A Prototype Universal Building Envelope Hygrothermal Performance Standard for Successful Net-Zero Energy Building Design

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ABSTRACT

A prototype universal building envelope hygrothermal performance standard that is intended to apply to all above- and below-grade envelope components is described. The standard is expressed as a definition of a water separation plane followed by a set of three requirements. The requirements are applicable to the envelope components on the interior and exterior sides of the water separation plane and on the interior side only when the exterior side components are structurally and biotically inert. The standard is discussed using experimental data to illustrate salient features. Application examples for an above-grade wall system and a commercial roof system are presented and their hygrothermal performance evaluated in terms of the universal standard requirements.

INTRODUCTION

Recent research (Goldberg 2010) has demonstrated that net-zero energy buildings are feasible in a cold climate in which the annual on-site solar photovoltaic generated electrical energy can exceed the annual energy consumption for heating, ventilating, and air conditioning by a factor of three or more. In order to achieve this level of performance, the building envelope incorporated foundation wall, above-grade wall, and roof/attic insulation with thermal resistances of 20, 40, and 80 $ft^2{\cdot}°F{\cdot}h/Btu$ (3.52, 7.04, and 14.09 $m^2{\cdot}K/W$), respectively. The envelope infiltration was reduced to 0.10 cfm/ft^2 (5.08×10^{-4} $m^3/s{\cdot}m^2$) at 50 Pa (1.04 lb_f/ft^2) envelope pressurization, while the minimum continuous ventilation rate was in compliance with the 2009 Minnesota Energy Code (State of Minnesota 2009a). For example, this required a continuous ventilation rate of 75.7 cfm (3.57×10^{-2} m^3/s) for a conditioned space of 3824 ft^2 (355.3 m^2).

These levels of envelope sealing and insulation thermal resistance pose significant challenges for building envelope durability beyond those currently experienced for typical new energy code compliant construction in cold climates. In addressing these issues for building foundation walls in Minnesota, research was undertaken (Goldberg and Huelman 2005) that led to the development of a set of hygrothermal durability performance criteria for foundation wall systems that have been embodied in the Minnesota Energy Code (State of Minnesota 2009b). These performance criteria have been generalized to the entire building envelope (Goldberg and Huelman 2009) and have been shown by proprietary research to be universally applicable for all climates (Goldberg and Stender 2009a, 2009b, 2009c). The universal performance criteria will be listed first in their entirety followed by a discussion and explanation.

UNIVERSAL BUILDING ENVELOPE HYGROTHERMAL PERFORMANCE STANDARD

The Universal Performance Standard is expressed as a basic definition combined with three requirements.

Basic Definition: Water Separation Plane

A *water separation plane* (WSP) is a single component or a system of components creating a plane that effectively resists capillary water flow and water flow caused by hydrostatic pressure and provides a water vapor permeance of 0.1 perms (5.75 $ng/s{\cdot}m^2{\cdot}Pa$) or less to retard water-vapor flow by diffusion.

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Requirement 1: Hygrothermal Performance

The building envelope shall be designed and built to have a continuous WSP between the interior and exterior. The envelope components on the *interior* side of the WSP must

a. have a stable annual wetting/drying cycle, whereby envelope system water (solid, liquid, and vapor) transport processes produce no net accumulation of ice or water over a full calendar year;
b. have an envelope system that is free of surface condensation for at least 4 months over a full calendar year;
c. have a twenty-four-hour running average sorption isotherm maximum moisture content corresponding to a surface equilibrium relative humidity of 80% at 20°C (68°F) and 1 bar (14.5 psi) in all moisture absorbent materials over a full calendar year;
d. prevent conditions of moisture and temperature from prevailing for a time period favorable to mold growth for the materials used; and
e. prevent liquid water from any vertical or inverted surface (that is, ceilings or roofs) reaching the adjoining or subvening floor system at any time during a full calendar year.

The envelope components on the *exterior* side of the WSP must either comply with stipulations a, b, c, and d or be structurally and biotically inert under conditions of continuous *and* intermittent immersion in water. Hence, the first alternate stipulation permits the use of wood-based materials on the exterior side of the WSP.

Requirement 2: Water Separation Plane Installation

The WSP shall be designed and installed to prevent external liquid or capillary flow across it after all exterior finishes and/or envelope component layers are installed.

Requirement 3: Air Barrier System

The building envelope system shall be designed and installed to have an air barrier system (ABS) between the interior and the exterior with the following requirements:

a. The ABS must be a material of combination of materials that is continuous with all joints sealed and is durable for the intended application.
b. Material used for the ABS must have an air permeability not to exceed 0.004 $ft^3/min \cdot ft^2$ under a pressure differential of 0.3 in. water (1.57 psf) (0.02 $L/s \cdot m^2$ at 75 Pa), as determined by either commonly accepted engineering tables or by being labeled by the manufacturer as having these values when tested in accordance with *ASTM Standard E2178-03, Standard Test Method for Air Permeance of Building Materials* (ASTM 2003).

In terms of this specification, there is no restriction on the WSP also serving as the air barrier and in most circumstances this would be the typical application. Further, the insulation system can be of any type and of any thermal resistance, provided that Requirements 1, 2, and 3 are met. In other words, there is no restriction on exceeding prescribed energy code minimum thermal resistance values to any desired extent or limiting the choice of insulation to types explicitly mentioned in an energy code.

DISCUSSION OF UNIVERSAL HYGROTHERMAL PERFORMANCE STANDARD

The essential element that differentiates the proposed standard from previous prescriptive approaches is the requirement of a WSP that explicitly creates a plane that separates the interior from the exterior across which all forms of water transport are nominally prevented. Thus building envelope components with a WSP are vapor closed, that is, vapor cannot traverse the component from the interior to the exterior. This closure is necessary in net-zero energy buildings to realize the very low envelope infiltration rates required and to minimize latent loads in the cooling season caused by the ingress of humid outside air, especially when exhaust-only ventilation systems are utilized. Thus, vapor entering the wall system from the exterior can only dry to the exterior, and vapor sourced from the interior can only dry to the interior.

The dynamics of the vapor management system design are specified in terms of Requirement 1. The specific elements of the requirement have been derived from at least 20 experiment-years of above- and below-grade building envelope testing in which most WSP locations in above- and below-grade wall assemblies have been evaluated (ESDP 2010). The principle concept is not to prohibit the formation of condensation within building envelope assemblies but to manage the condensation in such a way that it cannot produce mold and rot failures.

Hygrothermal Performance: Requirement 1(a)

With respect to the interior side of the WSP, Requirement 1(a) stipulates that there can be no net accumulation of water in either liquid or solid phases over a calendar year. This ensures that the wall system is hygricly stable over the long-term (10 years or more).

Hygrothermal Performance: Requirement 1(b)

Requirement 1(b) is derived from extensive work in testing building foundation wall systems (Goldberg 2002, 2004, 2006). The experimental data showed that if the envelope component condensing surfaces (typically the cavity side of interior vapor retarders and the interior wall surface) were free of surface condensation for at least 4 months during a calendar year, then the moisture content in the wall system never reached sustained levels that allowed the formation of mold and rot. This requirement does not stipulate that the 4 months of surface dryness be contiguous; however, it does require that the aggregate period of 4 months of dryness apply to the entire wall system simultaneously. This arises because in cold climates (such as Minnesota) with both exterior (summer) and interior (winter) sources of humidity, condensation occurs separately on the interior and exterior faces of the interior wall cavity. Thus, under these conditions, the wall system can have dry surfaces only throughout the assembly in the spring and fall swing months separating summer and winter. An example of this phenomenology is shown in Figure 1 for a foundation wall system comprising in interior to exterior order as follows: 0.5 in. (12.7 mm) gypsum board, 0.006 in. (0.152 mm) polyethylene vapor retarder, 24 in. (609.6 mm) on-center 2 × 4 stud frame with open-cell spray polyurethane insulation, 1 in. (25.4 mm) air gap, and 12 in. thick (304.8 mm) two-core masonry block wall.

With reference to Figure 1, the top panel reveals wetting of the wall surface (sensible temperature less than dew point temperature) from day 16 through about day 200 followed by intermittent drying through day 300 and more significant drying thereafter until about day 360. Thus, on the wall side, the period of surface dryness was about two months. The middle panel reveals the conditions in the insulation adjacent to the interior polyethylene vapor retarder. In this case, drying occurred for the first 192 days followed by wetting through day 348. Thus, the drying and wetting periods on the wall and vapor retarder cavity side surfaces are opposed. This is shown more explicitly in the bottom panel that plots the condensation

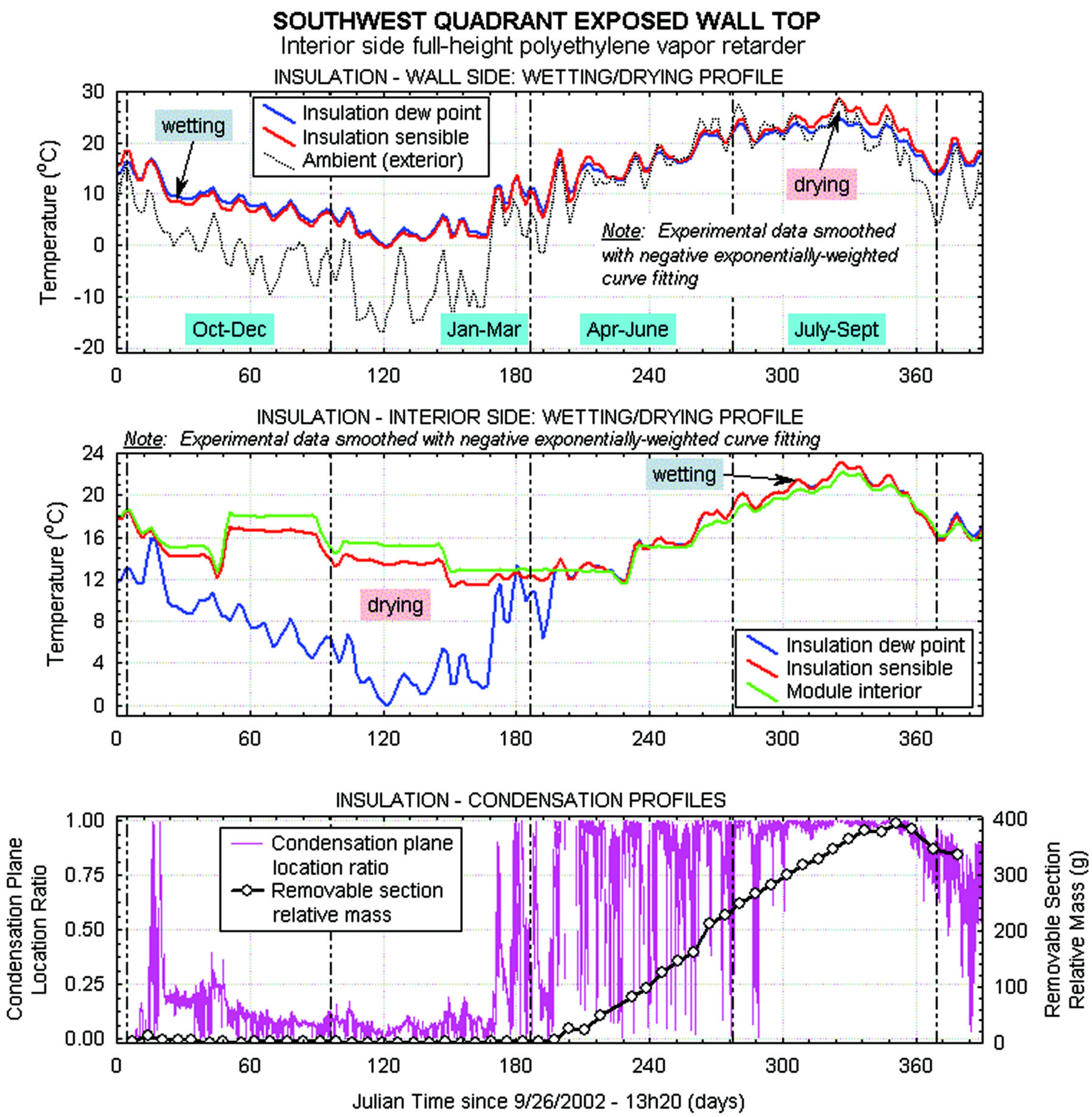

Figure 1 *Foundation wall assembly with warm-side vapor retarder wetting/drying performance.*

plane location ratio on the LHS axis (where a ratio of 1 indicates condensation on the vapor retarder side of the cavity). Condensation switches from the wall to the vapor retarder side around day 168 and back again around day 12. The removable section mass (a 1 ft [304.8 mm] square section of insulation that was removed for weighing) shows the amount of condensate absorbed when the condensation plane was on the vapor retarder surface. This wall configuration would not meet Requirement 1(b) because there is no instance when the entire wall system is dry simultaneously.

In contrast, consider Figure 2, which shows the same foundation wall system as Figure 1 except without a polyethylene warm side vapor retarder at all. In this case, the top panel shows a dry wall surface from at least day 216 through day 354 (4.6 months) that corresponds with the interfacial surface between the insulation and the gypsum also being dry, so meeting Requirement 1(b). It should be noted that in both cases discussed, the WSP would be a waterproofing membrane applied to the wall exterior.

Hygrothermal Performance: Requirement 1(c)

Requirement 1(c) is intended to address the traditionally difficult assessment of what constitutes a safe steady-state envelope system operating moisture content, particularly for wood-framed walls with exterior wood or wood-based

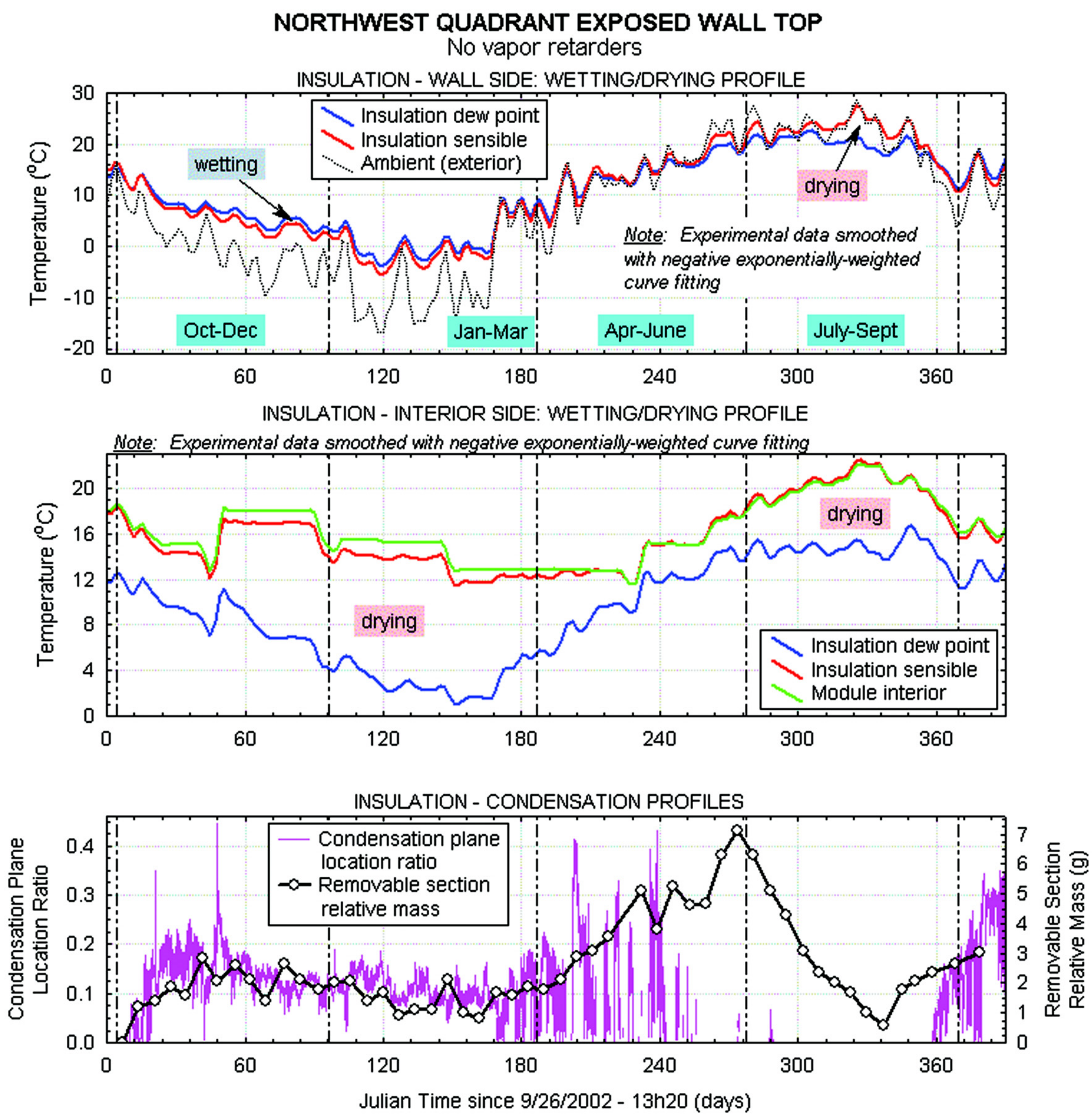

Figure 2 Foundation wall assembly without warm-side vapor retarder wetting/drying performance.

sheathing. The approach adopted to quantify an acceptable moisture content is based on *ANSI/ASHRAE Standard 160-2009, Criteria for Moisture-Control Analysis in Buildings* (ASHRAE 2009) and represents the endpoint of an evolutionary process. The intent was to develop a means of specifying moisture contents in a way that would be material independent, so the first approach was to specify moisture content in terms of saturation ratio (volumetric moisture content/(material porosity × water density)). Initially, Requirement 1(c) specified that the maximum saturation ratio over a calendar year could not exceed 10%. This yielded the results shown in Table 1 for a few common sheathing materials.

The 10% saturation ratio approach works well except for highly sorptive materials, such as wood fiberboard, in which it yields excessive moisture contents that were shown experimentally to produce surface mold growth (Goldberg and Huelman 2009). With this approach it was necessary to require that highly sorbent materials meet a 5% saturation ratio standard, which introduced the problem of defining what constitutes a *sorbent material*. This problem was overcome by adopting the approach used in ASHRAE Standard 160, which effectively specifies the material moisture content in terms of a surface relative humidity. This can be converted to a moisture content through the material's sorption isotherm.

In order to make this approach compatible with the numerical values in Table 1, which are based on empirical results, the three-tier temperature/relative humidity specification in ASHRAE Standard 160 was deemed insufficiently crisp to avoid application ambiguity in a building code context. Too great a departure from ASHRAE Standard 160 also was not desirable in order to retain credibility, so the compromise expressed in Requirement 1(c) was adopted, which allows a twenty-four-hour running average maximum relative humidity (RH) of 80% at the reference temperature and pressure cited. Note that in a cold climate in which the winter sheathing interior surface RH can approach 100% with a low sheathing moisture content (6% or less), this requires converting the measured winter RH to the RH at the reference temperature and pressure, so yielding the correct low surface RH for evaluation in terms of Requirement 1(c). This yields the results shown in Table 2.

Compared with Table 1, the RH-based specification is 13% more conservative for plywood, 5% more conservative for oriented strand board, but exactly the same as the 5% saturation ratio value for wood fiberboard. While being more conservative, the RH approach does allow a single-valued simple approach to maximum moisture content specification regardless of material sorbancy. Clearly, this conservative approach can be criticized as being excessively dry; however, particularly in the context of net-zero homes, it is judged to be prudent. This is particularly of note when these homes are required to operate at higher internal RHs for medical reasons (such as for people with bronchial and related diseases and allergies) and even for maintaining the condition of musical instruments.

Hygrothermal Performance: Requirement 1(d)

The wording of this requirement was formulated during the committee process that led to the adoption of the 2009 Minnesota Energy Code foundation wall performance clauses (State of Minnesota Statutes 2009B). Originally (Goldberg and Huelman 2005), the requirement was worded as "… a building foundation system shall be designed to have no visible or olfactory fungal or other biotic activity." The clear intent was to require no mold or rot at all using the detection methods usually adopted in practice. However, given that human-based detection methods are not objective from a building code perspective, defining a mold prohibition in terms of temperature and RH achieves the same purpose, especially for design calculation purposes. Data on fungal growth characteristics in terms of temperature and RH, usually expressed as isopleths parametric in germination time, are available (for example, Sedlbauer et al. [2001]).

Hygrothermal Performance: Requirement 1(e)

This requirement is included to eliminate excessive condensation. In theory, it is possible to have an envelope system that complies with Requirements 1(a)–1(d) but that can still produce excessive amounts of condensation during wetting periods. The liquid rundown prohibition limits the amount of allowable condensation to the amount that can be absorbed by the condensing plane material before it reaches saturation. This naturally accounts for different materials so that the amount of condensation that can be tolerated by wood fiberboard is orders of magnitude larger than can be tolerated by the surface of a polyethylene membrane (as an extreme exemplar).

Requirement 1 is completed by generalizing its application to the exterior of the WSP. This is accomplished by stipulating

Table 1. Saturation Ratio-Based Moisture-Content Specification

Material	Saturation Ratio, %	Mass-Based Moisture Content, %
Oriented strand board	10	12.8
Plywood	10	15.2
Wood fiberboard	10	30.4
	5	15.2

Table 2. Relative Humidity-Based Content Specification

Material	Moisture Content at 80% Surface Relative Humidity at Fiduciary Conditions, %
Oriented strand board	12.2
Plywood	13.2
Wood fiberboard	15.2

two options. The first option requires that the envelope outside the WSP be immune to structural failure, mold and rot both when continuously and intermittently immersed in water. This covers above- and below-grade building components exterior to the WSP that generally are composed of masonry or corrosion-resistant metals. For example, in the case of a cold-climate building foundation wall in which the WSP is a waterproofing layer applied to the *interior* surface of a masonry block wall, the wall cores would have to be drained in order to prevent structural failure through the freezing expansion of water in the cores.

Alternately, if the wall system is fabricated from organic materials or materials that can sustain mold growth outside the WSP, then all requirements except 1(e) must be met on the exterior of the WSP as well. Clearly 1(e) is excluded to allow for drainage of entrapped water from the exterior wall system.

This formulation eliminates the performance ambiguities inherent with current practice in which, for example, the water-resistive barrier is simultaneously required to be sufficiently vapor permeable to allow drying to the exterior while being sufficiently waterproofing to exclude bulk water intrusion.

Water Separation Plane Installation: Requirement 2

As the WSP is the critical component in the envelope system, Requirement 2 is inserted to avoid the problem with many current prescriptive codes in which critical components are inspected and passed prior to closing, are then damaged during the closing process, and eventually produce service failures. A very common example of this modality happens with exterior foundation wall insulation and waterproofing systems. Such systems are inspected prior to backfilling and then are damaged, often severely, by the backfilling process itself. Similar problems occur with cladding products that are stapled to the sheathing. Very often the staples used are too long or misplaced so that they penetrate the sheathing on the interior, producing condensation initiation points in cold climates. The resulting condensate can produce mold and rot at all the sheathing entry points. Requiring that the WSP be fully functional after the wall system is enclosed mandates that the closure be undertaken with due care and diligence to avoid damage. Also, it provides a clear benchmark for assigning liability in the event that the WSP is damaged during the wall system closure.

Air Barrier System: Requirement 3

Typical air barrier code language (State of Minnesota 2009c; IRC 2006) is entirely prescriptive, with language such as "… shall be continuously sealed to limit the leakage of air through the thermal envelope" (State of Minnesota 2009c) followed by a list of envelope locations that must be sealed. Unfortunately, some formulations of the prescriptive air sealing language also include a specification of the location of the air barrier, such as "The air barrier shall be installed on the warm-in-winter side of the thermal insulation" (State of Minnesota 2009c). Such formulations can lead to very significant problems, most typically confusion between sealing the envelope against outside-air infiltration and sealing the vapor retarder against vapor bypass. "Vapor bypass" is distinct from vapor advection and is a vapor transport mechanism in still air that produces excessive condensation on a downstream surface by unconstrained diffusion through low-permeability, parallel air paths that bypass the vapor retarder.

For example, consider the following above-grade experimental wall system in exterior to interior sequence: stucco; two-layer, 60-minute grade-D building paper; faced fiberglass batts without tabs; 2-mil (0.0508 mm) polyamide-6 facing; edge sealed 0.5 in. (12.7 mm) gypsum board; and 3 coats of latex paint. In this case, the gypsum functions as the air barrier in terms of the above traditional code definition, but the unsealed batt facing creates a vapor bypass around its edges. As shown in Figure 3 (Goldberg and Huelman 2009) for a northern exposure, this mechanism leads to a failure of Requirement 1(c). Moist air from the interior readily diffuses through the gypsum, even though advective transport is nominally blocked. The moist air bypasses the batt-facing vapor retarder at its edges, diffuses through the fiberglass batts, and condenses on the sheathing surface, yielding a maximum sheathing moisture content at day 140 in excess of 23% (top panel of Figure 3). The top panel also shows condensing conditions prevailing on the sheathing surface from day 0 through day 200, about the beginning of May (note that these data were collected at a test facility located near Duluth, MN, that has a very cold climate). The conventional air barrier language is insufficient to address this issue.

In the Universal Performance Standard, the infiltration vapor bypass and air sealing issues are separated and dealt with individually in Requirements 1 and 3, respectively. The vapor bypass avoidance is folded into the hygrothermal performance requirements; in other words, with reference to Figure 3, eliminating vapor bypass is necessary to meet Requirements 1(b), 1(c), and 1(d). Requirement 3 only governs the sealing of the envelope system against air infiltration. The language is exactly the same as in the current Minnesota Energy Code foundation wall performance option (State of Minnesota 2009b) and provides a quantitative rather than a

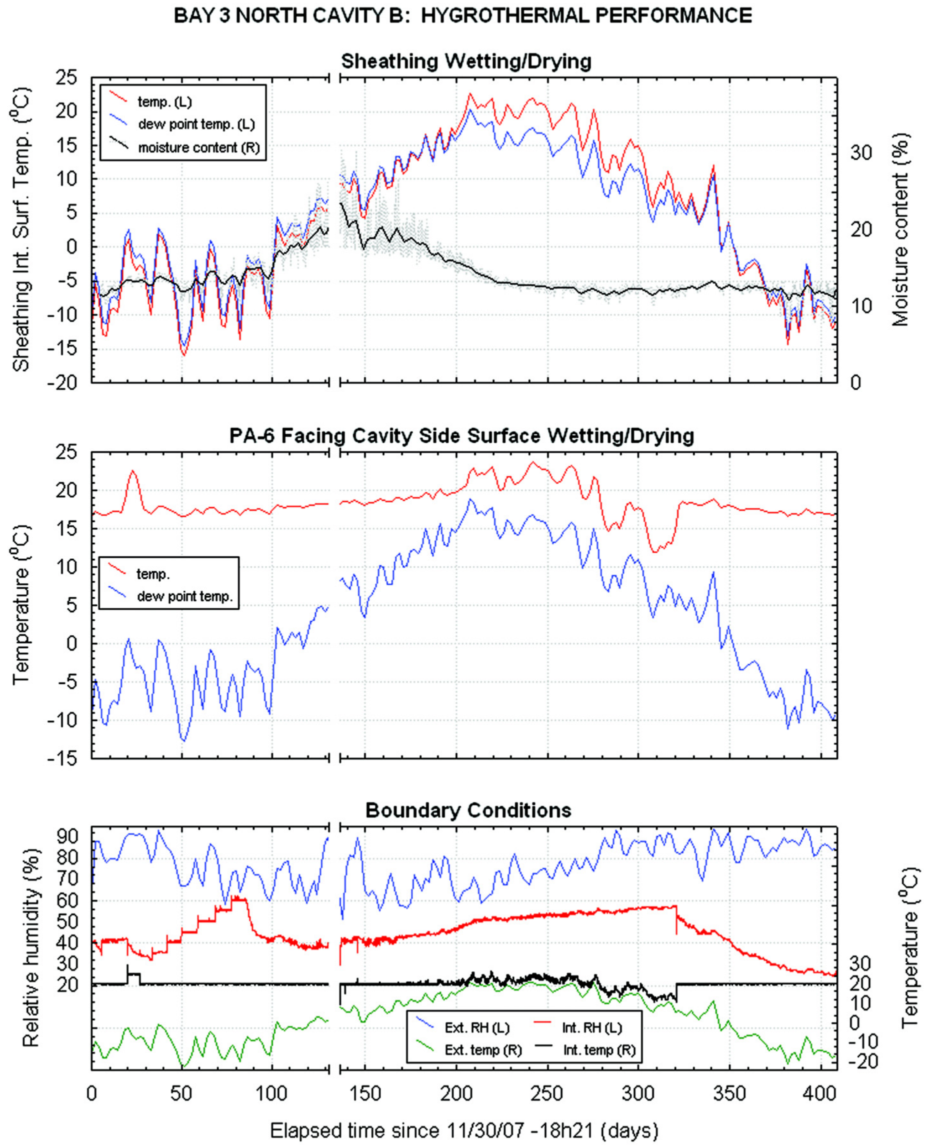

Figure 3 *Above-grade wall system north exposure cavity hygrothermal performance.*

prescriptive standard for materials qualifying for use as an air barrier based on the Canadian Construction Materials Centre test procedure (Di Leonardo 2000). Further, there is no restriction on the location of the air barrier; it can be located at any plane in the building envelope system. Typically, as noted previously, the WSP also functions as the air barrier.

The air barrier formulation of Requirement 3 is not yet optimum because Requirement 3(a) is still essentially prescriptive in nature and, thus, is open to interpretation and subject to inspection limitations. For example, the "all joints sealed" language requires visual inspection to insure compliance, and such inspection is purely qualitative.

A far preferable specification for Requirement 3 would be to specify a true performance standard for air leakage based on a whole building leakage test. For example, language such as the following:

> The building envelope system shall be designed and installed to have an air barrier system (ABS) between the interior and the exterior with the following requirement: The whole house air leakage rate shall not exceed 0.10 cfm/ft^2 (5.08×10^{-4} m^3/s·m^2) at 50 Pa (1.04 lb$_f$/ft^2) pressurization when tested with a single-point certified and calibrated blower door test apparatus.

The level of air tightness would be directly measurable and not prescriptive. There also is an issue of how overall envelope air tightness relates to the local impacts of air leaks on the durability of assemblies. As these local impacts typically manifest in condensation effects, their management is covered by the clauses of Requirement 1. The numerical value of the measured air leakage is debatable (and clearly a function of the level of envelope energy conservation desired), so the numerical value suggested is based on a practically realizable value that has been shown to yield net-zero energy performance (Goldberg 2010). However, during the code committee process leading to the adoption of the foundation wall performance standard (State of Minnesota 2009c), it became abundantly clear that the building industry had little appetite for such an approach and, therefore, it was not adopted.

APPLICATIONS OF THE UNIVERSAL STANDARD

Two applications will be presented. The first demonstrates how a literal application of the standard to a residential wall system can be insufficient without a thorough grasp of the hygrothermal physics of wall systems, while the second shows a successful application to a commercial roofing system.

Residential Wall System Application

An above-grade wall system that nominally meets the Universal Performance Standard is defined by the following layers in order of exterior to interior: Stucco (cladding); high temperature modified bituminous coated polyethylene membrane (WSP); 0.781 in. (19.8 mm) thick wood fiberboard (sheathing); unfaced fiberglass batts in 2 × 6 wood stud frame; 0.002 in. (0.0508 mm) polyamide-6 (PA-6) membrane; 0.5 in. (12.7 mm) gypsum wall board; and three coats latex paint. In this case, the bituminous coated polyethylene membrane forms the WSP and the system air barrier. The PA-6 membrane, having an RH-dependent permeance, retards heating season vapor diffusion from the interior when the interior RH is moderate (generally less than 45%) but allows any vapor generated by condensate within the cavity to diffuse back to the interior during the cooling season when the envelope vapor pressure gradient reverses. Previous research with PA-6 vapor retarders in a foundation wall application (Goldberg 2006) revealed that the transition point at which PA-6 becomes a nominal class II vapor retarder (with a permeance less than 1.0 perms (57.5 ng/s·m^2·Pa) is somewhat elastic and can permit fairly significant vapor diffusion at interior RHs as low as 40%. Thus, the wood fiberboard sheathing, being highly sorptive, is designed to function as a condensate buffer by safely absorbing any condensate diffusing through the PA-6 during the heating season before allowing it to dry out to the interior during the following cooling season.

This system was tested at a cold climate test facility through the 2008 calendar year (Goldberg and Huelman 2009) with a deliberately severe interior boundary condition protocol, as shown in the bottom panel of Figure 4. The interior temperature and RH profiles are defined by the black and red lines, respectively. From day 0 through day 30, the test bay was first pulsed with moisture and then allowed to dry out to a low interior RH of 30%. Thereafter, the interior humidity was increased in 5% increments every two weeks to a maximum of 60% before being set at 40% to obtain the envelope drying response. Interior humidification was discontinued after day 100 to monitor the natural response of the envelope through the balance of the year. The interior temperature was held constant at 68°F (20°C) from day 0 through day 200 and from day 320 to the end of the experiment. The interior temperature was allowed to float during the intervening period. Critics can certainly argue that this is an extremely harsh and practically unrealistic test regime; however, the intent was to push the limits to determine the hygrothermal performance with a significantly high signal-to-noise ratio.

The hygrothermal performance of the wall-system sheathing is shown in the top and middle panels of Figure 4 for the northern exposure that represents the worst case hygrothermal loading. With reference to the top panel, during the first 170 days (heating season), there are no periods evident where the dew point temperature exceeds the sensible temperature, but there instances when the two temperatures are equal. This is a characteristic of highly sorptive materials and indicates that the wood fiberboard surface did not reach a saturated condition. The sheathing reached a maximum average moisture content of about 24% (bold black line) and a maximum transient moisture content (dotted fuzzy black line) of about 26%. Note in Table 1 that these values correspond to a saturation ratio less than 10%, so the wood fiberboard was well within its safe moisture carrying capacity; however, in terms of Requirement 1(c), it exceeded the allowable maximum moisture content of 15.2% (Table 2) by a significant margin. It is also interesting to note that the maximum sheathing moisture content (measured as an average over the inside half thickness) achieved its maximum around day 135, a full month after interior humidification ceased at day 105. This is doubtless a result of the liquid diffusion characteristics of wood fiberboard in which a month was required for surface adsorbed condensate to migrate into the bulk material.

The middle panel of Figure 4 shows stable and unproblematic hygrothermal conditions on the cavity side of the PA-6 membrane. No condensation occurred throughout the test period, particularly from days 180 through 220, during which the sheathing dried to the interior. Note that the water separation plane on the sheathing exterior effectively eliminated any drying to the exterior.

As noted, the system failed Requirement 1(c) by a significant amount and, in fact, also failed Requirement 1(d) as shown in Figure 5, which depicts the mold growth on the cavity side surface of the wood fiberboard discovered when the wall system was dismantled.

This example demonstrates that a wall system design that should work in theory does not work in practice because, regardless of the fact that the wood fiberboard was operating well within its safe moisture carrying capacity, that safe carrying capacity is sufficient to create mold growth. The example also demonstrates that the Universal Performance Standard is effective guidance for producing durable designs.

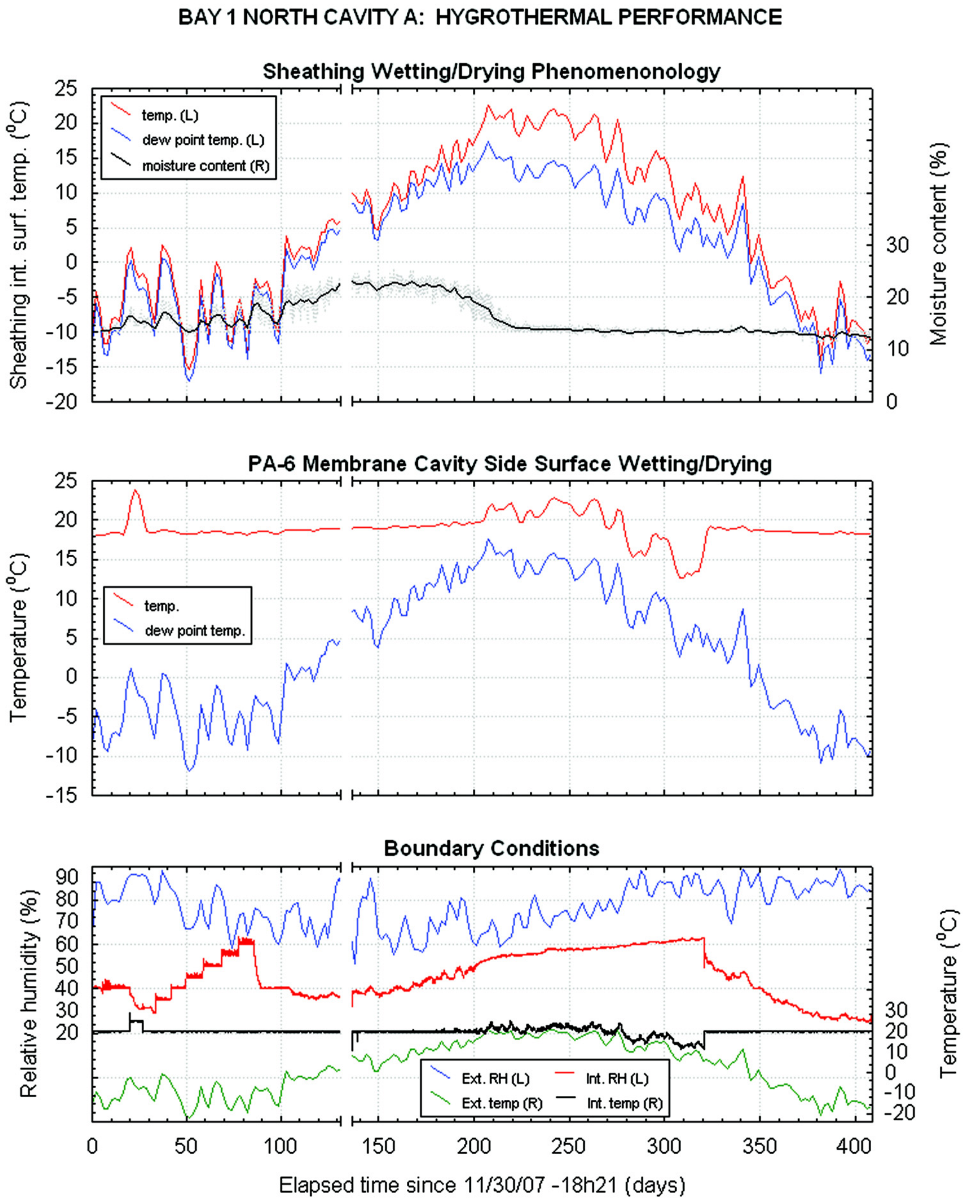

Figure 4 *Nominally Universal Standard compliant wall system hygrothermal response.*

Further, it demonstrates that in order for this kind of envelope wall design to work effectively, it needs to be vapor open—that is, the sheathing must have the potential of drying to the interior and the exterior. However, as discussed at the outset, this is not desirable for net-zero buildings. Thus, it may be argued that such a design is inherently unsuitable for net-zero energy applications.

Commercial Roof System Application

The second application was designed as a retrofit (Figure 6) for an existing commercial roof that failed as a result of the rotting of the plywood roof deck (Goldberg 2007). The water separation plane was placed beneath the shingles and replaced the more conventionally used roofing felt. The critical component was the insulating closed-cell spray polyurethane foam that also served as the system vapor retarder because the ceiling panels were vapor permeable. For this reason a high-density foam was selected that yielded a net permeance of 0.44 perm (25.3 ng/s·m^2·Pa) for the 2.5 in. (63.5 mm) design insulation depth. Note there are no vapor retarders on the warm-in-winter side of the insulation. The complicating factor in the design was the necessity of applying the spray foam insulation from the exterior since it was a retrofit application.

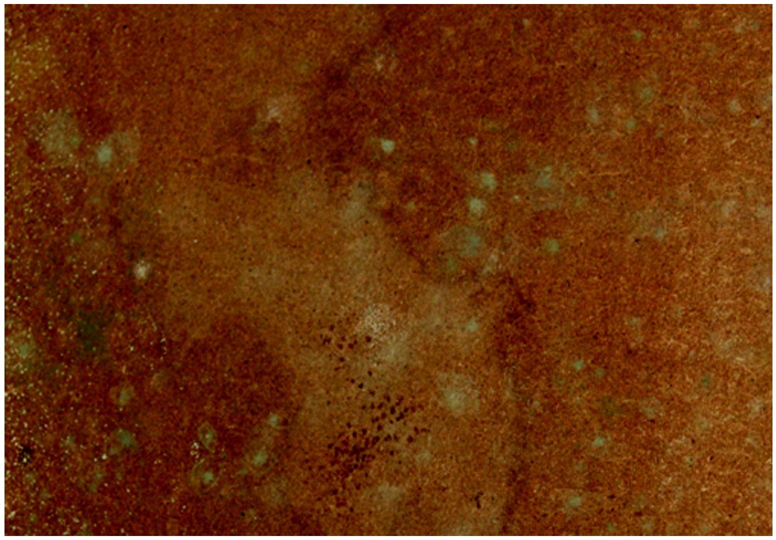

Figure 5 *Mold growth on cavity side surface of wood fiberboard sheathing.*

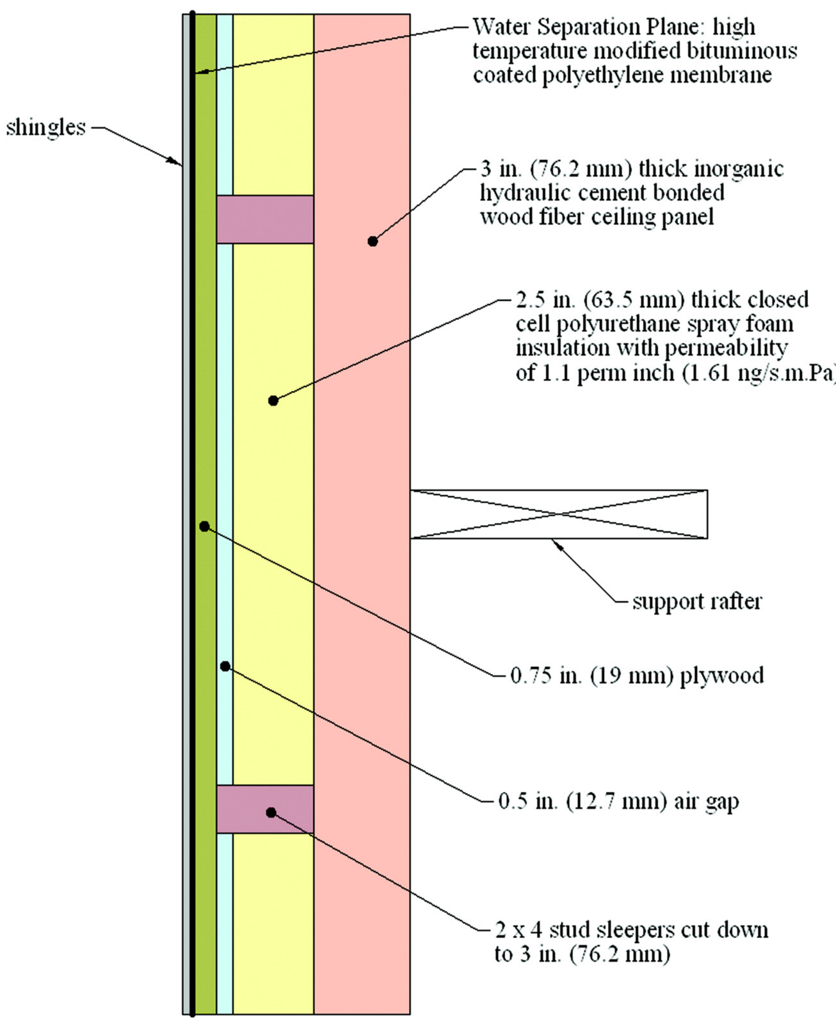

Figure 6 *Universal Standard compliant roofing system.*

Every effort was made to fill the sleeper cavities entirely by an application technique that initially overfilled the cavities and then ground the insulation flush with the sleepers using a barrel grinder. However, there were residual air pockets with an average depth of about 0.5 in. (12.7 mm), and so a uniform air gap of this dimension was included in the design as a factor of safety.

Transient exterior boundary conditions were derived from the Typical Meteorological Year (TMY2s) (Marion and Urban 1995) climate for Minneapolis, MN. This is indicated by the acronym "TMY" in Tables 3 and 4. Two sets of interior boundary conditions were evaluated. The first (denoted by "ASHRAE" in Tables 3 and 4) is based on the summer and winter comfort zones for people engaged in sedentary activity (ASHRAE 2001). This yielded cooling season (summer) conditions of 73°F (22.8°C) dry-bulb temperature and an RH of 77.9%, and heating season (winter) conditions of 68°F (20°C) dry-bulb temperature and 45% RH. The latter, somewhat elevated winter RH captured the actual interior setpoint of a musical instrument storage room in one of the retrofitted buildings. The second set of interior boundary conditions was derived from ASHRAE Standard 160 (ASHRAE 2009) (denoted as "ANSI-ASHRAE 160" in Tables 3 and 4) using the simplified method. For design purposes, this was reduced to 75°F (23.9°C) dry-bulb temperature and 70% RH in the cooling season and 70°F (21.1°C) dry-bulb temperature and 40% RH in the heating season. In both cases, the heating and cooling boundary conditions were linked by linear ramps.

The design was evaluated using the WUFI version 2.1 two-dimensional hygrothermal simulation program (IBP 2000). The cross section shown in Figure 6 was simulated for a period of ten years for each of the interior climate conditions, and the results are reported in Tables 3 and 4. Table 3 shows that the annual maximum plywood roof deck moisture content of 9.43% on a condensing plane was well below the 13.2% maximum permitted by Requirement 1(c). The maximum RH on any condensing surface was 83.4%, well below the approximately 95% RH threshold at which condensation initiates (Kunzel 1995), so meeting Requirement 1(b). The maximum annual sleeper moisture content was 6.7%, about half the Requirement 1(c) maximum of 13.9% permitted for softwood. Owing to the very low moisture content of the roofing system and the absence of any condensation, there was no possibility for any bulk water flow out of the assembly, so meeting Requirement 1(e). Finally, the low RHs are generally below the critical level for mold growth under transient conditions (Sedlbauer et al. 2001), so fulfilling Requirement 1(d).

Table 3. Hygrothermal Performance of Roofing System in Tenth Year of Operation

Measurement Location	Exterior/Interior Climate			
	TMY/ASHRAE		TMY/ANSI-ASHRAE 160	
	Max. MC, %	Condensation—Max. RH, %	Max. MC, %	Condensation—Max. RH, %
Underlayment/sheathing interface at sleeper: sheathing side	8.62	No—79.6	8.54	No—79.2
Underlayment/sheathing interface at cavity center: sheathing side	8.54	No—79.2	8.53	No—78.8
Sheathing/cavity interface at sleeper: sheathing side	8.18	No—77.4	7.98	No—76.4
Sheathing/cavity interface at cavity center: sheathing side	9.26	No—81.2	9.43	No—83.4
At center of sleeper within air gap	5.69	No—76.8	5.49	No—75.6
Sleeper/Tectum interface: sleeper side	6.70	No—82.8	6.31	No—80.5
Insulation/Tectum interface: Tectum side	4.98	No—79.6	3.58	No—69.2

Table 4. Wetting/Drying Stability Performance of Roofing System in Tenth Year of Operation

Measurement Location—Exterior/ Interior Climate	Exterior/Interior Climate Wetting/Drying Stability, %	
	TMY/ASHRAE	TMY/ANSI-ASHRAE 160
Underlayment/sheathing interface at sleeper: sheathing side	–0.1	0.0
Underlayment/sheathing interface at cavity center: sheathing side	–0.2	–0.1
Sheathing/cavity interface at sleeper: sheathing side	–0.1	0.0
Sheathing/cavity interface at cavity center: sheathing side	–0.2	–0.1
At center of sleeper within air gap	–0.1	0.0
Sleeper/Tectum interface: sleeper side	–0.5	–0.5
Insulation/Tectum interface: Tectum side	–0.3	–0.4

The annual wetting/drying stability of the assembly is shown in Table 4. The annual wetting/drying stability criterion (Goldberg and Huelman 2009) is defined in terms of moisture content (MC) as follows:

[(MC at end of year) – (MC at beginning of year)]/(average MC during the year) < 5%

Table 4 reveals that the assembly yielded an annual wetting/drying cycle that was stable at all locations for both interior climates. Most of the values were negative, indicating that the system actually dried slightly in the 10th year of operation, with the maximum values of zero indicating absolute stability. Thus, Requirement 1(a) was met.

Requirements 2 and 3 are satisfied by locating the WSP on the exterior surface of the roof deck and by using a material specifically designed to seal roofing nail penetrations. The shingles on the exterior side of the WSP meet the condition of being biotically inert for the term of their warranty (although shingles can sustain surface mold after a lengthy service period, this normally does not affect their rain shedding effectiveness). As shingles are not a structural component, the structural inertness requirement is not applicable.

The simulation analysis reveals that the roofing system satisfied the universal hygrothermal performance standard.

CONCLUSION

The prototype universal building envelope hygrothermal performance standard discussed is a generalization of a standard already embodied in the building code statutes of the State of Minnesota for residential building foundation walls. Generalizing the standard from a building component subject to arguably the most severe hygrothermal conditions to the above-grade envelope yields a performance-based methodology for unambiguously designing durable building envelopes, regardless of the amount of insulation employed. The standard embodies an intact and continuous water separation plane that intrinsically creates a very high level of air tightness. The standard embodies various tenets that interact synergistically to ensure that mold and rot cannot occur, while yielding an envelope design that has a significant margin of safety. These features make the standard ideally applicable to the envelopes of net-zero buildings in which high levels of insulation and air integrity are necessary to achieve the low levels of energy consumption for heating, ventilation, and air conditioning that are necessary to meet the net-zero energy goal.

It is recognized that applying the universal standard demands a thorough understanding of the underlying heat and mass transport physics, perhaps making the standard somewhat inaccessible. For this reason, particularly from a building code perspective, the preferred implementation approach is to use the standard to develop a library of compliant envelope cross sections that can be expanded as new products and building methodologies are developed (an example is given for foundation walls in Goldberg and Huelman [2005]). Such a library can then be used for and adapted to specific designs by practitioners.

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