is high enough to reduce attic moisture significantly. The exact emissivity and solar reflectance of the houses in this study are not known. The light color metal roof is most likely to have a higher solar reflectance and lower emissivity compared to asphalt shingles. This would result in a cooler sunlit surface and warmer overnight surface compared to asphalt shingles as demonstrated in Figure 8 and Figure 9.

CONCLUSION

This study has presented data collected over three years in newer unvented attic homes. The data presented here demonstrated that wood roof deck WMC was reasonably managed when ocSPF was properly installed on the underside of the deck in six unvented attic homes located in the northern parts of Climate Zone 2A. Some of the highest WMC levels were observed during the first year, due to inadequate sealing of reinstalled foam sections over roof deck sensors. The inadequately sealed foam seams resulted in higher moisture permeability through the foam and higher resulting WMC during cold weather in most homes. This illustrates the importance of maintaining the ocSPF over the life of the application and importance of a post-inspection of the foam any time after a contractor has performed work within the attic.

Various influences on roof WMC were investigated and found that seasonal outdoor temperature had the greatest influence. While there were daily trends of moisture into and out of the roof assembly in all homes, the greatest change in roof deck WMC occurred between the coldest and warmest seasons. The WMC was at its highest levels (between 15% - 20% WMC) during the colder periods when there was also less direct solar radiation. The WMC dropped to less than 15% WMC by March and remained between 10%- 15% WMC until the next winter. Roof WMC data was also collected from two different vented attic homes for comparison. The daily average moisture content of the vented attic roof decks rarely exceeded 10% WMC through all seasons.

This study found that one home with a metal roof had consistently lower WMC with minimal seasonal variation compared to asphalt composite shingle roofs. Five homes had composite shingles and one home had a painted metal roof. All roof materials were placed directly on top of OSB wood roof decks. During similar cold weather days, the hourly low point temperatures of a shingle roof deck averaged about 26°F (14.4°C) colder than the metal roof deck. The WMC of the shingle roof averaged 3.6% WMC greater than the metal roof.

This study was conducted in Climate Zone 2A and showed an increase in WMC in roof sheathing as the weather becomes colder. The IRC 2021 permits the same construction practice in Climate Zones1-3. Given that Climate Zone 3 has longer continuous periods of cold weather than zones 1 and 2, it is reasonable to expect higher WMC in Climate Zone 3 during cold weather. While this study does not substantiate that roof deck WMC in zone 3 is problematic, future study of WMC in unvented attics having ocSPF on the roof deck would help determine if future IRC modification is needed.

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REFERENCES

ANSI/RESNET/ACCA 310-2020. 2020. *Standard for Grading the Installation of HVAC Systems*. Residential Energy Services Network, Inc. Oceanside, CA. June 23, 2020.

APA – The Engineered Wood Association. 1999. *Moisture Control in Low Slope Roofs*. Engineered Wood Systems APA, Tacoma, Washington. EWS R525B, January 1999.

APA – The Engineered Wood Association. *Water Vapor Permeance of Wood Structural Panels and Wood Wall Construction*. Engineered Wood Systems APA, Tacoma, Washington. J450, February 2009.

Eklund, K., Kunkle, R., Banks, A., and D. Hales. 2014. *Ventilation Effectiveness Study Final Report*. Portland, OR. Northwest Energy Efficiency Alliance.

Forest Products Laboratory. 2010. "Wood handbook—Wood as an engineering material." General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

ICC. 2021 International Residential Code for One- and Two-Family Dwellings. International Code Council, Country Club Hills IL. November 2021.

Lstiburek, J. 2016. *Ping Pong Water and the Chemical Engineer*. Building Science Insights BSI-016. Building Science Corporation. October 2016.

Martin, E., T. Khan, D. Chasar, J. Sonne, S. Rosenberg, C. Antonopoulos, C. Metzger, W.R. Chan, B. Singer, and M. Lubliner. 2020. Characterization of Mechanical Ventilation Systems in New US Homes: What types of systems are out there and are they functioning as intended? *Proceedings of Summer Study on Energy Efficiency in Buildings*. Pacific Grove, CA.

Martin, E. and C. Withers. 2021. *Survey of Unvented Attics in Climate Zone 2A*. Final Report FSEC-CR-2106-21. FSEC Energy Research Center, Cocoa, FL.

Prevatt, D., A. Viswanathan, W. Miller, P. Boudreax, S. Pallin, and R. Jackson. 2017. 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

Sonne, J., C. Withers, and R. Vieira. 2016. Are Residential Whole-House Mechanical Ventilation Systems Reliable Enough to Mandate Tight Homes? *Proceedings of ASHRAE and AIVC IAQ* Alexandria, VA.

Ueno, K. and J. Lstiburek. 2016. Monitoring of Two Unvented Roofs with Air-Permeable Insulation in Climate Zone 2A. *Proceedings of Thermal Performance of the Exterior Envelopes of Whole Buildings XIII International Conference*. Clearwater, FL.