Moisture Performance of Sealed Attics in Climate Zones 1 to 4

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ABSTRACT

Sealed (also called unvented) attics are insulated at the roof deck while the ceiling plane is uninsulated. Sealed attics are usually not directly conditioned, but instead the conditions float between indoor and outdoor temperature conditions. The moisture performance of sealed attics has been investigated using a whole house hygrothermal simulation model to understand the risks for high moisture content in the roof sheathing and for high humidity in the attic. The results have also been validated against field test data. The analyzed shingled roof decks have been insulated either with open-cell spray foam or air-permeable insulation (fibrous insulation). The concept of the air-permeable insulation to perform as the condensation-control layer is analyzed.

A parametric study was carried out varying attic air leakage both to the indoors and outdoors, water leakage to roof sheathing, vapor permeance of the insulation, as well as the indoor air-moisture loads and exterior climate. The results show that the sealed attic can experience elevated humidity at warm temperatures which can create favorable conditions for mold growth unless the attic is intentionally conditioned or via duct air leaks. The vapor permeance of the insulation layers (and if a vapor-retarding coating is present) was a key factor that controlled the moisture content of the roof sheathing together with the overall airtightness. The air impermeable but vapor permeable insulation was not sufficient alone to prevent condensation in the roof deck.

INTRODUCTION

Conventional attic construction involves providing insulation on the floor of the attic and ventilation of the attic space (vented attic) from the outside. When an air-distribution system is installed in the vented attic, any duct or air-handler leakage creates an energy penalty in addition to conduction and radiation losses. An alternative to conventional vented attics is an unvented attic (UVA) (also known as a sealed attic). Insulating the attic roof deck and blocking ventilation of the attic space to the outside moves the thermal boundary to the sheathing roof line. The air-distribution system is now located within a semiconditioned space, which one would expect increases its overall efficiency, durability, and maintainability. The sealed attic can be built as an UVA with insulation in direct contact with the roof deck or with a ventilated roof deck with an airtight interior layer in the attic side of the ventilation gap. The ventilated roof deck is not common in UVAs, but is an option for a cathedral ceiling. The cathedral ceiling is an over-conditioned living space, whereas the sealed attic is only indirectly conditioned (no ventilation or intentionally heating/cooling supplied to the attic).

The conventional vented attics and the sealed attics both have clearly defined pros and cons.

A house with a vented attic typically has lower conduction heat loss and heat gain through the ceiling due to thicker insulation deployed on less heat transfer area than a house with an UVA approach, but the HVAC systems in the attic can cause an energy penalty. In a house with an UVA the HVAC system in the attic is inside the thermal boundary. The typical construction practice to build UVAs deploys spray foam sprayed directly under the roof sheathing. The UVA has its thermal boundary at the roof deck, whereas the vented attic has the thermal boundary at the ceiling level. The application to install the insulation in direct contact with the roof deck (UVA) results in a higher temperature gradient across the insulation

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Table 1. Common Features of Conventional Attics and UVAs

Feature	Conventional Attic	UVA
Conduction Loss	Small insulated area (ceiling). Easy to install thick insulation at low cost. Typical insulation: blown fiberglass or cellulose.	Larger insulated area (sloped roof deck). High R-value may be difficult to achieve. Typical insulation: spray foam (open or closed cell).
Airtightness	Airtightness plane is at the ceiling.	Airtightness plane is at the roof deck.
HVAC in the Attic	HVAC and air-distribution system is outside of thermal boundary. System efficiency is reduced with exposure to attic (≈outdoor) conditions.	HVAC is within thermal and air boundary. Duct/AHU leakage exchanges air between the attic and the living space.
Moisture Control	Attic ventilation removes attic moisture from water intrusion or from indoor air leaks	Roof deck may have difficulties in drying from water intrusion. Attic temperature and humidity are not moderated.

layer during the peak hours than when the insulation is installed on the floor of the attic. The lower temperature gradient in the vented attic (and thus the lower heat flow) through the insulation is the result of attic ventilation and the thermal radiation exchanges. Therefore, the insulation layers in the two systems perform under different temperature gradients. Additionally vented attics typically have more insulation and higher R-value than the roof deck in the sealed attics. Table 1 summarizes the common features of conventional and UVAs.

While providing energy benefits by bringing ductwork into conditioned space, the moisture performance of the UVAs has risks that deserve a closer look.

UVAs can be built with many different design options. The current building code requires the use of air-impermeable insulation only, or it allows for a combination of air impermeable and air-permeable insulation (ICC 2012). If air-permeable insulation is used in the UVA, the design has to include a condensation-control layer. The goal is to raise the temperature of the cold-side inner surface (i.e., underside of the roof deck, or inner foam surface) sufficiently that condensation will not occur, if interior air comes in contact with that surface. This is done by using what is referred to as air-impermeable insulation, such as rigid foam board or spray foam. The building code further sets vapor retarder requirements in climate zones (CZ) 5 and above. The air-impermeable insulation must be a vapor retarder (class II) or a class II vapor retarder coating has to be applied on the interior surface of the insulation in CZs 5 and above.

The building code asks for air-impermeable insulation such as rigid foam board or spray foam to be used as a condensation-control layer in all climates zones with the exception of the dry CZs 2B and 3B (ICC 2012). The moisture performance of the vented attic and the sealed attic insulated with spray foam are briefly presented here. In addition to investigating the moisture content of the roof deck, this paper focuses on the importance of airtightness of the attic to outdoors.

MOISTURE PERFORMANCE SIMULATIONS OF THE ROOF DECK IN VENTED AND UVAS

The analyses for the hygrothermal performance of the attics have to focus not only in the roof deck and its moisture performance but also on the conditions of the air in the attic itself. Previous studies such as Lstiburek and Schumacher have exclusively focused on the condensation control of the roof deck (2011). The temperature and humidity of the air in the UVA is not controlled but it is rather floating between the outdoor and indoor conditions. The impact of moisture intrusion events into the attic, for example, may create conditions that could promote mold growth. Moisture can enter the attic by diffusion through the roof deck, water leaks through the roof or by air leaks from outdoors (especially hot and humid climates) or from indoors.

UVAs are often allowed to have less insulation than what is generally required by the local building energy codes for vented attics. The lower R-value may in some areas be allowed prescriptively or the lower R-value has to be justified by trade-off calculations. When the heating and cooling systems and ducts are brought inside the thermal and the air barrier control boundary in the building enclosure, energy savings can be expected when the air handler and the ducts are not leaking to the outside.

UVAs are typically insulated with spray foam applied directly under the roof sheathing. There are different types of spray-foam insulation and they are typically divided into two main groups: open cell and closed-cell spray foam. Other qualities of spray foam products exist, but these two are considered most common. In terms of thermal and moisture performance, the two foam types have four major differences in material properties:

1. Open-cell foam is light density (0.5 lb/ft^3 [8 kg/m^3]) and soft, closed-cell foam is more rigid and has higher density (2 lb/ft^3 [32 kg/m^3])
2. Open-cell foam has a lower R-value per inch (R-3.5/in. [RSI-20/25.4 mm]) than closed-cell foam (R-6/in. [RSI-34/25.4 mm])
3. Open-cell foam is vapor permeable (20–50 perm-in. [29–73 ng/smPa]), closed cell is vapor tight (1–2 perm-in. [1.46–2.92 ng/smPa])
4. In order to be an air barrier, 3.5–5.5 in. (89–140 mm) of open-cell foam and 1 in. of closed cell is typically needed to satisfy the air barrier material requirement 0.02 L/s·m^2 at 75 Pa (0.004 cfm/ft^2 at 0.3 in. H_2O) to be considered air-impermeable material per code.

Most spray foams today need a fire-retardant coating when left exposed to the attic. The intumescent coating is applied directly on the foam. The coatings are typically low in permeance with permeance less than 1 perm and act as a vapor retarder. In the southern climates open-cell spray foam is more commonly used than closed-cell spray foam.

The effect of the water vapor-permeability of the spray-foam insulation on the roof deck moisture contents was investigated in the simulations by using two different permeances for the spray foam: spray foam classified as open-cell foam with permeability 23 perm-in. (33.58 ng/smPa) and one open-cell foam with higher permeability 54 perm-in. (78.84 ng/smPa). The open-cell foam was additionally simulated with an intumescent coating. Furthermore, the necessity of the code requirement for the condensation-control layer (air-impermeable insulation with a specified R-value) was evaluated by calculating the UVA without the air-impermeable insulation and with highly vapor-permeable fiberglass insulation installed in place of spray foam.

Simulations were carried out in selected cities in four different IECC CZs (Table 2).

Codes and Standards

International Residential Code (IRC) chapter R806.5 "Unvented attic and unvented enclosed rafter assemblies" requires air-impermeable insulation (ASTM E2178: Flow rate <0.02 L/sm^2 at 75 Pa [<0.004 cfm/ft^2 at 0.3 in. H_2O]) to be used in direct contact with the roof sheathing when insulating under the roof sheathing (ICC 2012). If air-permeable insulation is used in this scenario, then the air-permeable insulation has to be supplemented with a condensation-control layer (air-impermeable insulation) either on top of or under the roof sheathing. Only CZs 2B and 3B (dry climates) with tile roof are exempt. The required R-value for condensation control depends on the climate. The intent is to keep the surface where condensation would likely occur above 45°F (7.2°C) (monthly average) during the cold winter months. This would prevent or limit condensation in the roof in homes with typical moisture loads.

METHODS

The moisture performance of the attic was simulated in two ways: first the roof sheathing moisture content was analyzed with a building enclosure simulation model, and second the attic humidity was investigated using a whole house simulation model.

Building and Attic Selection

A typical residential wood frame home with an attic and shingles as roof cladding was selected for the study.

Simulation Model Description

The models used for the moisture analysis were WUFI-Pro Karagiozis and Künzel (2001) and WUFI-Plus which are members of the WUFI software family developed jointly by the Fraunhofer Institute for Building Physics and Oak Ridge National Laboratory. The North American versions of the software WUFI-Pro 5.1 is a one-dimensional hygrothermal (heat, air and moisture) simulation model which allows for realistic calculation of the transient coupled heat and moisture transport in multilayer building components exposed to natural weather. WUFI-Plus allows for modeling a whole building with the full interaction between the building enclosure parts and the indoor climate.

Table 2. CZs, Locations, and Applied R-Values of Roof Insulation

CZ	City, State	IECC 2012 R-Value	Modified R-Value for UVA Simulations
1	Miami, FL	R-30	R-21
2	New Orleans, LA Houston, TX	R-38	R-21
3	Atlanta, GA	R-38	R-21
4	Knoxville, TN	R-49	R-21
4	Baltimore, MD	R-49	R-21

Table 3. Minimum R-Values of Air-Permeable Insulation in UVAs (ICC 2012, Table R806.5)

CZ	Minimum Rigid Board or Air-Permeable Insulation R-value
2B and 3B tile roof only	None required
1, 2A, 2B, 3A, 3B, 3C	R-5
4C	R-10
4A, 4B	R-15
5	R-20
6	R-25
7	R-30
8	R-35

Climatic Boundary Conditions

Exterior. In hot and humid climates, there is less of a concern for condensation in the roof deck due to the mild or warm winter. In the summer the high outdoor humidity and air leakage can bring in moisture into the attic air.

Interior. During cold weather, the indoor moisture loads determine the indoor humidity together with the fresh air ventilation (or air leakage) rates. In the summer in hot and humid climates, the air moisture content is lower indoors than outdoors due to the dehumidification by the cooling system.

MODEL CALIBRATION

The focus of this study is to investigate the moisture performance of UVAs with special focus on air leakage and ventilation. The hygrothermal models were calibrated against measured attic data humidity and temperature data. Oak Ridge National Laboratory has been measuring the thermal and moisture performance of a test house in Knoxville, TN. Five months of temperature and relative humidity data were available from the beginning of August till the end of December for our model validation purposes. The house is a two-story unoccupied single family home with simulated interior sources for heat and moisture to represent realistic interior loads. The UVA has two main orientations North and South (with 16° deviation). The attic contains an HVAC system. The roof consists of the following layers starting from the outside:

1. Shingles
2. Felt underlayment
3. Oriented strand board (OSB) 0.5 in. (12.5 mm)
4. Open-cell spray foam 6 in. (152 mm) (installed in two installations)
5. Spray-on fiberglass 2 in. (51 mm)

Attic Airtightness Testing

The UVA is an indirectly conditioned space even though the whole space is inside the thermal and air barrier boundaries. It is important to understand the connections of the attic not only to the outside but also to the inside. In cooling climates, the stack effect works in the other direction than in the heating climate. In hot and humid (cooling) climates the stack effect and wind pressures will pull air from outside into the attic. On the other hand, the air leaks in the HVAC system (if located in the attic) effectively creating some conditioning in the attic. Additionally an imbalance in air leaks from the supply and return side may create a small pressure difference between the attic, the outdoors, and the living space. The airtightness of the ceiling plane plays a role in the air movements. A Building America project for UVAs in hot-dry climates noted that the whole building airtightness in a house increased by 50% when the attic hatch was opened (Building America 2003). Therefore, it was decided to do blower-door testing that would provide not only the whole building airtightness, but also individually the airtightness of the roof deck and the ceiling plane. Table 4 lists the volumes of the living space and the attic.

Table 4. Test House Areas and Volumes

Space	Area (ft^2 [m^2]), Volume (ft^3 [m^3])
Living space 1st & 2nd floors	2241 (209), 22293 (635)
Attic	1383 (129), 4564 (130)

Table 5. House and Attic Airtightness

Space	ACH50 (CFM50)
Whole house, attic hatch closed	4.1 (1525)
Whole house, attic hatch open	3.4 (1541)
Attic only, leakage to outdoors and indoors	18.9 (1440)
Attic only, leakage to outdoors only	4.4 (336)
Attic to indoors only (deducted from two previous measurements)	— (1104)

Note: The ACH50 values are for information only and are for the included volume of the space only (attic or whole house).

Several blower door tests were carried out for the house with two blower door systems. First, a whole house airtightness testing was carried out with the attic hatch closed. Second, a blower door system was installed in the attic hatch and the overall airtightness of the attic was performed with doors open to the outside in the living space to create outdoor pressure conditions both above the roof and below the ceiling. Third, the roof deck airtightness to the outside was performed by maintaining equal pressures in the attic and in the living space to eliminate the air leaks in the ceiling plane. These two tests allowed us to characterize the attic air leaks both towards the outdoors through the roof and towards the indoors through the ceiling plane. Results are presented in Table 5.

These results show that the attic can contribute to whole house air leakage by about 23%. Thus, we cannot ignore the air leakage between the attic and outdoors. It must be noted here that the ceiling plane is very leaky, which means that the guarded test as presented can have a big uncertainty and the results should be treated as such. Testing was carried out at multiple pressures and the authors feel that the results are representative. A set of whole building air leakage tests were carried out with the attic hatch closed or open. The attic pressure was monitored in the test with attic hatch closed. The attic zone pressure measured 7.7 Pa (0.03 in. H_2O) (attic-to-house) when the house interior was depressurized to –50 Pa (0.2 in. H_2O). The flow network analysis resulted in air leakage rate of 320 cfm50 (151 L/s at 50 Pa) for the roof deck, which is within 5% of the unguarded test result. An alternative test procedure is being developed to minimize the uncertainty caused by the leaky ceiling.

Pressure testing between the attic and the second floor showed that the air-conditioning system is providing a slightly negative pressure of 0.5 Pa (0.002 in. H_2O) in the attic, which shows an imbalance of airflow supply and return. This pressure difference causes air exchange between the attic and the living space. The ceiling plane was found to be very leaky and even small pressure differences cause air exchange. In effect, the air-conditioning system is providing some conditioning to the attic. Based on the ceiling airtightness characteristics, the airflow rate through the ceiling to the attic would be about 45 cfm (21 L/s) when the HVAC is on while the additional airflow rate from outdoors to the attic would be about 10 cfm (5 L/s) due to the pressure difference created by the air conditioning system.

Airflows in the Attic Due to Air Leakage in Hot Climates

What is the importance of understanding the air leakage of the attic itself? The house is fairly airtight with 3.4 ach50 overall. In hot climates, the stack effect works in the reverse fashion to the way it works in cold climates, i.e., the air tends to flow in from the top and out from bottom of the building when the outdoor air is hotter than the interior. Let's assume this house is in Houston, TX. Rough estimates for seasonal ventilation rates due to infiltration in Houston, TX give 0.29 ach for winter and 0.18 ach for summer (output from Tectite blower door software/Energy Conservatory with Houston weather) (Energy Conservatory 2007). Let's assume that we have this average ventilation rate in the summer and that the air infiltration occurs top-down as discussed above. In a top-down flow scenario, the whole house air leakage would flow from outdoors through the attic to the living space below. The amount of airflow is 18% of the whole house volume in an hour. For this house volume (including attic) the airflow rate is 0.18 1/h · 765 m^3 (27013 ft^3) = 138 m^3/h (38 L/s [82 cfm]). In terms of the attic volume this 138 m^3/h (38 L/s [82 cfm]) represents 138/130 ≈ 1 ach. It is clear that even if the whole-house air leakage is fairly small, the attic may still experience quite high air exchange with outdoor air. In hot and humid climates this air exchange would bring moisture into the attic which is one of the main research finding of this paper.

ORNL Attic Data

Figure 1 presents the measured and calculated temperature and relative humidity between the roof sheathing (OSB) and the spray-foam insulation. The figure shows simulation results with two different methods, which we will explain later in the paper. Locally-measured exterior weather data and interior conditions (attic temperature and humidity) were used in the simulations. During a period in October (80+ days from August 1st in Figure 1) a plastic sheet was placed on the roof for research purposes and this clearly increased the effect of solar radiation on the roof temperatures.

The test data reveals one behavior that is typically not consistent with simulation models. The wood handbook published by Forest Products Laboratory shows data for sorption isotherms for wood at different temperatures (Glass and Zelinka 2010). Figure 2 shows the modified sorption curves for OSB at different temperatures, which the author has created by simply scaling the level of the moisture content to match a measured sorption isotherm at room temperature. The higher the temperature, the lower the equilibrium moisture content of wood at different relative humidity. Figure 3 shows how the correct sorption isotherm for the high temperature will create as much as 25% higher vapor pressure in the material with the same moisture content. This means that even short times at a high temperature can create much higher vapor diffusion rates promoting drying of the roof deck. In airtight materials, total pressure inside the material can further increase vapor outflow. This effect is however not discussed here.

The water in the pore space of porous materials is in both liquid and vapor form. When the temperature of the material increases without the moisture content of the material changing, the liquid water evaporates creating a higher vapor pressure. A single sorption curve in modeling assumes that in this situation the relative humidity inside the material does not change because the moisture content does not change. However, the sorption curves have been measured for some materials such as wood at different temperatures /1/. The measurements show that a single sorption curve is not accurate at high temperatures above 60°C (140°F). Wood can absorb less water at high temperatures than at low temperatures at the same relative humidity. The effect of temperature-dependent sorption can be seen in the measured relative humidity data for this roof.

The results in Figure 1 have been calculated with two different methods: first with single sorption curve without temperature effects on the sorption, and second with multiple sorption curves that take into account the effect of temperature on the ability of the material to absorb and desorb moisture in the hygroscopic range. The hourly behavior of the relative humidity under the roof sheathing behaves in opposite ways depending on whether or not the temperature-dependent sorption is used or not. The relative humidity goes down when the temperature goes up if only a single sorption isotherm is used in the modeling. However, both the measurements as well as the simulations with the temperature-dependent sorption show that the relative humidity goes up when the temperature of the roof deck goes up. When looking at the daily average values, the hygrothermal model agrees quite well with the measured data for the north oriented roof whether the temperature dependent or a single sorption isotherm is used. In Figure 1 the quadratic mean of the difference in relative humidity between the simulated and the measured values was 7% and 9% for the north-oriented roof slope (15% and 21% for the south-oriented roof slope), for the simulations with and without the temperature dependent sorption, respectively. However, the south oriented roof shows much lower measured than simulated relative humidity. This could be due to several factors, one of them can be the temperature-dependent sorption isotherms that should be generated not only for the roof sheathing but also for other materials including even for the insulation layer. The results show the simulated results will match the measured data better when including temperature-dependent sorption isotherms for the roof sheathing (OSB) (Figure 4): the peaks and valleys of the fluctuations in the diurnal cycles match the measured ones. The actual difference (level) between the measured and simulated humidity on the interior surface of the roof sheathing is still quite high for the south-oriented roof (Figure 1B). The models used for building envelope analyses typically have material properties measured only at one temperature. This brief study shows that there is a need for more research to understand moisture performance at high temperatures.

This study focuses on predicting mold growth in the roof and in the attic and not on more severe damage such as wood rot. Moisture content in the roof deck is typically low due to high temperatures in CZs 1 to 4 unless the roof experiences water leaks. The moisture content measurements were not available for this study and they were not as much of interest because the conditions that describe conditions susceptible to mold growth are based on temperature, relative humidity, and time (Viitanen).

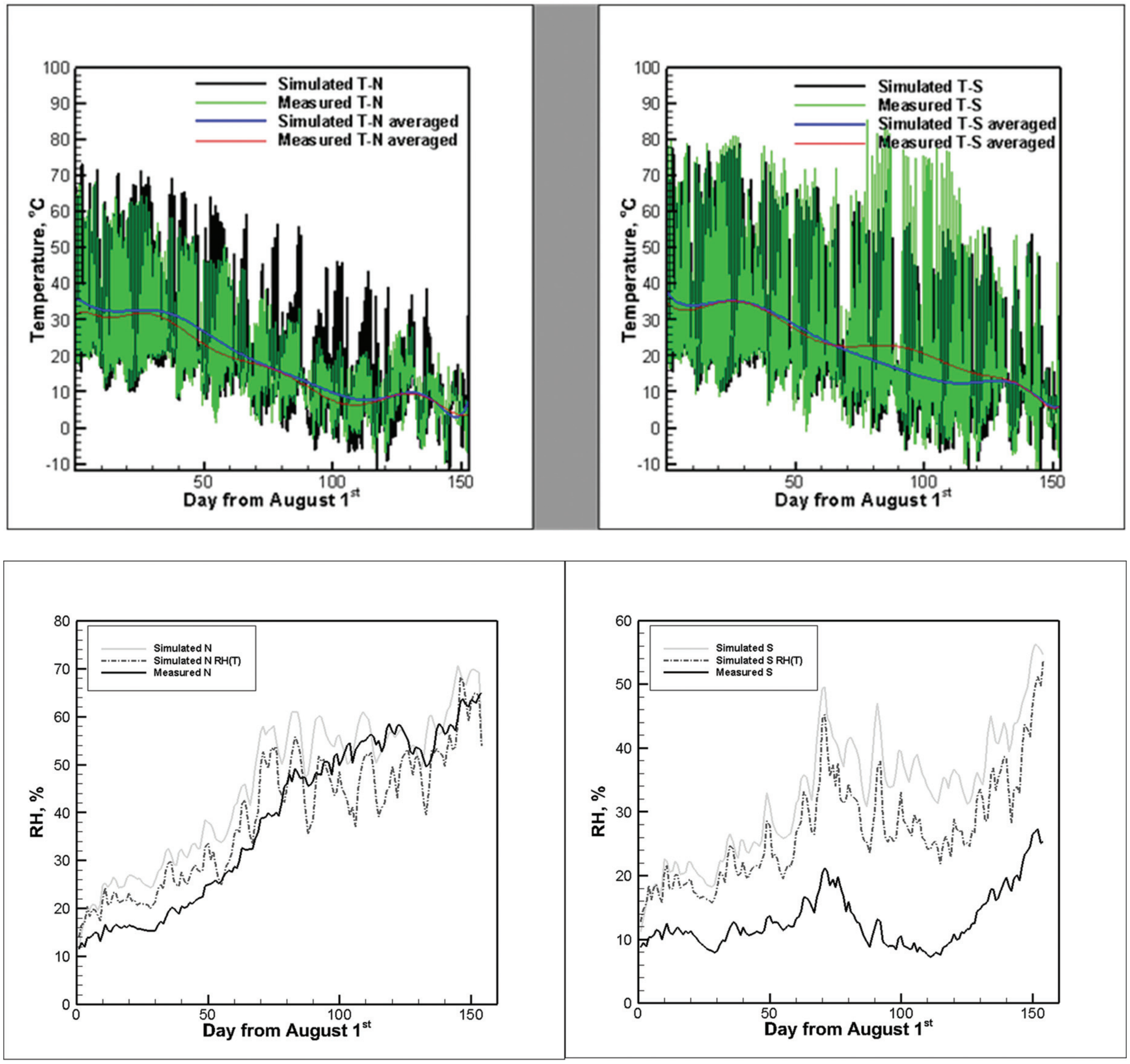

Figure 1 *Daily averages of the measured and the simulated temperature (top) and relative humidity (bottom) between the roof sheathing and the insulation in the test house:* A *= north orientation,* B *= south orientation. Results have been simulated with (Simulated N/S RH[*T*]) and without temperature dependent sorption.*

The effect of temperature-dependent sorption is less at low temperatures than at high temperatures. The condensation in the roof deck occurs at low temperatures, and therefore a single sorption isotherm as used in the hygrothermal models can be deemed sufficient for the purpose of studying condensation and moisture accumulation in the roof deck. The model calibration for the north-facing roof deck shows that the single curve captures the performance sufficiently in the long term. The south-facing roof deck has a low relative humidity and a high temperature which does not result in conditions that would be favorable for mold growth. The north-oriented roof deck would be the first to experience conditions susceptible for mold growth. The model that includes the temperature-dependent sorption is only for modeling building envelope parts and not whole building performance. The whole building model that was needed and used in the parametric analyses does not have the availability of temperature dependent sorption. Therefore, for those reasons the following condensation and attic humidity studies were made with a model using a single sorption curve only and without temperature effects on sorption isotherms.

SIMULATIONS IN CZS 1 TO 4

The focus of the simulations was to investigate two performance aspects of the UVA: the moisture content of the roof sheathing and the humidity of the attic space. These two are critical in terms of the durability and the safety of the building enclosure, and the indoor air quality. High moisture content of

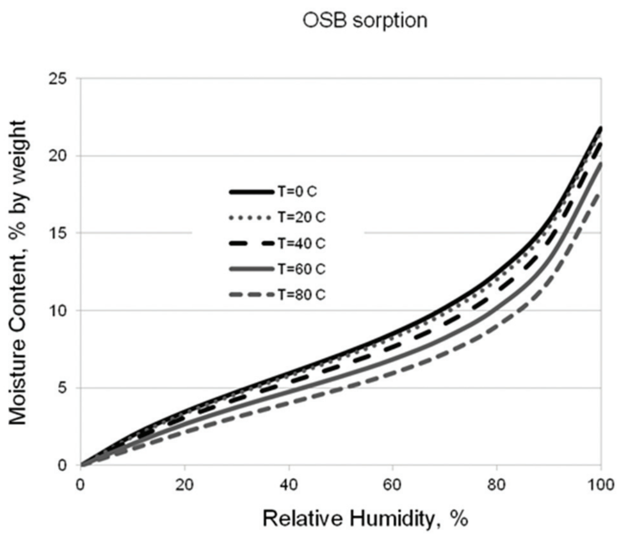

Figure 2 *OSB sorption curves as used in simulating the test house roof. The temperature-dependent sorption curves were estimated by scaling a curve measured at room temperature with the equation for wood in Wood Handbook/Forest Products Laboratory (Glass and Zelinka 2010).*

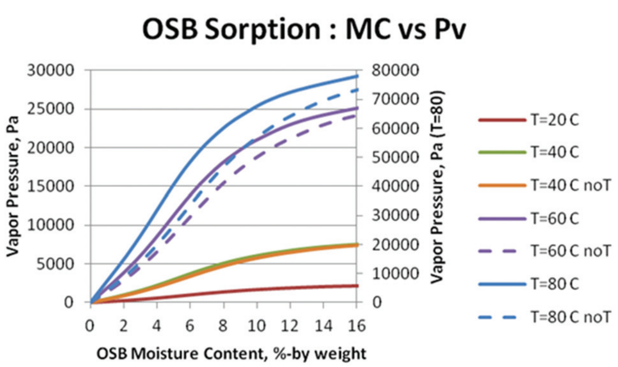

Figure 3 *Vapor pressure with and without temperature-dependent sorption for OSB (OSB moisture contents scaled down from wood data [FPL]). Curves with "no*T*" have been calculated with a single sorption isotherm defined at* T *= 20°C (68°F), the other curves are based on individual sorption isotherms for each temperature.*

the roof deck (over ~20% by weight) can reduce the structural strength of the roof sheathing, initiate mold growth on its surface and cause dimensional changes that in turn can cause visual degradation of the roof. High humidity (80% rh) in the attic air can cause mold growth on the surfaces exposed to the attic.

Description of the Attic and House

Two different types of roofs (UVA, vented attic) were simulated in four cities in the southern CZs 1–4. The cities were Miami, FL; New Orleans, LA; Atlanta, GA; and Baltimore, MD.

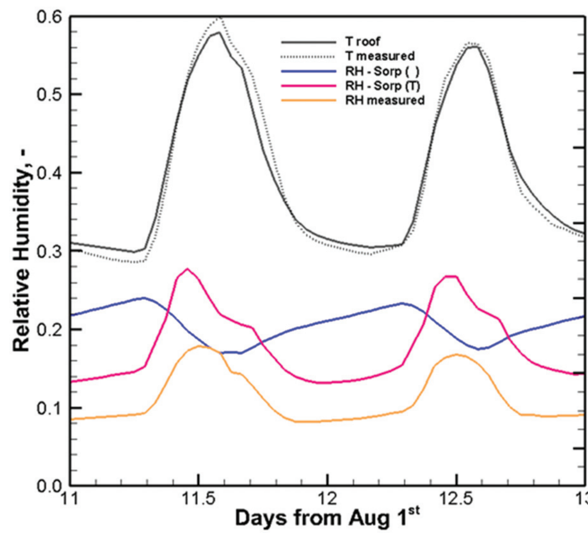

Figure 4 *The measured and the simulated relative humidity between the roof sheathing and the insulation for the south oriented roof. Temperature-dependent sorption is (RH – Sorp[*T*] or is not taken into account (RH-Sorp[ ]).*

Simulation Set Description

The roofs are oriented to the north with a roof pitch 4/12 (18.4°).

The roof layers in the UVA are from outside to inside as in the roof for model calibration with the exception of the fiberglass insulation on top of the spray foam. The material layers from outside to inside are: shingles, roofing felt, 0.5 in. (12.5 mm) OSB and 6 in. (152 mm) open-cell spray-foam (or fiberglass).

The vented attic has the same materials except that instead of the spray-foam insulation under the roof sheathing there is blown-in fiberglass on top of the ceiling drywall. The attic is ventilated at rate 2 ach with an average attic height of 0.9 m (3 ft).

Indoor and Outdoor Weather. The indoor moisture loads were calculated by assuming a house with the volume 500 m^3 (17,623 ft^3) that has 12 L/day (26.7 lb/day) moisture production and ventilation rate 0.25 ach (including natural and mechanical ventilation). This results in 4 g/m^3 (0.00025 lb/ft^3) moisture load. The moisture loads were chosen to represent not the conditions in an average home but rather the design conditions that would cover most homes (ASHRAE 2009). The important number in the calculations is the moisture load (4 g/m^3 [0.00025 lb/ft^3]) which results from the moisture production and the ventilation rate. The same moisture load can be realized in a home with less moisture production and with less ventilation, i.e., a home with no mechanical ventilation would need less moisture production to end up with the same moisture load. In the summer, cooling system dehumidifies the indoor air to a maximum of 60% rh during cooling hours. Indoor temperature was allowed to float between 21°C

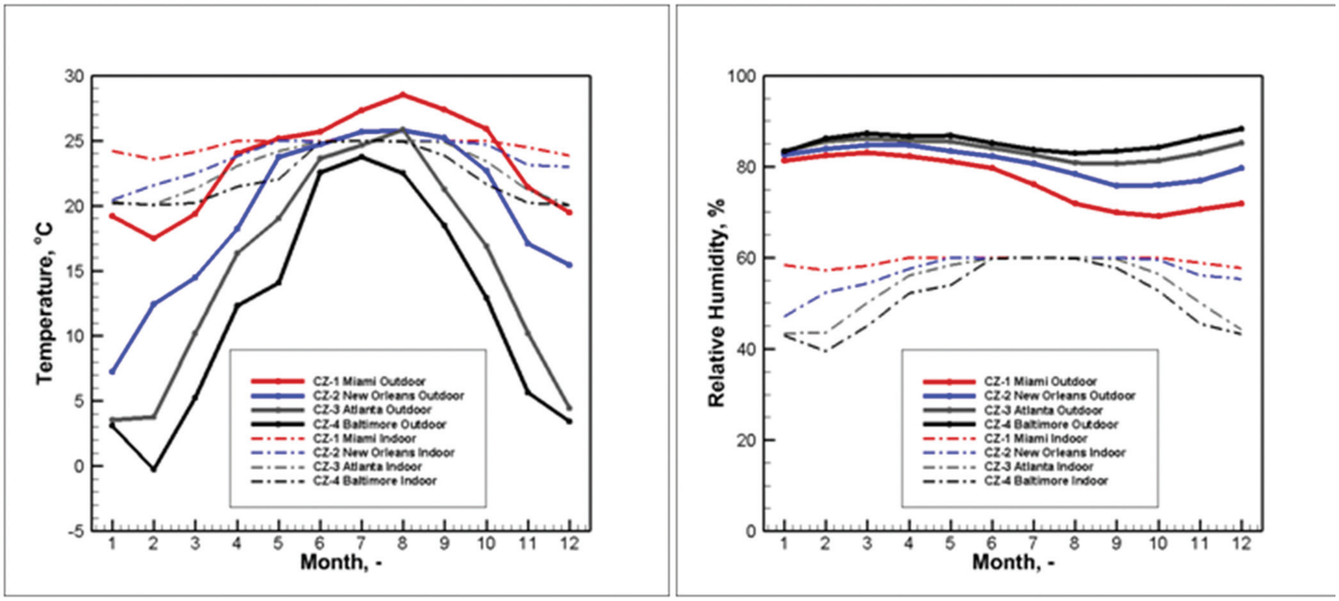

Figure 5 *Average monthly temperature (left) and relative humidity (right) for the weather and the indoor conditions used in the simulations.*

and 25°C (69.8°F and 77°F). The built-in cold year weather files in the WUFI software were used for the locations. The monthly average outdoor and indoor temperature and relative humidity are shown in Figure 5.

Results

Results are provided first for the moisture content of the roof sheathing both for the vented and the UVA configurations by varying the water vapor permeance of the insulation layers. The results are shown for the roof slope facing north, which is the most likely orientation to experience higher moisture contents due to lower temperatures than the south-facing roof slope. Then the air conditions inside an UVA in a hot and humid location are shown with different air leakage characteristics of the attic.

Moisture Contents of the Roof Sheathing. The moisture contents of the roof sheathing in the attics were monitored in the simulations for both the unvented and the vented attic. The moisture content of the OSB roof sheathing in the vented attic is shown in Figure 6, first without rain intrusion and second with 1% rain intrusion to the roof sheathing.

The vented attic performs well with low moisture contents in the roof sheathing with or without the rain intrusion. Even with 1% water intrusion, the moisture content of the OSB stays below 15% by weight at all times in all the four locations. The roof is capable of drying out water intrusion of 1% of the rain hitting the roof.

Figure 7 shows the moisture contents for the OSB in the UVA with open-cell spray foam (vapor permeance 23 perm-in. [33.58 ng/smPa]). The moisture contents are clearly higher than in the vented attic, except for the UVA with no water intrusion in Miami, which shows equal performance to the vented attic. Water intrusion into the roof sheathing at a rate of 1% from the rain hitting the roof elevates the moisture contents above 20% by weight in the OSB in all locations but Miami (CZ 1).

Spray foam is installed in the field and the quality can vary depending on many factors such as field conditions and installers' ability to control the spray equipment. As a result, the water vapor permeance of the installed insulation can vary too. Figure 8 shows the performance with a higher permeance 54 perm-in. (78.84 ng/smPa) for the spray-foam insulation. The moisture contents in the winter are higher with higher-permeance spray foam than with lower-permeance foam in all other climates but CZ 1 (Miami). Miami appears to have very little vapor drive from indoors towards the roof deck.

Spray foam must either have built-in fire-retarding chemicals or a fire-retardant spray will have to be added to allow for the insulation be left exposed in the attic. The intumescent coatings can be vapor retarders with low vapor permeance. In the simulations one of these products has been used together with the open-cell spray foam that has water vapor permeance 23 perm-in. (33.58 ng/smPa). Figure 9 shows the pros and cons of the coating. When the roof has no water intrusion, the additional vapor resistance (vapor permeance 1 perm-in. [1.46 ng/smPa] dry cup tests and 3 perm-in. [4.38 ng/smPa] wet cup) of the intumescent paint reduces the water vapor drive from the attic to the roof deck and the moisture contents of the OSB stay well below 10% after the drying from initial conditions. However, drying of the roof is greatly reduced as well, and if the roof has any water intrusion the moisture content of the OSB can quickly increase to risk levels (above 20%–26%).

An UVA can be insulated with an air-permeable insulation such as fiberglass if the local building code allows it in the

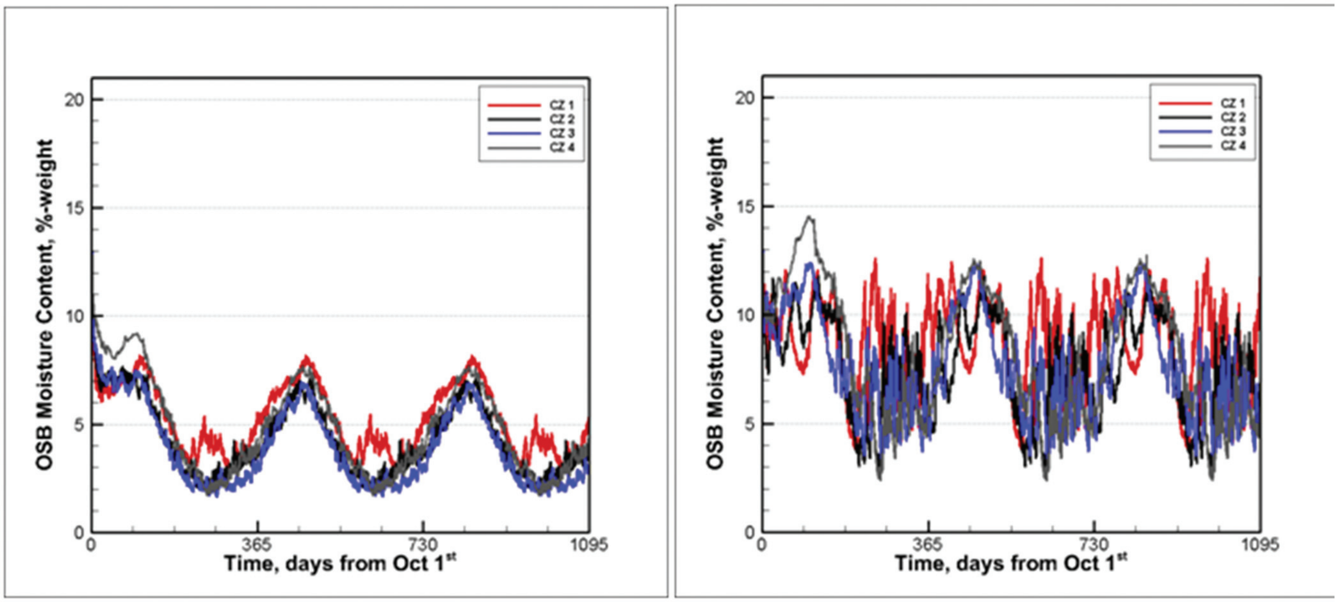

Figure 6 *Moisture content of the roof sheathing (OSB) in a vented attic with no rain intrusion (left) or with 1% rain intrusion to the roof sheathing (right).*

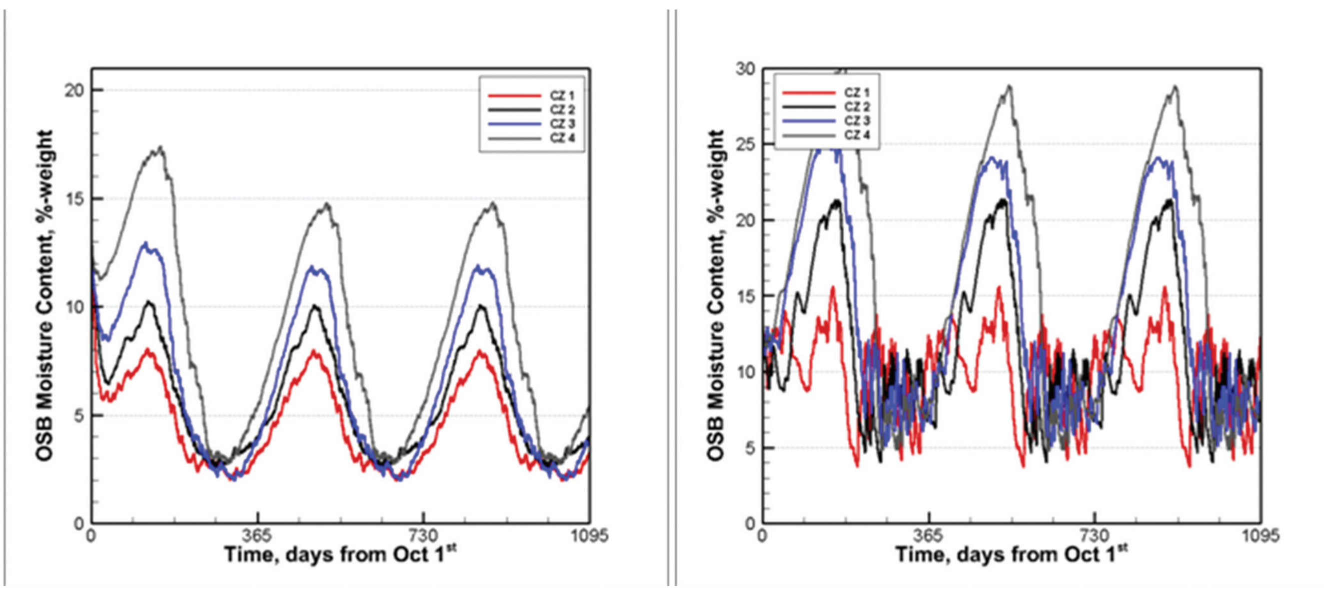

Figure 7 *Moisture content of the roof sheathing (OSB) in an UVA with no rain intrusion (left) or with 1% rain intrusion to the roof sheathing (right) when open-cell spray foam with vapor permeance of 23 perm-in. is used.*

location or CZ. The roof deck can and must be air sealed first to reduce air leakage between the attic and outdoors. Once the roof deck is air sealed blown-in fiberglass insulation is recommended to seamlessly and fully fill all gaps and edges below the roof deck. Dense-packed fiberglass insulation that is produced today has low air permeability that minimizes any air convection between the attic and the roof deck. Fiberglass insulation has high vapor permeability about 100 perm-in. (146 ng/smPa). The netting used for keeping the fiberglass in place can be tuned to have a desired water vapor permeance. Figure 10 shows the moisture content of the OSB roof sheathing with fiberglass insulation only without any additional vapor resistance in the netting. CZs 1 (Miami, FL) and 2 (New Orleans, LA) exhibit low moisture contents but CZ 3 (Atlanta, GA) with close to 20% moisture content and CZ 4 (Baltimore, MD) with above 30% moisture contents show signs of moisture stress. Figure 10 shows the results with netting that has vapor permeance of 10 perms. The additional vapor resistance has a beneficial effect of lowering moisture contents in the roof both without and with water intrusion.

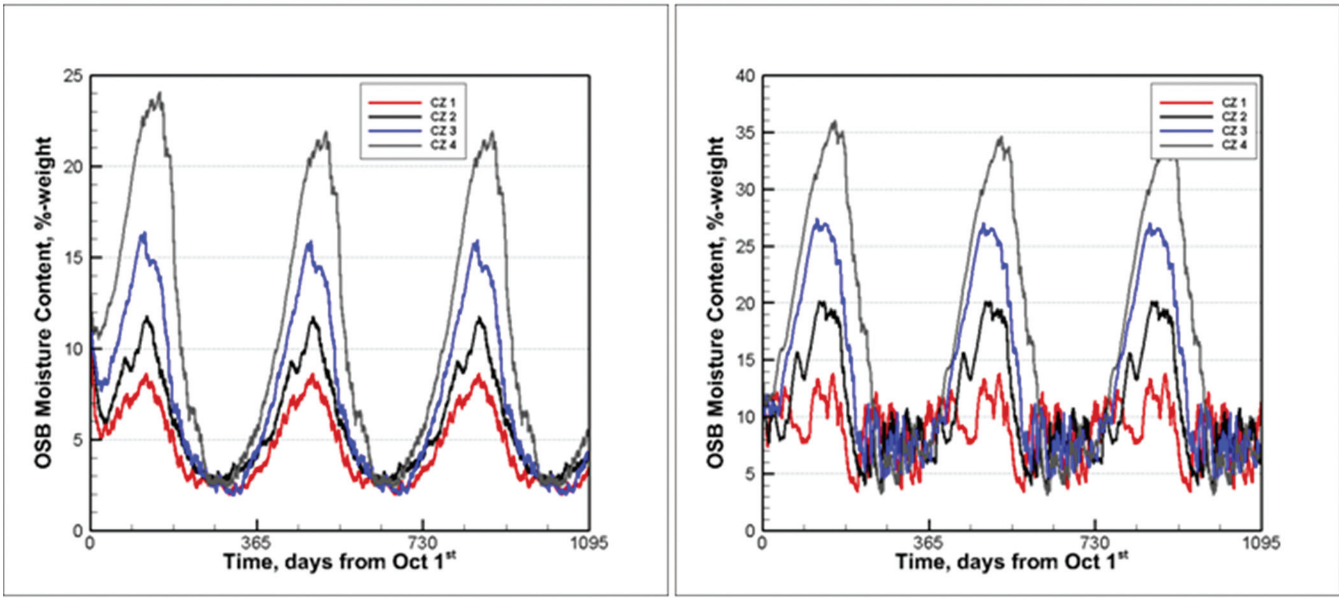

Figure 8 *Moisture content of the roof sheathing (OSB) in an UVA with no rain intrusion (left) or with 1% rain intrusion to the roof sheathing (right) when open-cell spray foam with vapor permeance of 54 perm-in is used.*

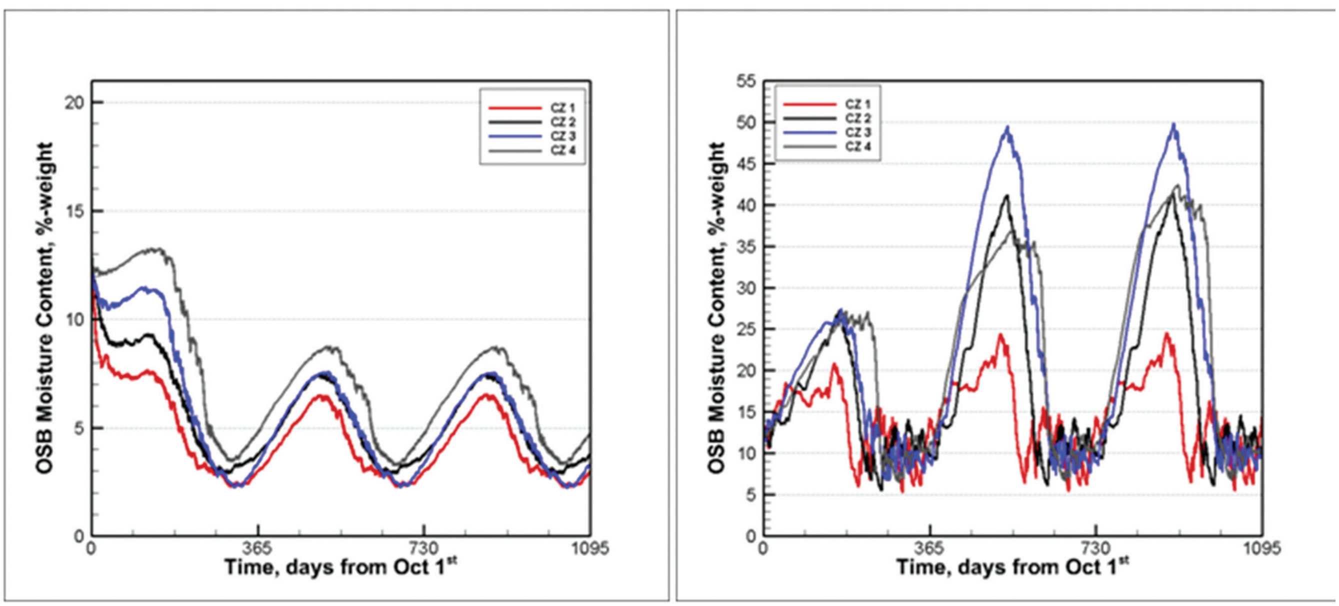

Figure 9 *Moisture content of the roof sheathing (OSB) in an UVA with no rain intrusion (left) or with 1% rain intrusion to the roof sheathing (right) when open-cell spray foam with vapor permeance of 23 perm-in is used together with an intumescent paint coating (permeance 1–3 perms from dry to wet).*

The building code requires the UVA systems built with air-permeable insulation to have R-5 air-impermeable insulation (in CZs 1–3 with the exception of tile roof in CZ 2B and 3B) as condensation-control layer (ICC 2012). In the light of the results shown above this requirement seems to be unnecessary.

Attic Humidity. Vented attics are ventilated by design whereas in the UVAs we attempt to achieve high airtightness to prevent any air exchange between the attic and outdoors. In cold climates some ventilation with outdoor air in the attic would remove moisture from the attic in the winter which would further reduce the possibility of moisture accumulation in the roof deck. In hot and humid climates the attic ventilation may not have the same effect and especially in summer time ventilating the attic with outdoor air could bring moisture into the attic elevating the humidity in the attic space. Therefore,

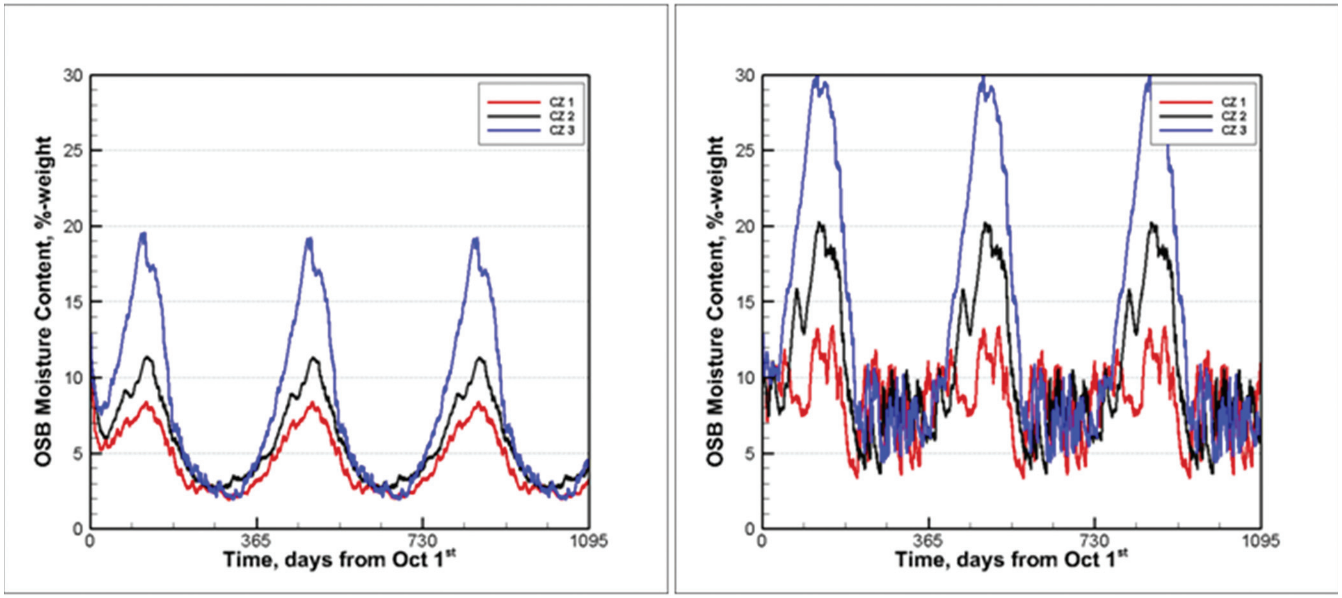

***Figure 10** Moisture content of the roof sheathing (OSB) in an UVA with no rain intrusion (left) or with 1% rain intrusion to the roof sheathing (right) when fiberglass insulation with vapor permeance of 100 perm-in is used.*

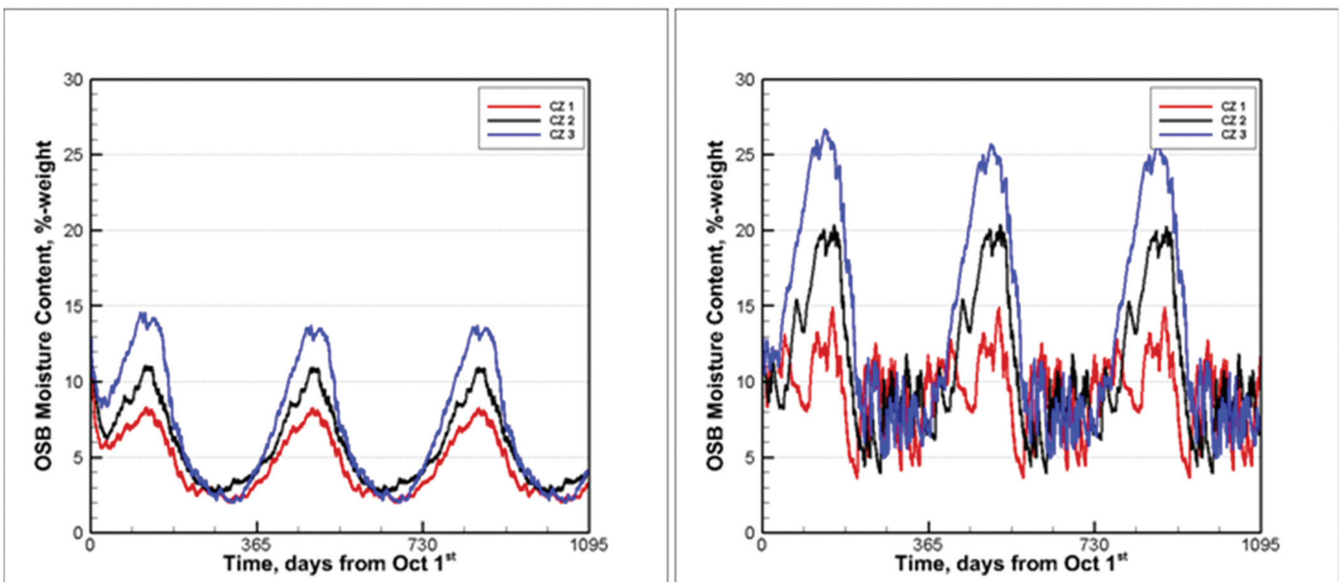

***Figure 11** Moisture content of the roof sheathing (OSB) in an UVA with no rain intrusion (left) or with 1% rain intrusion to the roof sheathing (right) when fiberglass insulation with vapor permeance of 100 perm-in. is used together with a netting on the attic side that has permeance of 10 perms.*

especially in the southern climates it is necessary to investigate the impact of the airtightness of the attic on the attic air temperature and humidity. Results are presented for an UVA in Houston, TX, which is in a hot and humid climate.

An UVA was simulated with the whole building simulation model WUFI-Plus with the focus on the air exchange between the indoors, the outdoors, and the attic. Figure 12 shows the attic air temperature and relative humidity when there is some air leakage between the attic and the indoors, and the attic and the outside. The air leaks from outdoors into the attic in the summer bring humid air into the unconditioned (or indirectly conditioned) attic space that has a temperature close to the indoor temperature. The additional moisture load into the attic can increase the relative humidity of the attic air to levels that are favorable to mold growth (over 80% rh). Note that this high humidity is inside the conditioned attic and the temperature in the attic is about the same as the indoor air temperature and thus the temperature conditions are always such that would allow for mold to grow. Earlier in the paper, the authors presented model calibration against measured attic data for the interior surface of the roof sheathing outside of the insulation adhered to the roof deck. The roof deck is exposed to a large temperature range, both low and high temperatures depending on the climate, and the relative humidity at these low and high temperatures has to be higher than at room temperature to allow for mold growth (Viitanen 1996).

Ideally, the attic would be conditioned to avoid uncontrolled high humidity. However, since the attic is not part of the living space, the interior surfaces of the attic are not finished (insulation is left exposed) and the attic space is not cleaned routinely it would be better for indoor air quality to avoid circulating air from the attic into the living space. Therefore, it is critical that in hot and humid climates the attic is air sealed to the outside carefully. Any holes created after installing the insulation have to be sealed with extreme care. Figure 13 shows how ventilating the attic with conditioned indoor air will reduce the attic humidity below the critical mold growth level 80% rh. The assumption in Figure 13 is that the airflows are balanced in the attic and that the HVAC does not pressurize or depressurize the attic. The more air leakage between the attic and the outdoors, the more conditioned air will be needed in the attic to maintain low humidity in the summer due to high outdoor humidity. If the HVAC system depressurizes the attic, the air leakage from outdoors to the attic will increase and the humidity level ends up higher.

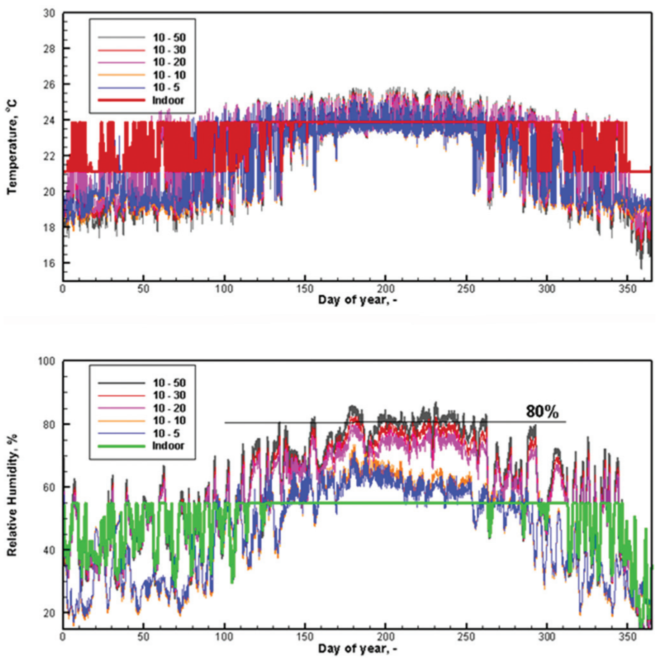

Figure 12 *Temperature (top) and relative humidity in the attic when the attic has different air leakage rates between indoors and outdoors. The first number in the line legends is the ventilation rate between the attic and the indoors (L/s) and the second number is the ventilation between the attic and the outdoors (air leakage in L/s). [1 L/s = 2.12 cfm]*

CONCLUSIONS

An UVA and a vented attic have been analyzed with hygrothermal models in terms of their moisture performance. The UVA has a lower tolerance to water penetration by allowing for less drying capability for the roof sheathing than the vented attic. The fire-retardant coatings, while they do reduce the condensation from indoor sources, further reduce the drying capability. The simulation results do not show the need for the condensation control insulation layer with R-value of R-5 in CZs 1 and 2 (ICC 2012).

The UVA is not directly conditioned but instead its temperature and humidity floats between that of indoors and outdoors. In hot and humid climates, or in any climate with hot and humid summer, the attic space can become humid even with seemingly low air leaks from outdoors to the attic. The UVA has no designed controls for temperature or humidity and the humidity in the attic can become high enough to allow for mold growth. Unless the house is very airtight overall (1–2 ach50) it is recommended to verify the airtightness of the roof deck by

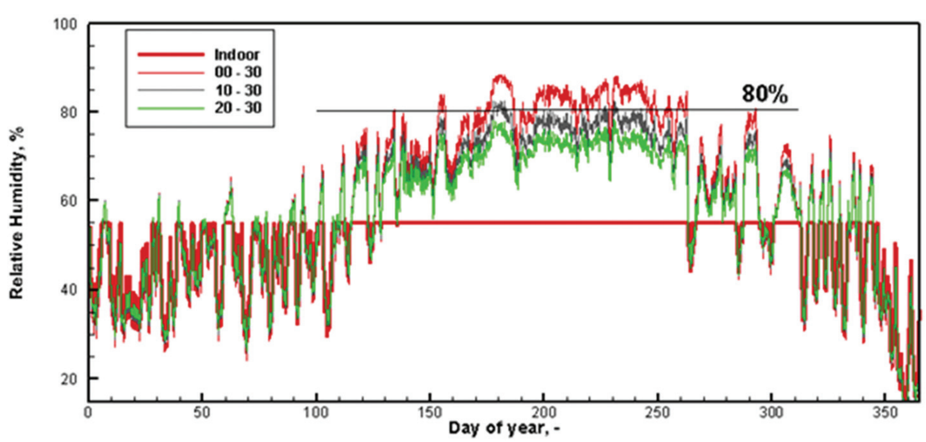

Figure 13 *The effect of balanced air exchange between the attic and the living space (0, 10, or 20 L/s [0, 21.2, or 42.4 cfm]) on the attic humidity when the outdoor air leakage is maintained at 30 L/s (63.6 cfm).*

carrying out either a guarded-blower door test or blower door tests with zone pressure measurements to find out the air leakage of the roof deck to the outside.

ACKNOWLEDGMENTS

Many thanks are due to Roderick Jackson, Philip Boudreaux, Tony Gehl and Diana, Hun (Oak Ridge National Laboratory) for their help and by allowing us to perform blower door testing of the test home and to analyze some of the measured attic temperature and humidity data.

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