Evaluation of Vapor Retarders in Roof Decks in High Humidity Environments by Hygrothermal Simulation

By Gourish Sirdeshpande, PhD

This paper was presented at the 2023 IIBEC Building Enclosure Symposium.

IN COLD WEATHER, high-humidity indoor environments such as indoor pools pose risks of moisture condensation in building enclosures, which in turn can cause mold, decay, buckling, corrosion, and eventually structural issues of durability. Most swimming pools are treated with chlorine, resulting in chloramines that off-gas into the pool's air space, irritating skin and eyes and creating respiratory hazards for swimmers and spectators. The chloramines also corrode building materials, especially metals. A good ventilation system[1] with effective air distribution and sufficient outdoor and exhaust air to remove toxic and corrosive chloramines is essential for the health and safety of swimmers, spectators, and other building occupants.

Acoustics and ambient noise are significant issues in natatoriums, as these spaces act as giant echo chambers. Most large community pools are considered learning spaces. Therefore, under the Acoustical Society of America (ASA)/American National Standards Institute (ANSI) acoustic standards for physical education teaching environments,[2] these types of natatorium spaces are required to meet certain minimum reverberation times. To control indoor acoustics, pools require sound-absorbing materials that are widely and uniformly distributed throughout the natatorium. Both wall treatments and roofs must be sound absorbers. Moisture loads in a natatorium can be nearly two to three times per unit volume the loads in a typical building.[1] Therefore, moisture transport driven by vapor pressure differentials enhanced by temperature gradients across the enclosure is an important factor to consider in the proper design of the roofs.

Current literature provides few guidelines for designing natatoriums to mitigate the risk of moisture condensation in roof decks. To avoid any risk of moisture condensation, design professionals frequently recommend a vapor retarder on the warm side of the roof assembly, presuming that a vapor retarder will safeguard the roof deck from condensation and moisture buildup.

Most roof installations in pools, irrespective of climate conditions, are perforated metal decks made of perforated metal, acoustic material, vapor retarder, insulation, roof decking material, and a roofing membrane (in that order, from inside to outside), as shown in **Fig. 1**. The entire assembly is anchored by screws that hold the components together. This type of anchorage typically results in pinholes and tears in the retarder. Even when a vapor retarder is used, corrosion is a commonly occurring issue with metal roof decks in natatoriums. Such occurrences question the role of a vapor retarder in moisture buildup and condensation in these roof decks.

Although building enclosure consultants and roofing professionals may assume that there is minimal risk of condensation with the use of a vapor retarder, this assumption may be incorrect. The study presented herein used hygrothermal modeling to investigate moisture migration and condensation in composite roof decks with

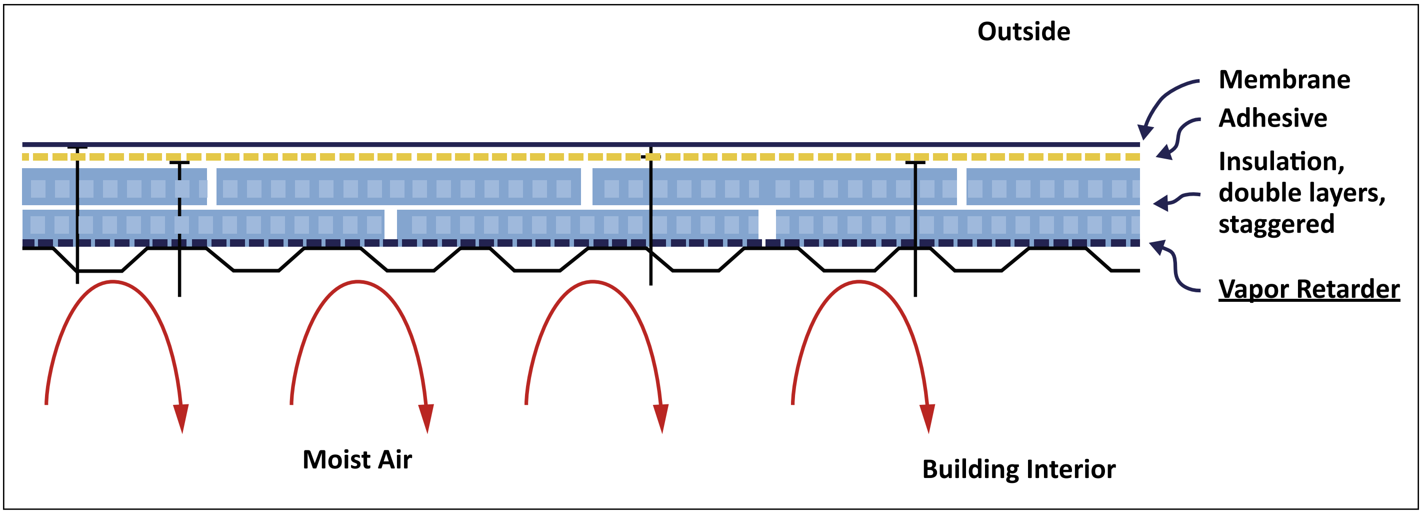


Figure 1. *A typical metal roof deck assembly.*

and without vapor retarders. In particular, the effectiveness of a vapor retarder to prevent condensation and moisture accumulation was highlighted in this investigation.

STEADY-STATE DEW POINT METHOD FOR ESTIMATING CONDENSATION

Most building enclosure professionals use the best-known simple steady-state design tool, the dew point method,[3] to evaluate condensation in roofs. This method assumes that steady-state heat conduction (under worst boundary conditions) and moisture diffusion govern heat flow and water vapor flow based on inside and outside temperatures and water vapor permeability of the assembly. Partial water vapor pressures in the roof deck are compared with saturation water vapor pressures based on calculated steady-state temperatures in the enclosure. If the calculated partial water vapor pressure is greater than saturation (estimated dew point), it is assumed that water vapor will condense in all parts of the roof assembly where the partial pressure is higher than the saturation pressure. The condensation rate is estimated based on the water vapor permeability of the assembly.[4]

The applicability of this method is severely limited by its assumptions about steady-state heat conduction and vapor diffusion. In reality, boundary conditions of temperature, humidity, wind, and radiation are in constant flux. Furthermore, water vapor permeances and thermal conductivity may vary with the relative humidity, temperature, and moisture content of the roof components. Nevertheless, many designers rely on the dew point method to select vapor retarders. Typically, a Class I vapor retarder with less than 0.1 perm is used in all metal roof decks.

TRANSIENT MODELING WITH HYGROTHERMAL SIMULATION MODEL

The features of a complete moisture analysis model include transient heat, air, and moisture transport formulations. Dynamic indoor and outdoor conditions as established by ANSI/ASHRAE Standard 160,[5] should be used for simulation. Extensive data on material properties are available in published literature.[6]

In this study, simulations were conducted on one of the types of roof decks recommended by the ASA/ANSI standard,[2] a composite roof deck assembly for high-humidity environments, to assess the performance of the selected type of roof deck in cold climates and the role of vapor retarders in that performance. The simulations were modeled with WUFI (WUFI is an acronym for *Wärme und Feuchte Instationär* [heat and moisture transiency]).[7]

This hygrothermal simulation model has been developed over the past three decades by Fraunhofer Institute for Building Physics and Oak Ridge National Laboratory to perform transient hygrothermal calculations to evaluate the long-term thermal and moisture performances of building enclosures, including roofs. The model has been validated repeatedly over the past two decades and has an extensive database of material properties and exterior climates from all US climate zones.[8,9]

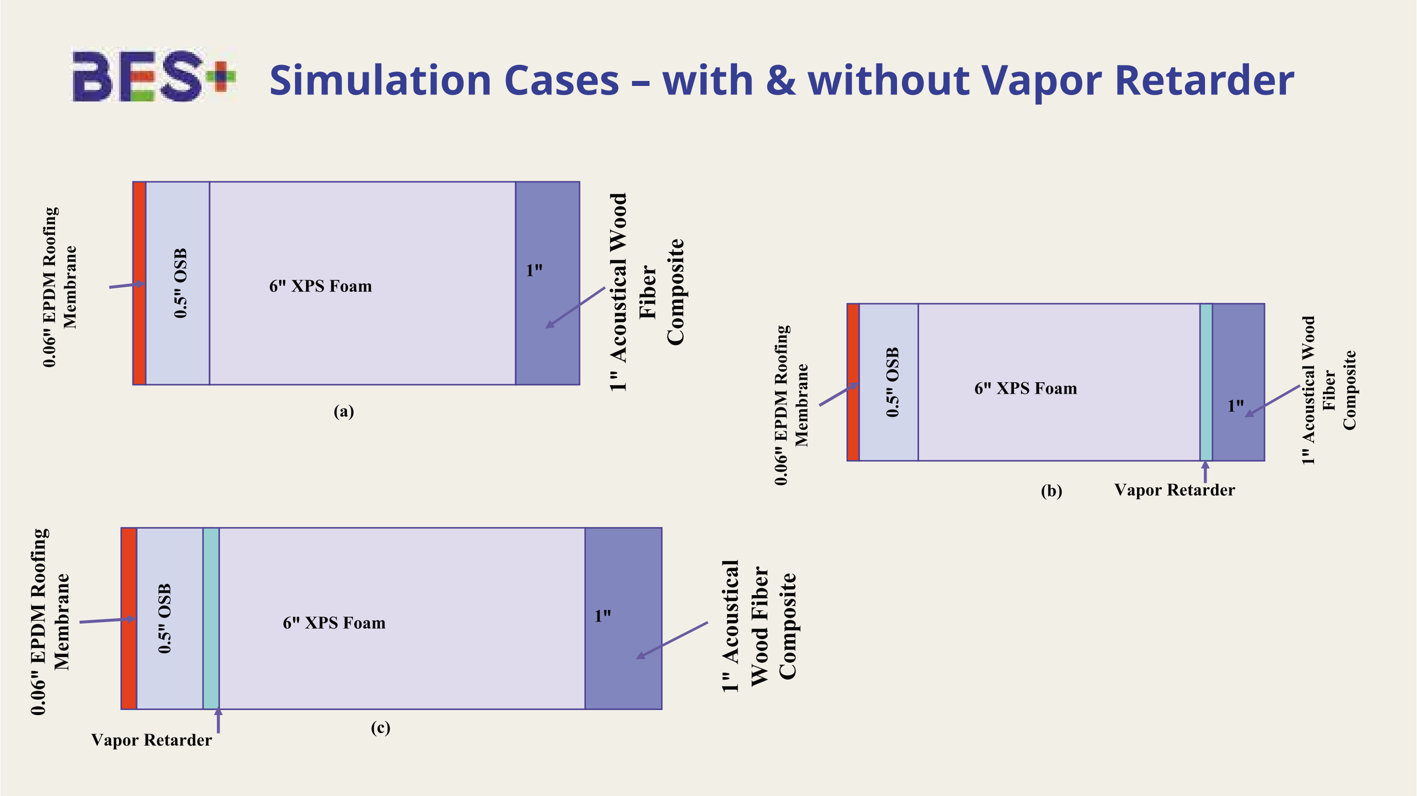
Figure 2 presents the schematic of the roof assemblies studied for transient heat and moisture flow. The basic assembly (from inside to outside) consisted of a wood-fiber–cement composite, extruded polystyrene (XPS) insulation, oriented strand board (OSB), and an ethylene propylene diene monomer (EPDM) roofing membrane. A vapor retarder (0.032 perm) was installed at two different locations, one on the warm side (Fig. 2b), and the other after the OSB (Fig. 2c).

A retarder with a very low perm-rating (<0.1 perm) was chosen to overstate the role of the vapor retarder. (The general understanding is that the lower the perm rating of the retarder, the less chance there is of condensation in the assembly.) The wood-fiber composite inside the pool space provided acoustical absorption, which is one of the requirements for good indoor environmental quality (IEQ) in the space. **Table 1** lists the primary transport properties of each of the components. The rest of the properties–moisture- and temperature-dependent transport properties and the equilibrium moisture content for each element—were obtained from the database provided in WUFI.

Fargo, North Dakota, in Climate Zone 7, was chosen for the location to simulate the roof performance. **Table 2** presents the boundary conditions and the main surface transfer conditions.

The hygrothermal simulation software includes the actual hourly averages of outside temperature, humidity, rain, wind, and the solar (short- and long-wave) radiation used in the simulation. To simulate a high moisture load in the natatorium, the inside conditions ranged from 40% to 65% relative humidity and 68°F to 80°F (20°C to 31.1°C).[5] For all components, the initial moisture content was assumed to be equilibrated at 50% relative humidity.

The roof deck assembly had a total *R*-value of 37 $ft^2 \cdot h\ ft^2\ °F$ (6.52 m^2K/W). To emulate realistic conditions, an air leak at the rate of 0.99 $ft^3/h\ ft^2$ (0.084 $L/s{\cdot}m^2$ @ 50 Pa) was included in the model.[5] The air leak was introduced at the interface of OSB and insulation, and it was set to start from the wood composite (inside) up to the EPDM layer for all the three cases. The stack height was set



BES+ Simulation Cases – with & without Vapor Retarder

Figure 2. *Roof deck assemblies: (a) without vapor retarder; (b) with vapor retarder after XPS foam installation; (c) with vapor retarder after the OSB installation. The exterior surface is on the left side in all cases. Note: EPDM = ethylene propylene diene monomer; OSB = oriented strand board; XPS = extruded polystyrene. 1" = 1 in = 25.4 mm.*

to 23 ft (7 m), and there was no mechanical ventilation overpressure. Air leaks (typically due to static pressure difference) can result in significant moisture transport from the pool space to the outside.

A no-coating option for permeance was selected on the left side, and a permeance of 10 perm was selected for the right side. The short-wave radiation absorptivity coefficient is an important variable when determining the outside surface temperature.[10] The roof deck had a dark roofing membrane (short-wave radiation absorptivity = 0.8) to absorb incident solar radiation, which would significantly elevate the daytime (and summer) surface temperatures since the pool was located in Climate Zone 7. Typically, white roofs are used in Climate Zones 1 through 3 to save energy (by lowering surface temperatures). If a white roofing membrane is used in a colder climate, the likelihood of exceeding a moisture content of 20% will be very high.[11] The simulation was carried out from 2000 to 2020.

SIMULATION RESULTS AND DISCUSSION

Moisture Accumulation in OSB

The primary concern regarding the roof's long-term performance would be moisture condensation and accumulation in the OSB over its service life. Decay and rot in wood occur when its moisture content exceeds 30%.[3] However, to provide an adequate

Table 1. Thermodynamic and transport properties of roof components

Properties	EPDM roofing membrane (0.06 in.)	OSB (0.5 in.)	XPS foam (6 in.)	Wood-fiber board (1 in.)	Vapor retarder (0.25 in.)
Bulk density, lb/ft^3 (kg/m^3)	53.1 (851)	34.5 (553)	1.79 (28.7)	18.7 (300)	54.6 (875)
Porosity	0.001	0.64	0.99	0.8	0.001
Specific heat capacity, BTU/lb°F (kJ/kg·K)	0.45 (1.88)	0.33 (1.38)	0.35 (1.46)	0.334 (1.4)	0.38 (1.6)
Thermal conductivity, BTU/h ft°F (W/mK)	0.12 (0.66)	0.07 (0.12)	0.014 (0.024)	0.29 (0.5)	0.87 (1.5)
Permeability, perm-in.	0.0014	0.96	1.3	10.3	0.008

Note: EPDM = ethylene propylene diene monomer; OSB = oriented strand board; XPS = extruded polystyrene. 1 in. = 25.4 mm.

Table 2. Primary boundary and surface conditions

	Conditions
Exterior climate (left side)	Fargo, ND; ASHRAE Year 1
Roof orientation/inclination	North/2 deg.
Heat resistance, h ft^2 °F/BTU (m^{2}K/W)	0.3 (0.053)
Short-wave radiation absorptivity	0.8
Long-wave radiation absorptivity	0.9
Interior (right side)	EN 15026, high moisture load
Heat resistance, h ft^2 °F/BTU (m^{2}K/W)	0.7 (0.123)

margin of safety, it is preferable to not exceed more than 20% moisture saturation.[12] **Figure 3** presents the simulation results for moisture content in the OSB for the three cases.

As seen in Fig. 3a, in the roof assembly without a vapor retarder, the average moisture content in the OSB reached a dynamic steady state in 5 years, and the maximum accumulation of water in the OSB did not exceed 11.6%. Therefore, there would be no risk of rot or decay since the percentage of moisture was well under 20%.

With the use of a vapor retarder on the warm side of the roof assembly (after the installation of foam), the maximum moisture content in the OSB was reduced to 11.3% (Fig. 3b). With the vapor retarder installed after the OSB, the maximum moisture content was around 10.8% (Fig. 3c). The vapor retarder primarily minimized the magnitude of the swing in moisture accumulation between winter and summer months without significantly affecting the average moisture accumulation over the 20-year period. These results show that using a vapor retarder in the roofing assembly offered no significant advantage, thus contradicting popular assumptions.

The simulations indicate that, even in Climate Zone 7, a roof assembly without the retarder could perform just as well as the one with the vapor retarder so long as there were a sufficient number of summer days with warm temperatures (where the temperature gradients cause the vapor drive from outside to the inside). In these conditions, the moisture content would reach a dynamic steady state, with the accumulation of moisture during the winter months being equal to the "drying" of the OSB during the summer months. This concept of a "self-drying roof" has been recognized by previous investigators.[12,13]

Notably, the simulation shows that the vapor retarder in the roof assemblies had minimal effect on moisture accumulation. Although the simulation illustrated the performance of a wooden composite deck, the conclusions on the role of the vapor retarder also hold true for a metal deck.

Moisture Profiles in the Assembly

The development of moisture profiles across the roof assembly provides insight into the

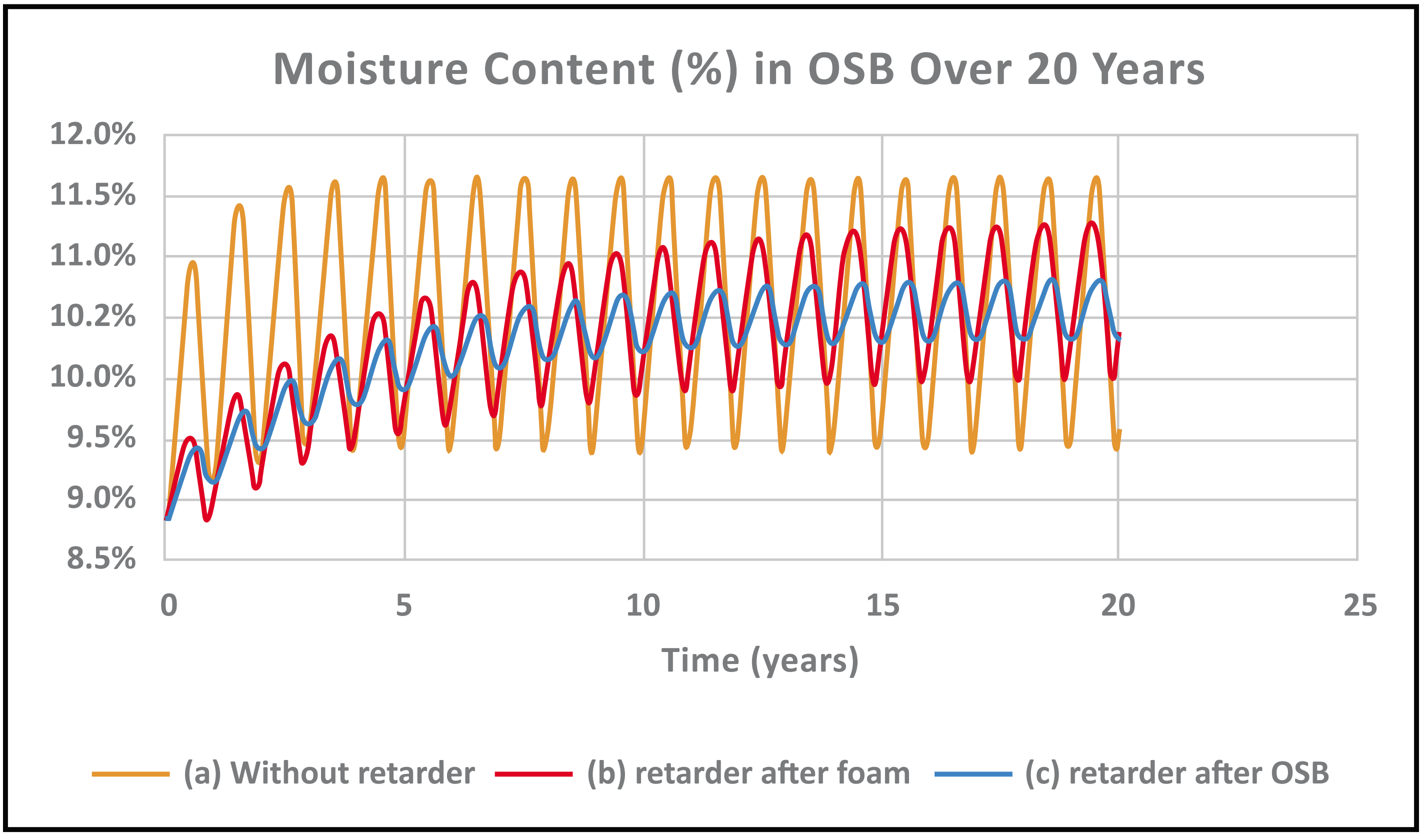


Figure 3. *Moisture content in the oriented strand board, 2000–2020.*

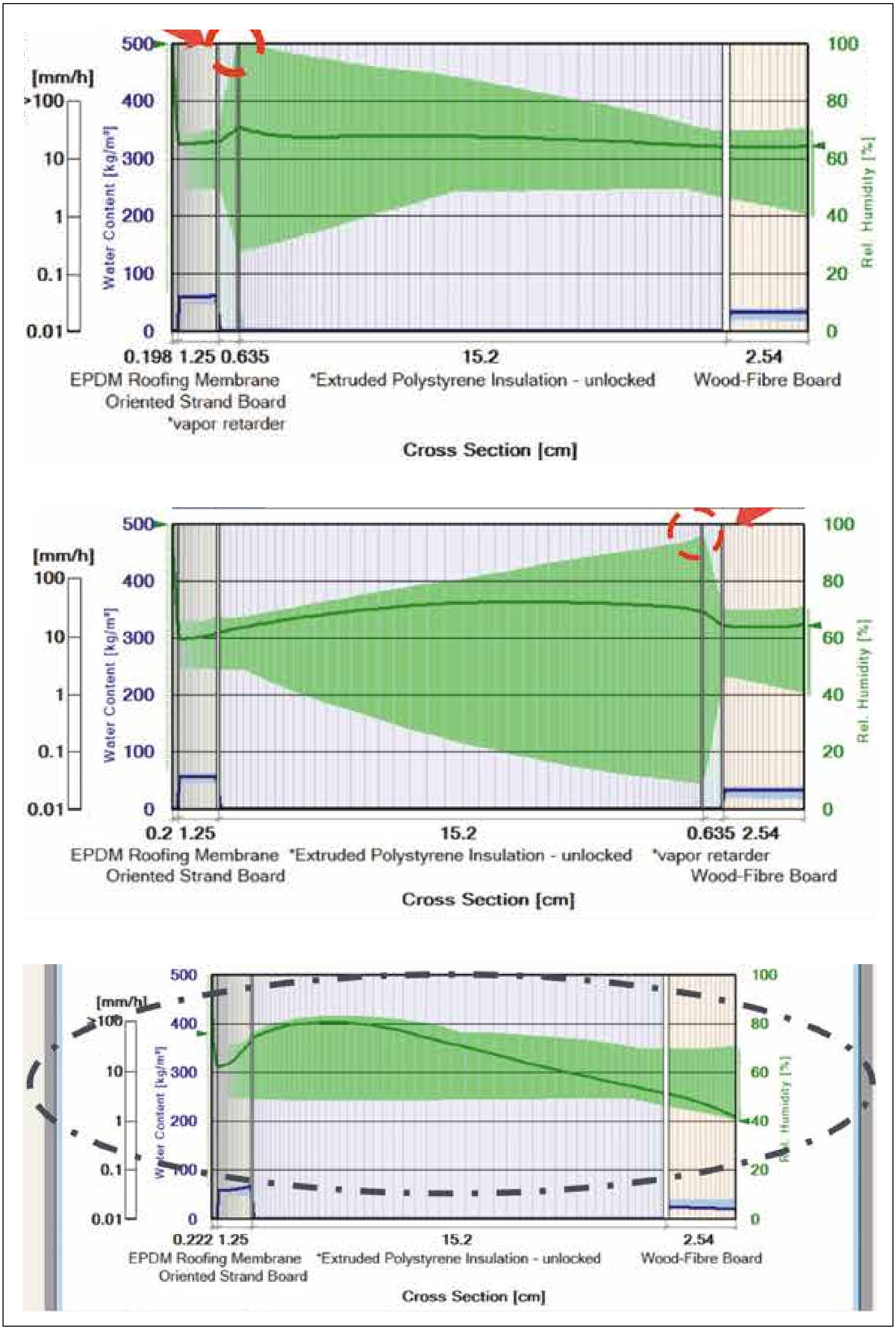


Figure 4. *Moisture distribution profiles in the roof assemblies, 2000–2020: (a) without vapor retarder; (b) with vapor retarder after the installation of XPS foam; and (c) with vapor retarder after installation of the OSB. The green regions represent the range of the relative humidity profiles in each component of the roof deck. These profiles are calculated based on partial vapor pressure corresponding to the equilibrium moisture content in each component at a given instant. The green lines represent the instantaneous relative humidity profiles. The blue lines represent the moisture content in each component (primary axis). Note: EPDM = ethylene propylene diene monomer; OSB = oriented strand board; XPS = extruded polystyrene. 1 kg/m*^{3} *= 0.062 lb/ft*^{3}.

dynamics of moisture migration and buildup inside the roof during the 20-year study period. **Figure 4** shows the distribution of the moisture profiles through each layer during the 20 years of simulated life. It is important to note that when the roof deck assembly did not have a vapor retarder (Fig. 4a), the maximum relative humidity reached in the assembly did not exceed about 80%.

However, when the roof deck assembly had a vapor retarder (Fig. 4b and 4c), the maximum relative humidity at the foam-retarder interphase reached about 100%, indicating that moisture condensation was quite likely to occur at that location. While the vapor retarder lowered the moisture flux from inside to the outside during winter, its presence inside the assembly retarded the downward (from outside to inside) moisture flux through the foam during the drying cycle (summer). With the occurrence of condensation at the foam-retarder interface, there would be a risk of mold or mildew buildup in the assembly.

In the case of a metal roof deck, with the retarder on the warm side, condensation would be associated with an increased risk of corrosion of the metal as the condensed water could seep through pathways created by screws and other anchoring hardware. Therefore, in general, using a vapor retarder would pose a higher risk and would not provide the intended safety of preventing condensation in the roof assembly in cold climates. These conclusions, which contradict common understanding and practice, can be generalized for natatorium roofs in Climate Zones 1 through 7.

In general, in addition to the roof deck attributes mentioned in this article, a good basis for natatorium roof design should include the following: (a) a continuous air barrier, (b) appropriate HVAC design and operation,[3] and (c) minimization of stack pressure by fan control.

CONCLUSION

The steady-state dew point analysis model used by many practitioners of roof deck design does not accurately characterize moisture transport in roof decks. As a result, its use can lead to suboptimal design. Hygrothermal modeling can accurately predict roof deck performance. Simulation results of a roof deck assembly in a natatorium in Climate Zone 7 derived from a widely used hygrothermal simulation model show that—contrary to the assumptions behind common practice—a vapor retarder does little to affect moisture transport and condensation in a roof deck assembly in the long run.

In Climate Zone 7, despite a high-moisture load in the natatorium, the roof deck assembly with or without a vapor retarder can be self-drying, with the moisture content in the OSB maintained below the "at-risk" level of 20%. Furthermore, this study shows that a vapor retarder can increase the risk of condensation by hindering the downward drying (outside to inside) and thus increase the risk of corrosion in a metal roof deck. Thus, contrary to common belief, a vapor retarder provides a false sense of safety (with regard to moisture transport and condensation) as it does not prevent or reduce the risk of moisture condensation and buildup in roof decks in cold climate zones.

REFERENCES

1. Lochner, G., and L. Wasner. 2017. "Ventilation Requirements for Indoor Pools." *ASHRAE Journal.* 59 (7): 16–24.
2. Acoustical Society of America (ASA). 2019. *Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools, Part 4: Acoustic Standards for Physical Education Teaching Environments.* ANSI/ASA S12.60-2019/Part4. Melville, NY: ASA.
3. ASHRAE. 2021. Chapter 25: "Heat, Air, and Moisture Control in Building Assemblies." In *ASHRAE Handbook–Fundamentals*. Peach Tree Corners, GA: ASHRAE.
4. TenWolde, A. 1994. Chapter 11: "Design Tools." In *Moisture Control in Buildings: The Key Factor in Mold Prevention.* West Conshohocken, PA: ASTM International.
5. ASHRAE. 2021 *Criteria for Moisture-Control Design Analysis in Buildings.* ANSI/ASHRAE Standard 160-2021. Peach Tree Corners, GA: ASHRAE.
6. Kumaran, M. K. 2006. "A Thermal and Moisture Transport Database for Common Building and Insulating Materials (RP-1018)." *ASHRAE Transactions.* 112 (2): 485–497.
7. Fraunhofer Institute of Building Physics (FIBP). WUFI Pro Version 6.5. 2020. Munich, Germany: FIBP.
8. Desjarlais, A., H. H. Pierce, and S. Pallin. 2017. "Using Hygrothermal Modeling to Resolve Practical Low-Slope Roofing Issues." In *Advances in Hygrothermal Performance of Building Envelopes: Materials, Systems and Simulations*, ASTM STP1599, edited by P. Mukhopadhyaya and D. Fisler, 291–302. West Conshohocken, PA: ASTM International.
9. Mundt-Peterson, S. O., and L. Harderup. 2013. "Validation of a One-Dimensional Transient Heat and Moisture Calculation Tool under Real Conditions." In *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference, Oak Ridge National Laboratory, Oak Ridge, TN.* Peach Tree Corners, GA: ASHRAE.
10. Bludau, C., D. Zirkelbach, and M. H. Kunzel. 2009. "Condensation Problems in Cool Roofs. *Interface.* 27 (7): 11–16.
11. Kehrer, M., and S. Pallin. 2013. "Condensation Risk of Mechanically Attached Roof Systems in Cold Climate Zones." Presented at the 28th RCI International Convention and Trade Show, Orlando, FL, March 14–19, 2013.
12. Desjarlais, A. 1995. "Self-Drying Roofs: What?! No Dripping?!" In *Proceedings of the Thermal Performance of the Exterior Envelopes of Buildings, VI Conference, 1995, Clearwater, Florida*, 763–773.
13. Bludau, C., H. M. Kunzel, and D. Zirkelbach. 2010. "Hygrothermal Performance of Flat Roofs with Construction Moisture." In *Proceedings, Buildings XI, Oak Ridge National Laboratory, Oak Ridge, TN.* Peach Tree Corners, GA: ASHRAE.

ABOUT THE AUTHOR

GOURISH SIRDESHPANDE, PHD

Gourish Sirdeshpande, *PhD, is a senior principal scientist at STR Resources in Lancaster, Pennsylvania. Previously, he was a senior principal scientist in research and development at Armstrong World Industries Inc., with over 35 years of experience. His interests are in heat and mass transfer modeling, composite materials, building energy, and indoor environment quality. He is the vice-chair of ASTM D22.05 on Indoor Air Quality and a member of the US delegation for ISO TC146-SC6 on Indoor Air Quality. He is a member of ASHRAE, ISIAQ, ASTM, and AIChE. He is also a member of ASTM D08.*

Please address reader comments to chamaker@iibec.org, including "Letter to Editor" in the subject line, or IIBEC, *IIBEC Interface* Journal, 434 Fayetteville St., Suite 2400, Raleigh, NC 27601.