André Desjarlais[1], *Helene Hardy Pierce*[2], *Simon Pallin*[1]

Using Hygrothermal Modeling to Resolve Practical Low-slope Roofing Issues

ABSTRACT: Within building envelope science, the use of tools to model performance of the building envelope has evolved and designers and scientists today have a myriad of tools available. Hygrothermal modeling is one such tool and when used correctly, offers designers and forensic investigators important information about the movement of moisture within the building envelope. This traditional use of hygrothermal modeling is maturing as models are validated with field experience, creating a confidence in the modeling tools and their predictive capabilities. Based on this confidence, application of hygrothermal modeling to a more practical application is an evolution whose time has arrived. With changes in materials and methods, the performance of roofing systems can often times no longer be based on experience alone and roofing contractors have been confounded by the unexplained and unplanned for presence of moisture in roofing systems. While hygrothermal modeling can be used to explain where the moisture came from, we propose that it should be used to prevent its occurrence. Unfortunately, over 70% of the roofing market is in reroofing and oftentimes, a designer is not engaged in the roofing system design. Without the expertise of a designer and given that hygrothermal modeling is not well understood by the roofing industry, its adoption as a tool that can prevent problems has not been widely seen. This paper presents an extensive summary of hygrothermal modeling performed for roofing systems and then show how the modeling can be used to create simple resources for roofing contractors to reduce the potential for moisture condensation at critical locations within the roofing system. The systems modeled have shown a propensity for moisture accumulation and the use of hygrothermal modeling to eliminate these problems is a practical application of a building science tool that can greatly improve the durability of roofing systems.

KEYWORDS: hygrothermal modeling, roofing systems, WUFI

[1] Oak Ridge National Laboratory, Oak Ridge, TN
[2] GAF, 1 Campus Drive, Parsippany, NJ 07054, e-mail: hpierce@gaf.com

Introduction and Background

Roofing systems, particularly in the western part of the United States, are often installed directly to a wood deck, with the building's insulation below the deck. This construction assembly has a long track record of performance and generally has been used without consequence with traditional built-up roof systems. In recent years, there has been an increase in anecdotal instances of wood deck deterioration being discovered in a relatively short period of time after a roofing system has been installed.

Investigations into these occurrences have generally concluded that interior moisture is condensing on the wood deck and causing rot. Hygrothermal modeling of specific roofing systems has confirmed these conclusions[1]. These failures are not being caused by roofing system leaks, but by the movement of moisture through the insulation and into the deck and roofing assembly. Unfortunately, these types of failures are becoming more common as the roofing industry, driven by a variety of influences including regulatory mandates, moves from traditional built-up roofing systems in these markets to reflective membranes, either white or highly reflective "cool"-colored single-ply membranes or white reflective cap sheets. The application of reflective coating can also result in this type of failure.

Review of the current literature on this phenomenon provides little practical guidance for the roofing professional. While hygrothermal analysis has provided answers *post mortem* it has not been used in a large study to further the body of work that would help roofing professionals given a set of different variables. Based on the need for some practical guidelines, a research project was initiated with Oak Ridge National Laboratory's (ORNL) Building Envelope Systems Research Group to model the potential for wood deck deterioration under a variety of conditions and to provide guidelines for the amount of insulation that could be installed over a wood deck to reduce this risk.

This modeling took into consideration:

- Six different geographic locations representing the climates of the most populous areas on the West Coast and two other geographic locations representing both a cold climate in the Midwest and a mild climate in the Southeast portion of the United States.
- Four different levels of interior moisture loads from a low relative humidity to a high relative humidity in compliance with ASHRAE 160 2011[2]
- Two different rafter depths (8 and10 in.) that are in common use
- Two different common wood deck types: plywood and oriented strand board (OSB)
- Three different levels of below-deck fiberglass insulation thickness (R-11 to R-30) to represent reroofing situations where lower insulation values may be present to higher insulation values more in compliance with current energy codes.

- Two different roofing membranes (one white and one black) to simulate going from a non-reflective to a reflective California Energy Commission Title 24-compliant membrane.

Using the hygrothermal calculation tool of WUFI (Künzel, 1995)[3], a total of 320 different (simulations based on the above parameters were performed.

Wood Decks: Simulations and the Definition of Failure

WUFI performs one-dimensional transient hygrothermal calculations to evaluate the long-term energy and moisture performances and durability of building envelopes, including roofs. WUFI has been successfully validated repeatedly over the past two decades (Kehrer and Schmidt 2008)[4] and has a large database of material properties and exterior climates from all U.S. climate zones.

For the purposes of this portion of the study, the moisture content of the wood deck material was the basis of defining "failure." The 2013 *ASHRAE Handbook of Fundamentals* (ASHRAE, 2013)[5] states that decay in wood decks typically requires over 30% moisture saturation; so for the simulations, "failure" was any set of parameters that resulted in over 30% moisture in the deck in years two to three of the simulation. In addition, those sets of parameters that resulted in 20-30% moisture in the deck were defined as "risky". These criteria are summarized in *Table 1*. When performing hygrothermal modeling, a three-year simulation period is typically performed. The logic behind this selection is the moisture content data for the first year can be impacted by the assumed initial moisture contents of the roofing components. Comparing Years 2 and 3 will indicate whether the moisture contents of the roofing system components have exceeded threshold values or are increasing at a rate that will eventually lead to failure. While three years is a short period of time relative to the expected performance life of a roofing system, and some conditions could result in saturation of the wood deck in a longer time period, certainly the results presented that indicate failure or risk to the deck provide roofing professionals with those conditions where caution is necessary and steps to protect the roof deck are most probably warranted.

Table 1. Evaluation Criterion for the Simulation Results

Maximum Water Content in Second and Third Year of Simulation	Evaluation Result
Value ≤ 20%	"Pass"
20% < Value ≤ 30%	"Risk"
Value > 30%	"Failure"

Simulation Parameters

The sites used for this study were in the Western U.S, San Diego, Los Angeles, San Francisco, and Sacramento in California; Portland, OR; and Seattle, WA and then Chicago and Atlanta to provide reference to other Climate Zones and ambient conditions. As found in the results, the varying climates do have a significant effect on the moisture accumulation in wood decks.

As anticipated, the amount of below-deck insulation also was an important factor, because higher levels of insulation result in “colder” wood decks under winter/cooler temperature conditions, which are conducive to moisture condensation on the wood deck. Because the intent was to provide guidelines for additional insulation thickness above the deck in order to decrease the influence of the exterior climate, the amount of insulation below the deck is critical to the resultant guidelines. Three combinations of rafter dimension and cavity insulation were used for each simulated outdoor climate. A 2x8 rafter with R-11 cavity insulation, a 2x10 rafter with R-11 insulation, and a 2x10 rafter with R-19 insulation were used in the simulated cities of Climate Zone 3. San Francisco, Sacramento, Portland, and Seattle were instead simulated with a 2x8 rafter with R-19 cavity insulation; a 2x10 rafter with R-19 insulation; and, finally, a 2x10 rafter with R-30 insulation. For Atlanta and Chicago, a 2x10 rafter with R-25 and R-30 insulation, respectively, was modeled. The air cavities created in these constructions are assumed to be unventilated. Since the modeling tool is one-dimensional, all of the simulations are performed at the center of the cavity. Previous experience has shown that this location is most sensitive to hygrothermal damage since the wood studs add additional safe moisture storage.
Two different types of deck were used: plywood and oriented strand board (OSB) with a ½-inch thickness. The roof assemblies were designed with an exterior TPO membrane with varying solar radiation absorptivity in accordance with either a “cool” white color or a traditional dark surface. The solar absorptivity for the white and the dark TPO surface was set to 0.35 and 0.90 respectively (solar reflectances of 0.65 and 0.10 respectively) and are indicated in the results as “white” or “black” for simplicity.

The indoor air humidity was simulated under four different scenarios: with a low, medium, and high moisture load (WTA 2004)[6], and as an excess of moisture in compliance the ASHRAE standard(ASHRAE 160 2011).

In all assemblies, an appropriate air space was applied to fulfill the thermal insulation requirements. On the interior side of the roof, a ½-in. gypsum board with a 10-perm latex paint was applied. The roof assemblies were assumed to be air tight and constructed with satisfying workmanship, i.e., no water leakage due to membrane flaws was simulated.

Results

Comprehensive information about portions of this study and the simulations conducted has been published in *ORNL/TM Report 2013-551*[7]. The results from the simulations demonstrate that the more northern climates are more sensitive to the radiative properties of the membrane when exposed to high interior moisture loads. Comparison of the simulated annual variations between San Diego, CA, and Portland, OR, illustrates this result in *Figures 1* and *2*.

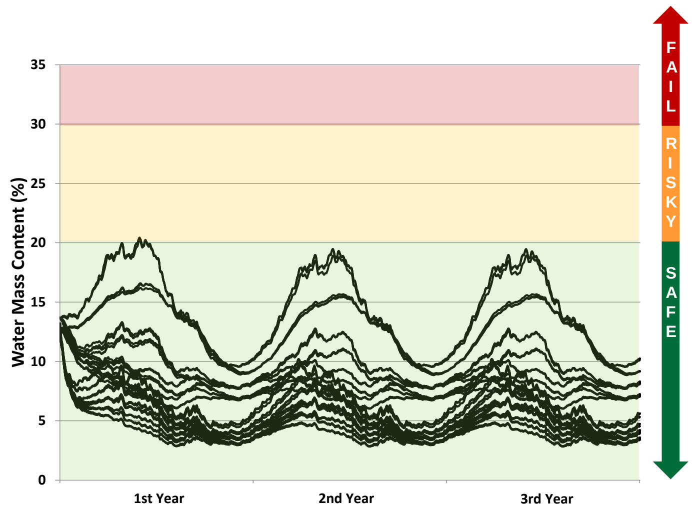

Fig. 1. Simulated annual variations of the moisture content in both the OSB and the plywood decks in the climate of San Diego.

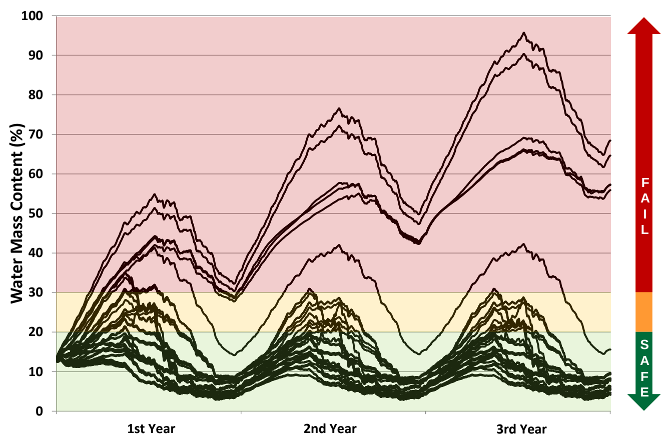

Fig. 2. Simulated annual variations of the moisture content in both the OSB and the plywood decks in the climate of San Diego.

Based on these results, it is clear that the level of indoor moisture plays a significant role in the level of moisture that can accumulate in the deck. This is graphically seen when the results are summarized for the highest indoor moisture generation level defined in ASHRAE 160 in Table 2.

Table 2. Summary of the evaluation of all the roof assemblies simulated with an excess of indoor moisture according to standard (ASHRAE 160 2011).

Indoor Humidity - ASHRAE 160												
Climate	**OSB**						**Plywood**					
	2x8		2x10		2x10		2x8		2x10		2x10	
	R-19 (R-11)[a]		R-19 (R-11)[a] (R-25)[b]		R-30 (R-19)[a]		R-19 (R-11)[a]		R-19 (R-11)[a] (R-25)[b]		R-30 (R-19)[a]	
	Black	**White**	**Black**	**White**	**Black**	**White**	**Black**	**White**	**Black**	**White**	**Black**	**White**
San Diego	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Los Angeles	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
San Francisco	OK	FAIL	OK	FAIL	OK	FAIL	OK	FAIL	OK	FAIL	OK	FAIL
Sacramento	OK	FAIL	OK	FAIL	OK	FAIL	RISK	FAIL	OK	FAIL	OK	FAIL
Portland	RISK	FAIL	RISK	FAIL	RISK	FAIL	RISK	FAIL	RISK	FAIL	RISK	FAIL
Seattle	RISK	FAIL	FAIL	FAIL	FAIL	FAIL	RISK	FAIL	FAIL	FAIL	FAIL	FAIL
Atlanta			OK	OK					OK	OK		
Chicago					FAIL	FAIL					FAIL	FAIL

a. *R*-values for San Diego and Los Angeles.

b. *R*-values for Atlanta.

The Use of Insulation to Reduce Deterioration Risk

The intent of this research was to determine the potential for wood deck deterioration and then to provide guidelines for the amount of insulation R-value that could be installed over a wood deck to eliminate this risk for western coastal climates where this construction practice is employed. Therefore, additional simulations were performed to determine the amount of additional insulation necessary to reduce the moisture content of the wood deck after three years to a level below 20% for the excessive interior humidity level in ASHRAE 160. This additional insulation is placed above the wood deck in order to reduce the effect of the below-deck insulation on the deck's temperature in the hygrothermal modeling. *Table 3* summarizes these simulations.

Table 3. Required R-values of the insulation boards situated between the wood deck and surface membrane

Required insulation *R*-value at indoor humidity according to ASHRAE 160												
Climate	**OSB**						**Plywood**					
	2x8		2x10		2x10		2x8		2x10		2x10	
	R-19 (R-11)[a]		R-19 (R-11)[a] (R-25)[b]		R-30 (R-19)[a]		R-19 (R-11)[a]		R-19 (R-11)[a] (R-25)[b]		R-30 (R-19)[a]	
	Black	**White**	**Black**	**White**	**Black**	**White**	**Black**	**White**	**Black**	**White**	**Black**	**White**
San Diego	-	-	-	-	-	-	-	-	-	-	-	-
Los Angeles	-	-	-	-	-	-	-	-	-	-	-	-
San Francisco	-	R-9	-	R-9	-	R-12	-	R-9	-	R-9	-	R-15
Sacramento	-	R-6	-	R-6	-	R-6	R-3	R-9	-	R-9	-	R-12
Portland	R-3	R-9	R-3	R-9	R-3	R-12	R-6	R-9	R-6	R-9	R-6	R-15
Seattle	R-3	R-9	R-3	R-9	R-3	R-9	R-6	R-9	R-6	R-9	R-9	R-15
Atlanta	NA	NA	-	-	NA	NA	NA	NA	-	-	NA	R-9
Chicago	NA	NA	NA	NA	R-12	R-15	NA	NA	NA	NA	NA	R-15

c. *R*-values for San Diego and Los Angeles.
d. *R*-values for Atlanta.

Because the simulations performed to determine how much additional R-value is needed to reduce the potential for deck deterioration was based on the highest level of interior moisture of the four levels included in the study, *Table 3* is also the most conservative of the results this type of simulation will generate for the input variables chosen in this study. Adding this level of insulation to the other failed scenarios caused by lower interior moisture content levels would mitigate their problems as well.

Beyond Wood Decks

Understanding how to avoid problems with moisture accumulation within the roofing system causally deteriorating wood decks is typically more important in the Western part of the United States. There are many more instances of unexplained and unplanned instances of moisture in roofing systems regardless of deck type that is not caused by the location of insulation below deck as typical in wood deck construction. Other than with wood decks, roofing construction typically is comprised of a deck, above deck insulation, and a roofing membrane. Traditionally with this configuration, moisture accumulation in the roofing system from interior humidity conditions is most often effectively handled by a vapor retarder, however, hygrothermal modeling can be used to predict when conditions are favorable for moisture accumulation to occur. With insulation placed above the deck in combination with a mechanically attached membrane, it was hypothesized that air leakage would be critical to creating conditions that would most likely result in moisture accumulation.

Based on the results of the wood deck modeling, work was undertaken to model the effects of air leakage, membrane color, interior humidity, and geographic location on the propensity for moisture accumulation in the form of condensation on the underside of the membrane. Assumptions for this modeling included use of a steel deck with two layers of insulation installed over the deck and a mechanically attached single ply membrane. The cities used for this part of the study were Baltimore (DOE Climate Zone 4), Chicago (DOE Climate Zone 5), Minneapolis (DOE Climate Zone 6), and Fargo (DOE Climate Zone 7).

Steel Decks: Simulations and the Definition of Failure

For the purposes of this part of the study, the collection of moisture on the underside of the roofing membrane was the basis of defining “failure”.

The simulation parameters included two layers of insulation with a total R-value of 25 and air leakage at 50 Pa varied to represent installation of the roofing system with increasing levels of air leakage due to both the installation itself (tightly butted insulation vs. insulation with excessive gaps) and the type of roofing membrane. Air leakage rates were based upon a series of roof system air permeance experiments performed in accordance with ASTM E2178, Standard Test Method for Air Permeance of Building Materials where an increasing number of gaps and penetrations were introduced into the test roof assembly to simulate insulation misfit or shrinkage, burn holes in the deck, and fastener penetrations. As noted above, the other parameters included increasing the level of interior humidity, geographic location, and membrane color. The inclusion of membrane color in this portion of the study was also important due to the anecdotal association given to white membranes and condensation in more traditional roofing system configurations.

For the purposes of this study, the amount of moisture that accumulated under the membrane was the basis of defining “failure.” The German Standard DIN 4108-3, Thermal protection and energy economy in buildings - Part 3: Protection against moisture subject to climate conditions - Requirements and directions for design and construction was used to set these guidelines. The standard states that if moisture accumulation is less than 0.5mm or 0.02 inches, there is little likelihood of a moisture related problem. Moisture accumulation levels between 0.5 and 1.0mm

(0.02 and 0.04 inches) can be viewed as potentially dangerous and therefore ae deemed “risky”. Above 1.0mm or 0.04 inches, there is a good chance that the roof system will have moisture related problems and these systems were assumed to fail. Table 4 summarizes the evaluation criteria.

Table 4. Evaluation Criterion for the Simulation Results

Maximum Thickness of Water under the Membrane	Evaluation Result
Value ≤ 0.5mm (0.02 in.)	“Pass”
0.5mm (0.02 in.)< Value ≤ 1.0mm (0.04 in.)	“Risk”
Value > 1mm (0.04 in.)	“Failure”

Results

The hygrothermal modeling performed for metal decks with insulation located above the deck and covered by a mechanically attached single-ply membrane is summarized in Table 5.

Table 5. Required R-values of the insulation boards situated between the wood deck and surface membrane

Climate Zone - 4								
Indoor moisture supply	Q_{50} = 0.27		Q_{50} = 0.56		Q_{50} = 1.0		Q_{50} = 2.0	
ASHRAE - Low	B	W	B	W	B	W	B	W
EN - Normal	B	W	B	W	B	W	B	W
EN - High	B	W	B	W	B	W	B	W
ASHRAE - High	B	W	B	W	B	W	B	W
Climate Zone - 5								
Indoor moisture supply	Q_{50} = 0.27		Q_{50} = 0.56		Q_{50} = 1.0		Q_{50} = 2.0	
ASHRAE - Low	B	W	B	W	B	W	B	W
EN - Normal	B	W	B	W	B	W	B	W
EN - High	B	W	B	W	B	W	B	W
ASHRAE - High	B	W	B	W	B	W	B	W
Climate Zone - 6								
Indoor moisture supply	Q_{50} = 0.27		Q_{50} = 0.56		Q_{50} = 1.0		Q_{50} = 2.0	
ASHRAE - Low	B	W	B	W	B	W	B	W
EN - Normal	B	W	B	W	B	W	B	W
EN - High	B	W	B	W	B	W	B	W
ASHRAE - High	B	W	B	W	B	W	B	W
Climate Zone - 7								
Indoor moisture supply	Q_{50} = 0.27		Q_{50} = 0.56		Q_{50} = 1.0		Q_{50} = 2.0	
ASHRAE - Low	B	W	B	W	B	W	B	W
EN - Normal	B	W	B	W	B	W	B	W
EN - High	B	W	B	W	B	W	B	W
ASHRAE - High	B	W	B	W	B	W	B	W

As noted, the cities modelled are Baltimore (Zone 4), Chicago (Zone 5), Minneapolis (Zone 6) and Fargo (Zone 7). Data is depicted that shows the impact of indoor moisture supply (the rows), air intrusion through the roofing system (the columns), and roof color (more columns). Data clearly shows that air intrusion is the biggest culprit when it comes to moisture accumulation in these roofing systems followed by moisture supply and then color. The colder, the more prevalent the problem.

Discussion and Conclusions

With regard to wood decks, the results of this study indicate that the moisture content of wood decks can be expected to vary greatly under different conditions, with the most influential of conditions being the location of the building (climate) and the interior moisture content. While there has been a significant number of anecdotal claims that the radiative properties of a roofing membrane (e.g., highly reflective) is the single-source cause of wood deck deterioration in the western part of the United States, this study clearly shows that that is not a factually based claim. However, the more reflective a roofing membrane, the higher the risk for moisture accumulation and deck failure when there is higher interior moisture.

With regard to steel decks and other deck types with insulation placed above the deck, air intrusion/ air leakage is the greatest contributor to moisture accumulation in a roofing system, and the potential for roofing system failure as defined herein increases in more northern climates. This study clearly shows that, like with wood decks, anecdotal claims the radiative properties of the roofing membrane is the single source cause of moisture problems in mechanically attached single ply systems are ill-founded.

When not caused by a roof leak, the propensity for water to accumulate in a roof system and/or the deck is the result of moisture movement via vapor drive from the building interior. In its simplest form, this is explained by the movement of water vapor from the interior up through the vapor-permeable insulation and into the deck when the exterior temperature falls, (e.g., at nighttime and during the colder months of the year). This movement is then reversed when the exterior temperature rises, driving the moisture back into the interior of the building. Understanding that interior water vapor “seeks the cold” explains this movement and also explains why those variables/parameters that raise the temperature at the deck such as roof color can reduce the potential for moisture accumulation, as well as why a reduction in the level of interior relative humidity reduces the amount of moisture available to cause problems with the deck and roofing system.

While this study showed a low potential for interior moisture-related accumulation in mild climates such as San Diego and Atlanta, the potential for deck deterioration does exist in these climates with high interior humidity and different insulation/deck constructions. Likewise, in northern climates, even moderate levels of interior humidity can significantly affect the potential for moisture accumulation. Each location and circumstance should be evaluated for its own merit.

References

[1] Dregger, P. (2012). "'Cool" Roofs Cause Condensation — Fact or Fiction?" 2012 Internation Roof Coatings Conference, Baltimore, MD, IRC.

[2] ASHRAE 160 (2011). ANSI/ASHRAE Addendum A to Standard 160-2009 Criteria for Moisture-Control Design Analysis in Buildings. Atlanta, GA, American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

[3] Künzel, H. M. (1995). "Simultaneous Heat and Moisture Transport in Building Components—One- and Two-Dimensional Calculation Using Simple Parameters." Dissertation, University Stuttgart, IRB Verlag. University Stuttgart.

[4] Kehrer, M. and Schmidt, T. (2008). "Radiation Effects on Exterior Surfaces." *Proceedings of Nordic Symposium on Building Physics* 2008, Copenhagen.

[5] ASHRAE (2013). *Handbook Fundamentals* - Chapter 25 - Heat, Air and Moisture Control in Building Assemblies. Atlanta, GA, American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

[6] WTA (2004). *Simulation of Heat and Moisture Transfer*. Guideline 6-2-01/E. München, WTA-Publications.

[7] Pallin, S., Kehrer, M., and Desjarlais, A., ORNL/TM-2013/551 (2013), "Hyrothermal Performance of West Coast Wood Deck Roofing Systems."