SUMMARY

In order to compare the efficacy of 2-mil PA-6 and 4-mil PE as warm-side vapor retarders and to clarify the impacts of stucco cladding on wall system hygrothermal phenomenology, eleven different above-grade envelope wall systems were continuously tested for a period of 13.5 months at the University of Minnesota’s Cloquet Residential Research Facility. Each system was tested simultaneously on both a north and a south wall exposure. Experimental hygrothermal performance data including sensible and dew point temperatures, relative humidities and sheathing moisture contents were collected continuously over the duration of the experiment with a data reliability in excess of 99%. A detailed photographic record of the dismantling of the all the test sections at the end of the experiment was assembled and reported herein.

A universal building envelope hygrothermal performance standard is presented as an extension of the building foundation wall hygrothermal performance criterion currently promulgated in the Minnesota Building Code and the performance of the tested wall systems is evaluated in terms of this standard.

As expected, none of the tested systems complied with the universal standard because none of the systems was designed specifically to comply with it. However, some of the systems tested did show that compliance with the standard is possible even for cavity insulated wall systems. In general terms, the results show that 2-mil. polyamide-6 vapor retarders yield superior hygrothermal performance as determined by sheathing moisture content to conventional 4-mil. polyethylene vapor retarders in the absence of complicating vapor bypass phenomenology. The negative consequences of vapor bypass effects at the edges of framing cavities in which the vapor retarder is not sealed to the framing were clearly demonstrated. The experimental data do not provide any evidence that stucco cladding is inappropriate for use in a cold climate or that stucco systems by themselves are the cause of wall system biotic failures.

TABLE OF CONTENTS

Definition of terms 3
A. INTRODUCTION 3
B. UNIVERSAL BUILDING ENVELOPE HYGROTHERMAL PERFORMANCE STANDARD 4
C. WALL SYSTEMS TESTED 6
D. INSTRUMENTATION 15
E. BOUNDARY CONDITIONS 17
F. RESULTS 18
   F.1 Section 1 – Sheathing Moisture Content 18
   F.2 Section 2 – Cavity Relative Humidity 28
   F.3 Section 3 – Detailed Hygrothermal Performance 43
G. TEST SYSTEM DISMANTLING 75
H. UNIVERSAL ENVELOPE HYGROTHERMAL PERFORMANCE STANDARD COMPLIANCE 130
I. CONCLUSIONS 132
J. REFERENCES 133
DEFINITION OF TERMS

Water Separation Plane (WSP) A single component or a system of components creating a plane that effectively resists capillary water flow and water flow caused by hydrostatic and hydrodynamic pressure and provides a water vapor permeance of 0.1 perms or less to retard water vapor flow by diffusion.

Water Resistive Barrier (WRB) A membrane applied to the sheathing exterior to resist the flow of bulk water by diffusion (capillary flow), hydrostatic pressure (gravity driven rundown) and hydrodynamic pressure (wind-driven rain) while allowing the transport of water vapor by diffusion.

Saturation Ratio (SR) The ratio of the water content mass to the maximum water content mass when liquid fills the entire pore volume within the material (given by the volumetric porosity multiplied by the water density at normal temperature and pressure (20 °C and 1 bar)).

A. INTRODUCTION

In partnership with the CertainTeed Corporation and the Minnesota Lath and Plaster Bureau, the Energy Systems Design and Cold Climate Housing Programs at the University of Minnesota have investigated experimentally the hygrothermal performance of a range of above-grade wall systems over a continuous period of 13 months beginning in December, 2007. Some of these systems conform to a universal building envelope hygrothermal performance standard that is a generalization of the foundation performance standard included in the State of Minnesota Residential Energy Code, while others are compliant with existing code above-grade wall prescriptive rules. This research had a strong focus on understanding the basic heat and mass transport physics for both standard and innovative systems in absolute terms and as a means of validating simulation codes, rather than as a residential application emulation exercise. Hence, for example, some of the imposed boundary conditions were severe and not likely to be encountered in market applications.

In terms of particular components, the research systems were focused on:

• comparing the efficacy of 2-mil PA-6 (polyamide 6) membrane as a warm-side vapor retarder to standard 4-mil PE (polyethylene); and,
• clarifying the hygrothermal interactions between stucco cladding and various wall systems as they relate to biotic failure mechanisms.

A range of moisture management strategies were evaluated including:

• an exterior water separation plane (WSP) in combination with an interior PA-6 warm side vapor retarder
• a comparison of Kraft paper and PA-6 as a warm side vapor retarder in combination with two layers of 60-minute grade D as an external water resistive barrier (WRB)
• open-cell polyurethane foam without any interior vapor retarder
• closed-cell polyurethane foam adjacent to the sheathing combined with fiberglass batts
• the efficacy of wood fiberboard sheathing as a moisture sequestration system in combination with an external WSP
• the efficacy of a dedicated moisture sequestration system in combination with OSB sheathing

1 Minnesota Rules, chapter 1322.1102, section N1102.2.6.12 Foundation wall insulation performance option, https://www.revisor.leg.state.mn.us/rules/?id=1322.1102
• a comparison of the relative impact of stucco and lapped fiber cement board cladding on the wall system hygrothermal performance
• a performance comparison of PA-6 faced fiberglass batts that are friction fit into the stud pockets (without sealing to the stud faces), to that of unfaced batts with interior PA-6 sealed to the stud faces.

B. UNIVERSAL BUILDING ENVELOPE HYGROTHERMAL PERFORMANCE STANDARD

Based on the research used to develop a foundation insulation performance standard (Goldberg and Huelman, 2005), other research on above-grade wall systems (Goldberg, 2006 and Goldberg, 2007) as well as over 10 years of experimental research at the Cloquet Residential Research Facility (CRRF), the following universal hygrothermal performance standard for building envelopes has been postulated as a generalization of the foundation wall performance standard included in the Minnesota Residential Energy Code:

**Requirement 1**
The building envelope shall be designed and built to have a continuous water separation plane (WSP) between the interior and exterior.
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 24-hour running average sorption isotherm maximum moisture content corresponding to a surface equilibrium relative humidity of 80% 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.
e. Prevent liquid water from any vertical or inverted surface (that is, ceilings, roofs) reaching the adjoining or subvening floor system at any time during a full calendar year.

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.

**Requirement 2**
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**
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 or 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 ft³/min.ft² under a pressure differential of 0.3 in. water (1.57psf) (0.02 L/s.m² at 75Pa) 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 E2178.

There is no restriction on insulation either in terms of type or quantity provided that the above three requirements are met.
The moisture content limit stipulated in Requirement 1c represents the current, recently changed status of an ongoing evolutionary development of a consistent and phenomenology-based (as opposed to experiential or anecdotal) standard for maximum envelope system component moisture content (MC). There has been a great deal of debate and research about what constitutes an acceptable continuous carrying MC for sorbent building materials and for wood and wood derivative products in particular. The approach adopted up till this point by the PI in developing the universal standard has been to require that the maximum MC corresponds to that of a saturation ratio (SR) of 10%. This has represented a compromise between what is commonly deemed acceptable in field practice (nominally 16-18% maximum MC) and the PI’s design practice of a MC no more than 10% for sorptive sheathings (OSB, plywood) and framing lumber. Materials with high sorbency such as wood fiberboard are exceptional in that they can withstand higher levels of MC. In these cases, the design standard is a 5% saturation ratio.

However, ASHRAE/ANSI recently has published standard 160 (ASHRAE/ANSI, 2009, TenWolde, 2008) that defines allowable MC’s essentially in terms of material sorption isotherms by specifying limits on the material surface relative humidity (RH). In particular, the MC criterion is stated as:

1. 30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F), and
2. 7-day running average surface RH < 98% when the 7-day running average surface temperature is between 5°C (41°F) and 40°C (104°F), and
3. 24-hour running average surface RH < 100% when the 24-hour running average surface temperature is between 5°C (41°F) and 40°C (104°F).

Taking the 80% surface RH as the continuous running maximum, then according to particular sorption isotherm experimental data for oriented strand-board OSB (Kumaran et al., 2002), this corresponds to an equilibrium OSB MC of 12.2%. A 10% SR for OSB corresponds to 12.8%, so the 160 criterion is actually slightly more restrictive than the 10% SR standard. For plywood, 160 calls for 13.2% MC and the 10% SR is yields 15.2% MC, so 160 again is more conservative. For fiberboard 160 gives 15.4% MC and the 10% SR yields 30.4%, so 160 is significantly more conservative. In the case of fiberboard though, as noted above, the design SR standard is a 5% SR bringing the fiberboard MC down to 15.2%, in agreement with 160.

Hence the difference between 160 and the 10% SR criterion really is in the time frames - 160 allows a 30-day running average of 80% surface RH, whereas Requirement 1c allows only a 24 hour running average. This brings 160 into convergence with the 10% SR approach that has proved effective in CRRF experiments to date. Further, technically, standard 160 allows a 97.9999% RH for 7 days that, as the data presented in this report shows, is at least flawed in concept.

However, the formulation of standard 160 in terms of surface RH is more generalized than the 10% SR approach, since it avoids the necessity of requiring a different 5% SR limit for highly sorptive materials. Thus Requirement 1c has been modified to adopt the 160 formulation within the context of the experimental data supporting the 5%/10% SR specification.

This change was implemented after the draft of this report was finalized, and hence, the results are discussed in terms of the 10% SR standard rather than the MC equivalent of the 80% surface RH standard just adopted. In this context, it must be emphasized that for the OSB sheathing used in the majority of the systems tested, Requirement 1c is more conservative than the 10% SR standard.
The universal performance standard is aimed at achieving life-cycle envelope durability in the presence of the very high levels of insulation and air-tightness that are necessary to realize the envelope energy conservation performance for passive, net-zero and gross-zero energy residential buildings.

C. WALL SYSTEMS TESTED

The wall systems tested are described in Table C.1. Each system was tested on both north and south exposures so that the system arrangements were symmetric about the test bay east/west axis centerline. Test panels with 2 or 3 moisture isolated stud pockets each containing a particular test system were installed into bays 1 through 4 at the University of Minnesota’s Cloquet Residential Research Facility located near Cloquet, MN, about 35 miles south west of Duluth.
<table>
<thead>
<tr>
<th>Bay/exposure:</th>
<th>BAY 1 NORTH AND SOUTH</th>
<th>BAY 2 NORTH AND SOUTH</th>
<th>BAY 3 NORTH AND SOUTH</th>
<th>BAY 4 NORTH AND SOUTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stud pocket:</td>
<td>A C</td>
<td>A B C</td>
<td>A B C</td>
<td>A B C</td>
</tr>
<tr>
<td>Cladding:</td>
<td>Stucco</td>
<td>Stucco</td>
<td>Stucco</td>
<td>Fiber Cement Board</td>
</tr>
<tr>
<td>WRB:</td>
<td>High-temperature modified bituminous coated PE membrane(^a)</td>
<td>2 layers 60-min. Grade D</td>
<td>2 layers 60-min. Grade D</td>
<td>Spun, bonded Polyolefin</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High-temperature modified bituminous coated PE membrane(^a)</td>
</tr>
<tr>
<td>Sheathing:</td>
<td>25/32&quot; wood fiberboard</td>
<td>1/2&quot; OSB</td>
<td>1/2&quot; OSB</td>
<td>1/2&quot; OSB</td>
</tr>
<tr>
<td>Insulation:</td>
<td>Unfaced fiberglass batts</td>
<td>Wool felt(^b)</td>
<td>Open cell SPU</td>
<td>Faced fiberglass batt (with tabs)</td>
</tr>
<tr>
<td></td>
<td>Unfaced fiberglass batt</td>
<td></td>
<td>-2 in. thick closed cell SPU R-13</td>
<td>Faced fiberglass batt (without tabs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open cell SPU</td>
<td></td>
<td>Unfaced fiberglass batt</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Unfaced fiberglass batt</td>
</tr>
<tr>
<td>Warm-side vapor retarder:</td>
<td>2-mil PA6 4-mil PE</td>
<td>2-mil PA6 none none</td>
<td>Kraft facing</td>
<td>2-mil PA6 facing 4-mil PE 4-mil PE 2-mil PA6 2-mil PA6</td>
</tr>
<tr>
<td>Interior sheathing:</td>
<td>1/2&quot; Gypsum</td>
<td>1/2&quot; Gypsum</td>
<td>1/2&quot; Gypsum</td>
<td>1/2&quot; Gypsum</td>
</tr>
<tr>
<td>Finish:</td>
<td>3 coats latex paint (1 prime, 2 finish)</td>
<td>3 coats latex paint (1 prime, 2 finish)</td>
<td>3 coats latex paint (1 prime, 2 finish)</td>
<td>3 coats latex paint (1 prime, 2 finish)</td>
</tr>
<tr>
<td>Potential for compliance with universal performance standard:</td>
<td>yes yes no no no no no yes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes
\(^a\) Available under trade names such as “Winterguard HT” (CertainTeed Corporation) and “Grace Ultra” (W.R. Grace & Co.).
\(^b\) Type F-10.
Noted at the bottom of each insulation test system is a statement of the potential for its compliance with the universal performance standard described in Section B. As requirement 1 of the standard stipulates the existence of a water separation plane, only test systems 1A (bay 1, pocket A), 1B and 4C have the potential for compliance because of the use of a waterproofing membrane on the exterior side of the sheathing.

A schematic of a 3-pocket test panel is shown in Figure C.1 (the two-pocket panels in bay 1 are configured identically). Each test pocket was moisture separated in the vertical plane from its neighbors by a waterproofing membrane (between a double stud at the center pocket to maintain hygric symmetry). The isolation was carried through to the sheathing so that the center pocket sheathing is isolated from its neighbors by a silicone-caulked seam. Closed cell polyurethane foam was installed in the side guard pockets to create an air tight seal to the outside test panel frame.

![Figure C.1 Test panel configuration with three insulation system test pockets](image)

This concept of moisture sealing was carried through to the air-sealing configuration of the warm side vapor retarders beneath the gypsum board as shown in Figures C.2 through C.6. In all cases, the sealing refers only to the left and right hand edges of the warm side vapor
retarder, the top and bottom edges were not sealed. No specific measures were taken to air-seal the edges of the interior gypsum. Hence the sealing configurations cited in the captions to Figures C.2 through C.6 specifically refer only to the vertical edge sealing status of the warm side vapor retarder at the left and right hand sides of each stud pocket.

Only the north side panels are shown as the south side panels are identical (discussion continues after Figure C.5).
Figure C.2  Test bay 1 cavity vapor retarder air-sealing details:
1N-A & 1S-A: left unsealed, right sealed
1N-C & 1S-C: left sealed, right unsealed
Figure C.3  Test bay 2 cavity vapor retarder air-sealing details:

2N-A & 2S-A: left unsealed, right sealed
2N-B & 2S-B: left sealed, right sealed
2N-C & 2S-C: left unsealed, right unsealed
Figure C.4 Test bay 3 cavity vapor retarder air-sealing details:
3N-A & 3S-A: left unsealed, right sealed
3N-B & 3S-B: left unsealed, right unsealed
3N-C & 3S-C: left sealed, right unsealed
Figure C.5  Test bay 4 cavity vapor retarder air-sealing details:

4N-A & 4S-A: left unsealed, right sealed
4N-B & 4S-B: left sealed, right sealed
4N-C & 4S-C: left sealed, right unsealed

There was a dual purpose to the sealing arrangement:

• Firstly, to vapor isolate the center test cavity (note that the outer cavities are isolated by virtue of the CSPU in the guard cavities relative to vapor transport between the cavities).

• Secondly, to demonstrate the effect of vapor bypass by creating conditions in the outer test cavities in which one edge was air-sealed and the other edge was not. Vapor bypass is the impact of vapor diffusion through any air gaps between the vapor retarder and the studs (or through cracks between spray foam insulation and the studs). Note that vapor bypass is a completely separate effect from an air advection and therefore exists even
when a separate “air barrier” exists (that is, when the air barrier and the vapor retarder are not the same layer). This occurs for example when a separate air barrier is provided by sealed gypsum. The impacts of vapor bypass do not affect the measurements at the center of the test cavities, but they are clearly visible at the edges as reported in detail in Section G that reports the photographic record of the dismantling of all the test cavities.

Outside views of the completed test panels as installed on the north and south exposures of the CRRF are shown in Figures C.6 and C.7. Each test panel was meticulously bulk water and vapor sealed around the edges both on the interior and the exterior.

Figure C.6  North view of test panel exteriors - fiber cement board clad panel on the far left

Figure C.7  South view of test panel exteriors – fiber cement board clad panel on the far right
D. INSTRUMENTATION

The instrumentation was installed at the area centroid of each stud pocket. For all stud pockets except 2A and 2C, the instrumentation in exterior to interior order was as follows:

- average sheathing moisture content. The impedance was measured by a 2 point stainless steel probe routed to a Delmhorst model MT-60V moisture transmitter (serial no. 133) via custom-built cascade isolation multiplexers. The measurement system (probe and transmitter) was calibrated for wood fiberboard and OSB as shown in Figures D.1 and D.2 respectively.

- exterior cavity surface absolute humidity and temperature. A Lofrango Engineering rev. C. absolute humidity sensor was mounted adjacent to the sheathing surface and a type-T thermocouple was attached directly to the sheathing surface. Each absolute humidity sensor has a unique OEM-supplied calibration for the capacitive sensing element. This arrangement of sensors permits the dew point temperature and relative humidity on the interior surface of the sheathing to be determined. The absolute humidity sensors can function without degradation under the continuous saturation conditions encountered at the sheathing interior surface during the experiment.

- interior cavity surface absolute humidity and temperature. The same sensor arrangement used on the interior sheathing surface also was deployed on the cavity side of the warm side vapor retarder.

In the case of stud pocket 2A exterior surface, the absolute humidity sensor was deployed adjacent to the wool felt while the temperature sensor was attached directly to the sheathing. In the case of stud pocket 2C, a third absolute humidity and temperature sensor pair were place on the interior surface of the closed cell spray polyurethane foam so that the absolute humidity sensor was adjacent to the foam surface and the thermocouple was adhered to the foam surface.

The bay interiors were heated and humidified. No air conditioning or dehumidification was provided. In each bay, heating was by means of a forced air furnace with an electric resistance coil while humidification was provided by a steam humidifier. The furnace and humidifier were controlled by a centralized direct digital control system with variable control band limits.

The following continuous boundary condition data were collected:

- interior temperature and relative humidity in each of the 4 test bays
- interior barometric pressure
- north exposure exterior temperature and humidity
- south exposure exterior temperature and humidity

Data were measured every 4-5 minutes and aggregated over 20 minutes with the aggregated values stored for each 20 minute period. Over the continuous experimental monitoring period of 407 days, the data collection reliability was 99.1%, that is, 0.9% of the data was lost as a result of a protracted power outage.
WOOD FIBER BOARD MOISTURE SENSOR CALIBRATION

Quintic fit MC = 898.253343-587.088731V+159.642647V^2-
21.692033V^3+1.458458V^4-0.038727V^5

Figure D.1

OSB MOISTURE SENSOR CALIBRATION

Figure D.2
E. BOUNDARY CONDITIONS

The detailed exterior and interior temperature and humidity boundary conditions for each test system can be found in Section F.3 in Figures F.9 onwards. The interior setpoint temperature (heating only) was held constant at 20 °C (68 °F) for all the test bays while the interior relative humidity (RH) setpoint (humidification only) was varied to produce the process RH temporal profiles shown in Figure E.1. From day 0 through day 20, the bays were humidified to 40% RH to test the performance of the humidifiers and check for leaks. During this shakedown, a defective (leaking) humidifier was replaced. From day 20 through day 31, all the bays were dried out to 30% RH or less. Thereafter, from day 31 through day 96, the RH was increased in 5% increments up to a maximum of 60% such that the bays were held at each level for about 2 weeks. From day 96 through day 105, the RH was maintained at 40%, at which point humidification ceased and the RH was allowed to float for the rest of the experiment. Thus during the last 40 days of the experiment in the heating season of year 2, the bays experienced an indoor RH of 30% or less. Thus the response of the wall systems to both high and low humidity setpoints was obtained and can be compared.

![Interior Relative Humidity Boundary Conditions](image)

This RH setpoint protocol was intended to explore the comparative hygrothermal phenomenology of the tested wall systems under harsh moisture conditions to characterize their unique responses with a sufficiently high signal to noise ratio. Of particular interest was how the systems possessing potential compliance with the universal performance standard would behave in comparison with more traditional / best practice systems in which both sides of the stud cavity have membranes with at least Class II vapor permeance (0.1 to 1 US perms).
needs to be emphasized that such an RH boundary condition regime is not typical of that experienced in cold climate residential buildings and thus extrapolating the results to typical practice should be undertaken with caution. In particular, while it is reasonable to infer that a test system that performed well during the experiment would also perform well under typical conditions, the inverse inference (that a poorly performing test system also would perform poorly under typical conditions) may not be correct.

F. RESULTS

The experimental results are organized into three sections.

- In the first section (Figures F.1 through F.4), the sheathing moisture contents for all the test pockets are displayed in two graphs on the same page (one each for the north and south exposures).
- The second section (Figures F.5 through F.8) depicts the relative humidity profiles on the condensing surfaces within the stud pockets with all the profiles for each exposure appearing on the same page.
- Finally, the third section (Figures F.9 through F.12) show the detailed hygrothermal performance for each test pocket with reference to the imposed interior and exterior temperature and humidity boundary conditions.

With the exception of some of the graphs in the third section (F.3), each time series profile has been smoother with a negative exponential curve fit to filter out the diurnal variations allowing the seasonal trends to be clearly seen. In Section F.3, the moisture content profiles show the unsmoothed profile superimposed upon the smoothed profile in order to reveal the transient maxima and minima.

Each graph is followed by a brief commentary as necessary.

F.1 Section 1 – Sheathing Moisture Content
Figure F.1 Commentary

The basic dynamics applicable to all the test systems are revealed in Figures F.1. On the northern exposure (Figure F.1.1), up to about day 100, water vapor transported by diffusion from the bay interior condenses and aggregates in the form of ice on the sheathing surface. After day 100 as the exterior temperature increases, the ice melts and is absorbed into the sheathing so that the sheathing achieves its maximum moisture content (MC) around day 140. The MC remains at a maximum for a period of 50 days before drying, in this particular case, principally to the interior (as a consequence of the WSP on the sheathing exterior).

As the only difference between cavity A and C was the difference in warm-side vapor retarder (VR) (2-mil. PA-6 in A and 4-mil PE in cavity C), the differences in revealed moisture dynamics are essentially a function of the permeance of the warm-side vapor retarder alone. Hence, during the condensate accretion and sheathing wetting phases, the MC of A exceeds that of C because the volume of vapor crossing the VR is larger for the higher permeance PA-6. The magnitude of the difference is about 2% of MC. Conversely, during the drying phase, the sheathing MC in cavity A decreases much more rapidly than that of cavity C, again as a result of the increased permeance of the PA-6 in cavity C. In the second heating season, after day 380, the MC’s in both cavities are similar because in the presence of the low interior RH’s (less than 30%, Figure E.1), the permeance of the PA-6 is low enough so as not permit a significantly larger diffusive transport of vapor than the PE.

A key assessment of the overall moisture performance of the wall system is the maximum MC realized relative to the “acceptable” carrying MC of the sheathing. The definition adopted in this research is defined by the prior (as discussed in Section B) universal hygrothermal performance standard Requirement 1c that stated that the maximum annual MC should not exceed 10% of the saturation ratio (SR) of the sheathing material. Therefore, in the case of the wood fiberboard sheathing used in all the Bay 1 test cavities, the 10% SR ratio limit corresponds to an MC of 30.3%. Thus by this standard, both cavities A and C performed satisfactorily over the single year test period with maximum MC’s less than 24%. However, wood fiberboard qualifies for the design standard of a 5% SR which mandates an acceptable maximum MC of 15.2% (15.4% for the new Requirement 1c). Hence by the revised standard, the moisture performance of the wood fiberboard systems was unacceptable.

The dynamics of the southern exposure (Figure F.1.2) are quite different as a consequence of the direct solar radiation impinging on the cladding surface during the diurnal cycle. In this case, on average, in cavity A, any condensate accumulating overnight on the sheathing surface is melted and evaporated during the following day a process allowed by the relatively high permeance of the PA-6. Hence over the first 150 days, the sheathing MC remains relatively constant, quite unlike the case in cavity 1N-A in which there is no solar gain to drive a diurnal wetting/drying cycle. The response of cavity 1S-C with a relatively impermeable PE vapor retarder does not permit a diurnal drying cycle. In particular, evaporated condensate simply condenses on the interior surface of the PE during the day and returns to the surface of the sheathing during the night. This produces a gradually increasing sheathing MC because, during the day, the solar gain melts any accreted ice so it can be absorbed into the sheathing.

The overall MC maxima on the southern exposure are significantly less than those on the northern exposure as might be expected from the different wetting/drying dynamics and do satisfy the 5% SR standard. Thus, from an MC perspective, a northern exposure is a more severe operating environment than the southern exposure. The basic design strategy in Bay 1 is to use a WSP on the outside of the sheathing that, owing to its high sorptance, also serves as a seasonal and diurnal moisture sequestration system moderating the detrimental impacts of effectively eliminating any drying potential to the exterior. The experimental data reveal that this
approach is not effective in achieving acceptable MC performance in a system that potentially can meet the universal performance standard. However, as discussed in section G, the mold growth requirement of the standard was not met as a result of the high sheathing MC’s in absolute terms.
For the northern exposure (Figure F.2.1), cavities A and C behaved in approximately the same way, while cavity B demonstrated a markedly different phenomenology. In cavity A the essential moisture dynamics were the same as in Figure 1.1, namely a period of condensate accumulation on the sheathing surface through day 80, followed by sheathing wetting up to day 140, then a period of stasis followed by drying. The wool felt served as the moisture sequestration layer as planned so that the maximum MC of just less than 14% exceeded the 10% saturation ratio limit for the OSB sheathing (12.8% MC) by 1% or so.

The dynamics of cavity C in which no interior vapor retarder was installed yielded very similar sheathing MC to cavity A, however, via a different mechanism. In this case, much of the incoming water vapor condensed on the interior surface of the closed cell spray polyurethane foam (CSPU) (see Figure F.6.2) thus decreasing the amount that diffused through the CSPU to reach the sheathing surface for subsequent absorption. In this case, the maximum MC achieved just exceeded the 10% SR limit.

In contrast, in the cavity B system that consisted entirely of open cell spray polyurethane foam (OSPU) without any discrete warm-side vapor retarder, the sheathing reached essentially a saturated moisture content level. This behavior is consistent with that observed in a previous experiment in which OSPU was tested in an interior foundation insulation application, again, without a warm-side vapor retarder (Goldberg, 2004). During the first 100 days, condensate accreted within the porous structure of the OSPU beginning at the sheathing interface and extending inwards. As the outer layers froze, they created in essence an impermeable plane sealing off the chance of any drying to the exterior. As the exterior temperature rose after day 100, the accreted moisture rapidly melted and was absorbed into the OSB sheathing that reached an MC of more than 32% (upper range limit of the MC transducer).

After day 175, rapid drying to both the exterior and interior was realized, however, the drying was not sufficient to completely dry out the very large moisture gain so that as the second year heating season commenced, the cavity B sheathing MC reached and exceeded the 10% SR limit. These data reveal that a discrete warm-side vapor retarder at least is necessary to achieve a more acceptable sheathing wetting/drying cycle with OSPU. The three coats of latex paint applied to the interior surface of the gypsum were neither effective nor sufficient in providing an adequate level of vapor retardation.

On the southern exposure (Figure F.2.2), the solar driven diurnal wetting/drying cycle again was sufficient to keep the sheathing MC in cavities A and C well below the 10% SR limit throughout the year. However, this cycle was insufficient to eliminate ice accretion at the sheathing surface in cavity B, so that a peak of MC in excess of the 10% SR limit was experienced at day 85. However, this was far less severe than experienced by cavity 2N-B. Thus again, the data indicate that the northern exposure is the more severe operating environment in MC terms.
Figure F.3.1

BAY 3 NORTH: SHEATHING MOISTURE CONTENT TEMPORAL PROFILES

Figure F.3.2

BAY 3 SOUTH: SHEATHING MOISTURE CONTENT TEMPORAL PROFILES
The configurations in test Bay 3 are more representative of common practice in a northern climate comprising an exterior permeable water resistive barrier (WRB, 2 layers of Grade D-60 min. building paper) and an interior vapor retarder. The purpose of the Bay 3 systems was to compare the performance of interior vapor retarders other than continuous 2-mil. PA-6, using 4-mil. PE as a reference. Nominally, all 3 systems yielded sheathing MC’s that exceeded the 10% SR limit on the northern exposure (Figure F.3.1). For cavity A with Kraft faced fiberglass batts, the maximum MC after the ice melting phase reached 15%, higher than the 13.5% achieved by the 4-mil PE cavity. This was a consequence of the higher Kraft paper permeance allowing more vapor into the cavity. However, the higher permeance also allowed a greater degree of drying so that at the onset of the second year heating season at day 350, the cavity A sheathing had a 3.5% lower MC than the cavity C sheathing.

In contrast, the cavity B sheathing reached a maximum MC of 23.5% even though the batt facing was 2-mil PA-6. The key difference between cavity B and cavities A and C was that the PA-6 facing had no tabs so that the friction fit between the batt and the studs eliminated any degree of advective sealing at the vapor retarder / stud interface (compared with some sealing afforded by the Kraft facing tabs and a fairly good seal with the 4-mil PE). This created a substantial water vapor bypass around the edges of the PA-6 facing allowing accumulation of ice at the edges (mainly) of the studs adjacent to the sheathing leading to absorption and the elevated cavity B sheathing MC observed.

This highlights a common misperception that gypsum itself can form an adequate air barrier that can prevent this phenomenology from occurring. In this case, the vapor was transported through the gypsum by the same combination of diffusion and minimal advection (air leakage) in all three cavities, the key difference being the gaps in the vapor retarder in cavity B. Thus in order to avoid water vapor bypass, it is necessary to maintain a continuous advection barrier at the vapor retarding surface as well regardless of the state of sealing of the gypsum.

On the southern exposure (Figure F.3.2), the maximum MC for all 3 cavities was less than 10%, well below the operating maximum. While cavity B still showed the effects of the vapor bypass at the stud/PA-6 interface as shown by the higher MC’s prior to day 100, the effect was not deleterious to the sheathing performance. Again the solar radiation driven diurnal wetting/drying cycle was adequate to prevent a major accumulation of ice produced by the by-passed vapor condensation.
Figure F.4 Commentary

The Bay 4 test systems were intended to evaluate the impact of differing warm-side vapor retarders in the presence of a non-stucco cladding, namely fiber cement board. Examining the north exposure data first (Figure F.4.1), it is clear that the exceptional case is cavity C. Cavities A and B (4-mil PE and 2-mil PA-6 respectively) are quite similar with the differences attributable to the permeance of the vapor retarders consistently revealed throughout the data set. In particular, during the wetting period through day 100, cavity B has a higher MC as a result of higher vapor fluxes through the higher permeance PA-6, while during the drying phase through day 220, cavity B sheathing dries faster to a lower MC, again as a result of the higher PA-6 permeance. The maximum MC reached by 4N-B sheathing was about 13.3% and that of 4N-A about 12.5%, both essentially meeting the 10% maximum SR test.

Comparing cavities B and C, the only difference is application of a WSP in 4N-C compared with a permeable WRB in 4N-B. The maximum MC reached by the 4N-C sheathing was 14.5%, thus failing the 10% maximum SR test. This is clearly a consequence of the presence of the WSP that prevented drying to the exterior as occurred with 4N-A and 4N-B with a spun, bonded polyolefin WRB.

Comparing the MC results for test systems 3N-C (Figure F.3.1) and 4N-A addresses the impact of different cladding types in a conventional application, that is, using a 4-mil PE warm-side vapor retarder. The systems are identical except that 3N-C includes a stucco / 2 layers of Grade D-60 while 4N-A has fiber cement board / spun bonded polyolefin (SBP). The maximum sheathing MC in 3N-C was 13.5%, while that of 4N-A 12.5%, a less than 1% sheathing MC difference. Hence these data do not suggest that the exterior cladding is a major influence on the north exposure hygrothermal performance for the experimental conditions and wall geometry (particularly, the absence of rough openings).

The southern exposure MC profiles of Figure F.4.2 all easily meet the 10% SR criterion with a maximum MC for the cavity 4S-C sheathing of less than 9.1%. However, the effect of the WSP in cavity C is clearly evident in the MC spike at day 65 that is absent in 4S-A and 4S-B. Again comparing 3S-C (Figure F.3.2) and 4S-A to elucidate the effect of a difference in cladding. Cavity 4S-A (stucco) shows a maximum sheathing MC less than 9.2% during the wetting phase while with fiber cement board, the maximum sheathing MC is less than 8.2%, again about a 1% sheathing MC difference. Thus on both the north and south exposures, these data indicate that the net effect of the nominally less permeable, more water sorptive stucco/2-layers Grade D-60 cladding system over fiber cement board/SBP is of the order of a 1% sheathing MC difference.
The graphs of section 2 provide insight to the MC phenomenology discussed in section 1. Thus the RH results of Figure F.5 elucidate the MC results of Figure F.1 for Bay 1; for Bay2, F.6/F.2; for Bay 3, F.7/F.3; and, and for Bay 4, F.8/F.4. In general, the saturated RH conditions (100%) indicate the presence of phase change (condensation) while the magnitude of the sheathing MC
indicates the magnitude of the condensation, that is, how much water vapor was transported through the exterior and interior layers to the sheathing.

Figure F.5.1 Commentary

Considering the northern exposure results of Figure F.5.1, the RH data indicate that no condensation occurred at either the sheathing or warm-side vapor retarder cavity surfaces for both 4-mil PE and 2-mil PA-6, although at the height of the cooling season (Day 209), the RH on the 4-mil PE in 1N-C came close to saturation at 95% (the PA-6 reached a maximum RH of less than 80% in compliance with its relatively high permeance at that RH). Conversely, at day 100 during the wetting period, the 1N-A (PA-6) sheathing surface reached 97% compared with 92% for 1N-C (PE). This is more or less typical of the difference between PE and PA-6 in practice – PA-6 yields somewhat greater sheathing wetting during the heating season but higher interior drying potential and a significant reduction of condensate formation potential on the vapor retarder during the cooling season.

The absence of sheathing condensation is consistent with the MC results of Figure F.1.1 indicating that the sheathing operated within the 10% SR limit.
Figure F.5.2
Figure F.5.2 Commentary

On the southern exposure, the diurnal solar radiation driven wetting/drying cycle more clearly demonstrates the differences between PA-6 and PE since the PA-6 cavity (1S-A) generally retains less moisture. This is revealed by the higher RH levels seen in 1S-C at the surface of the sheathing during the heating season and the surface of the PE during the cooling season. Note that since 1S-C is essentially a vapor sealed cavity (WSP on the exterior, PE on the interior), there is a small net retention of moisture within the cavity over each year so that eventually, the cavity becomes moisture unstable and significant amounts of condensate with rundown appear on the PE surface while the sheathing tends to saturation².

However, the absence of saturation conditions is consistent with the MC results of Figure F.1.2 and the relatively lower sheathing MC’s recorded for 1S-A and 1S-C indicate that the magnitude of the net (or time-integrated) vapor flux on the southern exposure is less than that on the northern exposure owing to the presence of the diurnal wetting/drying cycle.

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² As an anecdotal (at this stage) elucidation of this phenomenology, unpublished simulation research conducted by the PI on this form of instability indicates that it begins to manifest after at least 8 years and becomes problematic after 10 years.
Figure F.6.1

BAY 2 NORTH: RELATIVE HUMIDITY TEMPORAL PROFILES

CAVITY A: stucco/2 layers 60 min. Grade D/OSB/wool felt/unfaced fiberglass batts/
2-mil PA-6 membrane/gypsum/3 coats latex paint.

CAVITY B: stucco/2 layers 60 min. Grade D/OSB/open cell spray polyurethane/
gypsum/3 coats latex paint.

CAVITY C: stucco/2 layers 60 min. Grade D/OSB/closed cell spray polyurethane/
unfaced fiberglass batt/gypsum/3 coats latex paint.

Elapsed time since 11/30/07-10/21 (days)
Figure F.6.1 Commentary

The RH profiles in cavity A indicate that condensation did not occur on the surface of the wool felt sorptive layer through day 110, but, from Figure F.2.1, did occur on the surface of the sheathing, although to a relatively small extent (maximum sheathing MC less than 14%). This points to one of the key aspects of the physics of condensation, namely that regardless of where the condensation plane is located with the bulk of a sorptive or porous material (as defined by the equality of the dew point and sensible temperatures), the condensation only manifests on the nearest upstream impermeable surface. In this case, the condensation plane occurred within the bulk of the wool felt, manifested on the surface of the sheathing and then was drawn back into the felt by capillary flow. Owing to the presence of the relatively permeable PA-6 warm-side vapor retarder, the RH on the PA-6 cavity side surface did not exceed 84% during the middle of the cooling season.

In cavity 2N-B with no warm-side vapor retarder and OSPU insulation, the RH profile on the sheathing surface does not remain consistently saturated through day 100, but oscillates between saturation and just below saturation. This is indicative of the moisture accumulation mechanism of accretion by freezing discussed previously (Figure F.2 commentary) in which the humidity equilibrium with respect to ice varies in RH magnitude as the temperature changes, so that the RH decreases with decreasing temperature. As the temperature increases to freezing the RH increases as the quantum bistable phase change state is approached. The interior surface of the insulation is essentially in equilibrium with the bay interior RH as shown by the RH profile on the cavity surface of the gypsum sheathing.

In contrast, cavity 2N-C with the 2-layer insulation system shows fairly consistent saturation during the heating seasons (through day 110 and after day 350), however, the volume of the condensation is fairly small (see Figure F.2.1, maximum MC of about 13%). Saturation conditions also existed on the surface of the CSPU from day 60 through day 90 indicating that the cured surface of CSPU is sufficiently impermeable to function as a condensation plane. This is another example of a condensation plane occurring within the bulk of the fiberglass insulation manifesting on the nearest upstream impermeable surface. Looking at this another way, in terms of optimizing the relative batt/CSPU “flashing” thickness, the $R_{US-13}/R_{US-12}$ batt/CSPU ratio (3.5 in. thick batts, ~ 2 in. CSPU thickness) embodied in the 2N-C test system is inadequate, the CSPU should be thicker or the batt thermal resistance decreased. Increasing the CSPU thickness would also decrease its permeance to further reduce and perhaps eliminate the condensation on the sheathing surface. It is estimated that the installed permeance of the CSPU was about 1.7 perms, insufficient to eliminate sheathing condensation. Again, without an interior vapor retarder, the gypsum cavity side RH was essentially in equilibrium with the bay interior.
Figure F.6.2
Figure F.6.2 Commentary

The RH levels in cavity 2S-A were low confirming the low levels of sheathing MC revealed by Figure F.2.2.

The RH at the sheathing surface in cavity 2S-B approached 100%, but never sustained saturation for a significant period in agreement with the maximum sheathing MC of 14% reported in Figure F.2.2.

More interesting phenomenology occurred in cavity 2S-C, in which consistent condensation still occurred on the CSPU surface between days 60 and 90 just as in the case of the northern exposure. This was a consequence of the R_{US-12} CSPU effectively screening off the solar radiation diurnal drying from the CSPU condensation surface. While the RH at the sheathing surface did flirt with saturation occasionally, generally no condensation was present indicating that the diurnal cycle was adequate to maintain average diurnal temperatures above the dew point in the bulk of the CSPU insulation. During the second heating season (after day 360), the interior RH was too low to create condensing conditions on the surface of the CSPU.
BAY 3 NORTH: RELATIVE HUMIDITY TEMPORAL PROFILES

CAVITY A: stucco/2 layers 60 min. Grade D/GSB/Kraft faced fiberglass batt/gypsum/3 coats latex paint

Relative humidity (%)

CAVITY B: stucco/2 layers 60 min. Grade D/GSB/unsealed 2-mil PA-6 membrane faced fiberglass batt/gypsum/3 coats latex paint

Relative humidity (%)

CAVITY C: stucco/2 layers 60 min. Grade D/GSB/unfaced fiberglass batt/4-mil PE membrane/gypsum/3 coats latex paint

Relative humidity (%)

sheathing interior surface
PA-6 cavity side surface

sheathing interior surface
PE cavity side surface

Elapsed time since 11/30/07 - 10-21 (days)

Figure F.7.1
Figure F.7.1 Commentary

While saturated conditions existed at the sheathing surface of cavities 3N-A and 3N-B for the majority of the experimental period (through day 170 and after day 350), the magnitude of vapor transport into the cavity was relatively low as shown by the maximum MC’s of 15 and 13.5% shown by the 3N-A and 3N-B sheathing respectively (Figure F.3.1). Nevertheless, the protracted period of condensation point to the limitations inherent in using either Kraft facing with tabs or unsealed edge PA-6 facing.

In comparison, the 4-mil. PE in cavity 3N-C did not remain consistently at saturation, and the period of approximate saturation was significantly reduced compared with cavities A and B (through day 100 and after day 370). As discussed in the Figure 3 commentary, this was more a function of vapor retarder edge sealing than the permeance characteristics of the membranes themselves.

In all 3 cavities, the RH on the vapor retarder cavity side did not exceed 90% throughout the experiment indicating the absence of any warm-side condensation.
Figure F.7.2
Figure F.7.2 Commentary

The solar radiation driven wetting/drying cycle was adequate to overcome the vapor bypass effects at the batt facing edges in cavities 3S-A and 3S-B so that the maximum sheathing surface RH in both cavities did not exceed about 96 % during the experiment. Comparing Figures F.7.1 and F.7.2 give an indication of the very significant difference in north and south facing hygrothermal phenomenology again indicating that the north exposure is the more severe condition.
Figure F.8.1

BAY 4 NORTH: RELATIVE HUMIDITY TEMPORAL PROFILES

CAVITY A: fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/4-mil PE membrane/gypsum/3 coats latex paint

CAVITY B: fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/2-mil PA-6 membrane/gypsum/3 coats latex paint

CAVITY C: fiber cement board/modified asphalt coated membrane/OSB/unfaced fiberglass batt/2-mil PA-6 membrane/gypsum/3 coats latex paint
Figure F.8.1 Commentary

On a northern exposure, all three test cavities reveal very similar condensation phenomenology. Cavities 4N-A and 4N-B with an SBP WRB remained at saturation through day 100, while cavity 4N-C with an exterior WSP was saturated a while longer through day 121. Similarly, during the second heating season, cavity 4N-C reached near saturation sooner at day 373 or so, while the other two cavities never reached saturation during the second heating season. Once, again for cavities A and B, from Figure F.4.1, the magnitude of condensate was small producing maximum MC's just above and just below the 10% saturation limit for cavities A and C respectively.

In all three cavities, the interior cavity RH was less than 80% throughout the experiment indicating the absence of any condensation there.
Figure F.8.2

BAY 4 SOUTH: RELATIVE HUMIDITY TEMPORAL PROFILES

CAVITY A: fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/
4-mil PE membrane/gypsum/3 coats latex paint

CAVITY B: fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/
2-mil PA-6 membrane/gypsum/3 coats latex paint

CAVITY C: fiber cement board/modified asphalt coated membrane/OSB/unfaced fiberglass batt/
2-mil PA-6 membrane/gypsum/3 coats latex paint

Relative humidity (%)

Elapsed time since 11/30/07 - 10/21 (days)
Figure F.8.2 Commentary

On the southern exposure, in agreement with Figure F.4.2 with an overall maximum MC across all three test cavities less than 9.1 %, the RH conditions were benign with an absence of any condensation. The impact of the exterior WSP in cavity 4S-C can be seen in the elevated sheathing surface RH of about 90 % relative to the less than 80 % sheathing surface maximum of the other two cavities.

F.3 Section 3 – Detailed Hygrothermal Performance

This section is presented for reference purposes and represents a synthesis of the discussion for the RH and MC phenomenology discussed in sections F.1 and F.2 above. The results are presented in the format of one test section per page in three graph panels with the top two panels showing the wetting/drying behavior at the cavity inside and outside condensation planes. The top panel also includes the smoothed sheathing MC profile with the transient MC profile superimposed\(^3\). The bottom panel depicts the interior and exterior temperature and humidity boundary conditions.

The wetting/drying behavior is depicted by temporal profiles of sensible and dew point temperatures on the condensation surface. Wetting occurs when the sensible temperature is less than or equal to the dew point temperature and drying when the sensible temperature exceeds that of the dew point.

In the light of the previous discussion, the graphs in this section are self-explanatory and so commentary is restricted to highlight interesting phenomenology only.

\(^3\) Note that the transient profile is not “noise” or in any way erroneous, but the actual MC data recorded at an interval of 20 minutes.
CAVITY A configuration:
stucco/modified asphalt coated membrane /wood fiberboard/unfaced fiberglass batts/
2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure F.9.1.1
Figure F.9.1.1 Commentary

The top panel clearly illustrates the phases of the experiment. Prior to day 100, the sheathing sensible temperature was below freezing producing an accretion of ice on the sheathing surface. After day 100, the sensible temperature was consistently above freezing melting the ice and producing an increase in MC in the sheathing as the resulting liquid was absorbed. Note that after day 100, the sensible temperature was consistently above the dew point temperature so that evaporation occurred simultaneously with the liquid absorption. However, the evaporation only became sufficient to start drying the sheathing around day 170 corresponding to a sheathing temperature of about 10 °C.

As the sensible temperature was above that of the dew point throughout the experiment, no wetting of the PA-6 membrane occurred.
CAVITY C configuration:
stucco/modified asphalt coated membrane /wood fiberboard/unfaced fiberglass batts/
4-mil PE membrane/gypsum/3 coats latex paint

Figure F.9.1.2
Figure F.9.1.2 Commentary

The relative effect of the lower permeance of the PE vapor retarder can be seen at day 210 at the PE membrane surface. At this point, condensation on the PE cavity surface did occur in comparison with the absence of any condensation in cavity 1N-A with a PA-6 vapor retarder.

Also, comparing the top panels of Figures F.9.1.1 and F.9.1.2 shows that during the first 100 days, the wetting/drying behavior with PE and PA-6 is essentially the same. This refutes the perception that somehow use of a Class II vapor retarder (0.1 to 1 perm) somehow is “better” than a Class I vapor retarder (< 0.1 perm) in preventing the occurrence of condensation on the sheathing. However, a Class II vapor retarder increases the magnitude of the vapor flux into the cavity during the wetting period compared with a Class I retarder but also increases the magnitude of the drying when the vapor flux reverses. In the case of an RH proportional permeance vapor retarder such as PA-6 in which the vapor ingestion occurs at a lower RH than the vapor egression (since during egression, the cavity side surface of the PA-6 is a condensing surface), the rate of vapor egression exceeds the rate of ingestion. Thus over an annual cycle, the net transport into the cavity is significantly less than that with Class I retarder, and generally is stable (not net annual accumulation of moisture within the cavity). It is only in this sense that RH proportional permeance vapor retarders offer superior performance to conventional fixed permeance vapor retarders. However, when using such a retarder, it is essential that the sheathing be able to sequester the increased condensation safely without structural or biotic degradation.
CAVITY A configuration:
stucco/modified asphalt coated membrane /wood fiberboard/unfaced fiberglass batts/
2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure F.9.2.1
CAVITY C configuration:
stucco/modified asphalt coated membrane /wood fiberboard/unfaced fiberglass batts/
4-mil PE membrane/gypsum/3 coats latex paint

Figure F.9.2.2
Figures F.9.2 Commentary

In comparing the sheathing wetting/drying profiles in the top panels of Figures F.9.2.1 and F.9.2.2 for PA-6 and PE vapor retarders in cavities 1S-A and 1S-C respectively, note that the PE membrane cavity sheathing, apparently paradoxically, showed wetting from day 50 through day 80 despite the lower permeance of the PE. This was a result of the lower permeance of the PA-6 allowing the egress of solar radiation evaporated moisture on a diurnal basis that was blocked by the PE in cavity 1S-C. However, the evaporated 1S-C sheathing moisture did not condense on the PE membrane.
CAVITY A configuration:
stucco/2 layers 60 min. Grade D/OSB/wool felt/unfaced fiberglass batts/
2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure F.10.1.1
CAVITY B configuration:
stucco/2 layers 60 min. Grade D/OSB/open cell spray polyurethane/gypsum/
3 coats latex paint

Figure F.10.1.2
The top panel again clearly shows the mechanism of sheathing wetting as discussed previously. Prior to day 100, the average sheathing surface sensible temperatures were below freezing producing the ice accretion in the OSPU insulation. As the average temperature exceeded freezing, there was a rapid increase in sheathing MC as it absorbed the melted ice. More precisely, with regard to the diurnal sheathing temperature variation, the temperatures exceeded freezing on a transient basis starting at day 65, so that some transient melting occurred with a corresponding transient increase in the sheathing MC up to the transducer upper measurement limit as shown by the superimposed transient MC profile.
CAVITY C configuration:
stucco/2 layers 60 min. Grade D/OSB/closed cell spray polyurethane/
unfaced fiberglass batt/gypsum/3 coats latex paint

Figure F.10.1.3
Figure F.10.1.3 Commentary

The center panel shows the relative severity of the degree of wetting that occurred at the CSPU interior and sheathing surfaces from day 60 through day 100 by the degree of surface undercooling relative to the dew point temperature at the temperature profile maxima. Compared with the same loci in the adjacent cavity 2N-B (Figure F.10.1.2) sheathing surface wetting/drying profiles, the 2N-B profiles show much smaller temperature differences, indicating a less severe degree of wetting (in terms of condensate mass accumulation per unit time, but not in terms of time-integrated total condensate).
CAVITY A configuration:
stucco/2 layers 60 min. Grade D/OSB/wool felt/unfaced fiberglass batts/
2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure F.10.2.1
CAVITY B configuration:
stucco/2 layers 60 min. Grade D/OSB/open cell spray polyurethane/gypsum/
3 coats latex paint

Figure F.10.2.2
Figure F.10.2.2 Commentary

The sheathing wetting through day 110 on the southern exposure yielded a condensate deposition far less than that in the corresponding northern exposure cavity (Figure F.10.1.2). The effect of the diurnal wetting drying cycle is revealed by the average surface temperature exceeding the dew point temperature at day 40, an effect absent in 2N-B.
CAVITY C configuration:
stucco/2 layers 60 min. Grade D/OSB/closed cell spray polyurethane/
unfaced fiberglass batt/gypsum/3 coats latex paint

Figure F.10.2.3
CAVITY A configuration:
stucco/2 layers 60 min. Grade D/OSB/Kraft faced fiberglass batt/gypsum/3 coats latex paint

Figure F.11.1.1
CAVITY B configuration:
stucco/2 layers 60 min. Grade D/OSB/unsealed 2-mil PA-6 membrane faced fiberglass batt/gypsum/3 coats latex paint

Figure F.11.1.2
CAVITY C configuration:
stucco/2 layers 60 min. Grade D/OSB/unfaced fiberglass batt/4-mil PE membrane/gypsum/
3 coats latex paint

Figure F.11.1.3
The sheathing wetting process in cavities 3N-A and 3N-B lasted though day 190 while only through day 100 in cavity 3N-C. This is another indicator of the large impact of vapor bypass in increasing the mass of vapor transport into the cavity.
CAVITY A configuration:
stucco/2 layers 60 min. Grade D/OSB/Kraft faced fiberglass batt/gypsum/3 coats latex paint

Figure F.11.2.1
CAVITY B configuration:
stucco/2 layers 60 min. Grade D/OSB/unsealed 2-mil PA-6 membrane faced fiberglass batt/gypsum/3 coats latex paint

Figure F.11.2.2
CAVITY C configuration:
stucco/2 layers 60 min. Grade D/OSB/unfaced fiberglass batt/4-mil PE membrane/gypsum/
3 coats latex paint

Figure F.11.2.3
Figures F.11.2 Commentary

On the southern exposure, cavity 3S-C with a small amount of vapor bypass did not produce any wetting of the sheathing surface through day 80 unlike cavities 3S-A and 3S-B in which wetting occurred from day 50 through day 80.
CAVITY A configuration:
fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/
4-mil PE membrane/gypsum/3 coats latex paint

Figure F.12.1.1
CAVITY B configuration:
fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/
2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure F.12.1.2
CAVITY C configuration:
- fiber cement board
- modified asphalt coated membrane
- OSB
- unfaced fiberglass batt
- 2-mil PA-6 membrane
- gypsum
- 3 coats latex paint

Figure F.12.1.3
Figures F.12.1 Commentary

Of previously unnoted interest is a comparison of the minimum sensible / dew point temperature difference at the vapor retarder surface during the cooling season that occurred at day 210. In cavity 4N-A (Figure F12.1.1), the minimum difference was about 5 °C, in cavity 4N-B, 8 °C; and, in cavity 4N-C, about 4 °C. The larger difference in 4N-B was a result of the higher permeance of the PA-6, while in 4N-A and 4N-C, both with PE membranes, the 1 °C smaller temperature difference in 4N-C is attributable to the presence of the sheathing exterior WSP that essentially eliminated drying to the exterior. What is of significance, however, is that the effect of that exterior drying restriction was so small.
CAVITY A configuration:
fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/
4-mil PE membrane/gypsum/3 coats latex paint

Figure F.12.2.1
CAVITY B configuration:
fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/
2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure F.12.2.2
CAVITY C configuration:
fiber cement board/modified asphalt coated membrane/OSB/unfaced fiberglass batt/
2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure F.12.2.3
G. TEST SYSTEM DISMANTLING

All the test systems were dismantled on 1/12/2009. The manual moisture content readings taken with an uncalibrated, handheld Delmhorst meter are presented for reference purposes in Table G.1.

As a rough check on the accuracy of the manual MC readings, the final MC readings recorded by the data acquisition with the calibrated MC sensors are shown in shaded italics in the “sheathing centerline – middle” column. The agreement is satisfactory under dry conditions for OSB sheathing (south test cavities of Bays 2, 3 and 4) but poor to very poor for the north test cavities where the manual readings consistently and on occasion excessively overshot the calibrated readings. In the case of cavities 2N in particular where the manual readings really were excessive, this is likely a consequence of:
(a) the manual probe also detecting the moisture in any adhered foam insulation or felt material,
(b) a function of the depth of penetration of the pins (the continuous calibrated MC readings are an average over the sheathing thickness), and,
(c) most predominantly, exposure of the sheathing surface to the warm interior air already had melted the ice in the insulation adjacent to the sheathing (note the observation that the OSB surface was wet for 2N-B).

This latter effect was present in all cases on the northern exposure in which ice had accumulated on or adjacent to the sheathing surface. Thus clearly, the significance of the MC readings is not in their absolute value but rather as a snapshot of the relative wetness of the wood components of the test systems after the insulation had been removed.

On this basis, in general, the manual readings support the experimental results. In particular, they confirm that test cavities 2N-B, 3N-A and 3N-B yielded the highest sheathing moisture contents, while the southern exposure test cavities were relatively dry. Specific notes relevant to particular test cavities are exemplified by the dismantling photographic record.

Only photographs of abnormal phenomenology or departures from a nominally pristine appearance are reported. The salient photographs are presented for each test cavity in turn followed by a brief description of the relevant features. Test cavities not reported photographically were pristine in appearance without any sign of mold or wetness.
Table G.1  Observations and manual moisture content measurements - 1/12/2009

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<th>Right Stud</th>
<th>Sheathing Centerline</th>
<th>Sheathing Top</th>
<th>Sheathing Bottom</th>
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76
G.1 Test cavity 1N-A: stucco/modified asphalt coated membrane/wood fiberboard/unfaced fiberglass batts/2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure G.1.1
- staining of surface in upper left quadrant indicates wetness/rundown
- green blotches show mold growth
Figure G.1.2
- mold growth on surface of sheathing
Figure G.1.3
- staining on exterior surface of batt indicating mold

Figure G.1.4
- surface staining on bottom plates indicates bulk water rundown and accumulation
Figure G.1.5
- PA-6 membrane binding to gypsum attachment screw
G.2 **Test cavity 1N-C**: stucco/modified asphalt coated membrane /wood fiberboard/unfaced fiberglass batts/4-mil PE membrane/gypsum/3 coats latex paint

Figure G.2.1
- surface staining of surface in upper right quadrant and along right stud indicates wetness and rundown
- green blotches show mold growth
Figure G.2.2
- rust on head and upper shank indicates presence of high gypsum surface moisture (from imposed boundary conditions)

Figure G.2.3
- staining on exterior surface of batt indicating mold
Figure G.2.4
- rundown pattern and mold growth detail
G.3 **Test cavity 1S-A**: stucco/modified asphalt coated membrane/wood fiberboard/unfaced fiberglass batts/2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure G.3.1
- surface staining in upper left corner indicating wetness

Figure G.3.2
- surface staining in upper right corner indicating wetness
Figure G.3.3
- surface staining in bottom right corner indicating wetness

Figure G.3.4
- curling of removed PA-6 indicative of high moisture content
G.4 **Test cavity 1S-C:** stucco/modified asphalt coated membrane/wood fiberboard/unfaced fiberglass batts/4-mil PE membrane/gypsum/3 coats latex paint

![Image of测试区域1S-C](image.png)

**Figure G.4.1**
- significant surface staining in top left quadrant and along left hand side stud indicating significant condensation and rundown
- mold/staining on upper portion of left hand stud
Commentary
These observations demonstrate the effect of the diurnal solar radiation driven wetting/drying cycle. Melting of overnight accumulated ice (in progress at the time of the photograph) produces surface wetness and rundown as well as biotic activity.
Figures G.4.4

- mold and staining on left hand side stud
- mold growth on surface of left hand side stud indicating the presence of significant condensation on the PE membrane surface at least at the edges of the cavity
Figure G.4.5
- mold on horizontal top surface of batt
G.5 Test cavity 2N-A: stucco/2 layers 60 min. Grade D/OSB/wool felt/unfaced fiberglass batts/2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure G.5.1
- surface staining along left and right hand studs indicating wetness and rundown
Figures G.5.2

- Frost accumulation on surface at edge of framing
- Surface staining indicating presence of wetness and rundown
Figure G.5.3
- mold growth and wetness on sheathing surface of wool felt

Figure G.5.4
- sheathing surface of wool felt wet indicating presence of condensation plane on sheathing surface
G.6 Test cavity 2N-B: stucco/2 layers 60 min. Grade D/OSB/open cell spray polyurethane/gypsum/3 coats latex paint

Figure G.6.1
- void between OSPU insulation and sheathing
- no evidence of wetness on scraped surface of sheathing

Commentary
The continuous interface between the insulation and the sheathing prevents the formation bulk water. Melted condensate is absorbed directly by the sheathing so that there is insufficient time for mold to form on the sheathing surface.
Figure G.6.2

- Frost accumulation within the pores of the OSPU adjacent to stud (specular reflection off ice crystals)
- Void between insulation and sheathing at top edge of cut-out
Figure G.6.3
- frost on scraped surface of sheathing (specular reflection off ice crystals)
Figure G.6.4
- large void between insulation and sheathing evident from profile of top surface of removed insulation section
G.7  **Test cavity 2N-C**: stucco/2 layers 60 min. Grade D/OSB/
closed cell spray polyurethane/unfaced fiberglass batt/gypsum/3 coats latex paint

Figure G.7.1
- CSPU flashing thickness of 2 in.
Figure G.7.2
- bottom framing plate and floor surface stained showing presence of wetness from rundown off surface of CSPU
- mold on surface of bottom framing plate

Figure G.7.3
- bottom plate mold and staining details
Figure G.7.4
- condensate droplets on surface of CSPU

Figure G.7.5
- sheathing surface pristine with no voids at the cut-out location
Figure G.7.6
- staining/mold on side stud above surface of insulation
- crack between insulation and stud
G.8 Test cavity 2S-A: stucco/2 layers 60 min. Grade D/OSB/wool felt/unfaced fiberglass batts/2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure G.8.1
- staining on surface of felt in upper right corner
- curling of PA-6 indicates presence of high membrane moisture content
Figures G.8.2
- staining/mold on interior surface of felt in upper right hand corner
- staining sheathing surface, right hand side stud and top plate in the corner

Figure G.8.3
- PA-6 binding on gypsum attachment screw
G.9 Test cavity 2S-B: stucco/2 layers 60 min. Grade D/OSB/open cell spray polyurethane/gypsum/3 coats latex paint

Figure G.9.1
- possibility that markings on bottom plate are staining from condensate
G.10  **Test cavity 2S-C:**  stucco/2 layers 60 min. Grade D/OSB/closed cell spray polyurethane/unfaced fiberglass batt/gypsum/3 coats latex paint

Figure G.10.1
- staining/mold on bottom plate indicating presence of bulk water rundown

Figure G.10.2
- staining does not extend beyond surface of insulation indicating plate/insulation bonding prevents surface liquid movement
Figure G.10.3
- crack between insulation and left hand side stud
G.11 **Test cavity 3N-A:** stucco/2 layers 60 min. Grade D/OSB/Kraft faced fiberglass batt/gypsum/3 coats latex paint

Figure G.11.1
- surface staining indicating wetness and rundown in upper quadrant, along left hand side stud and intermittently along right hand stud
- insulation frozen to surface in places
Figure G.11.2
- frost on surface of stud with build-up along stud and plate edges
staining on bottom plate indicating accumulation of condensate rundown
G.12 Test cavity 3N-B: stucco/2 layers 60 min. Grade D/OSB/ unsealed 2-mil PA-6 membrane faced fiberglass batt/gypsum/3 coats latex paint

Figure G.12.1
- frost/ice accumulation along left hand side stud and in top right hand corner indicating severity of facing edge vapor bypass
- insulation frozen to sheathing surface
- sheathing surface staining from melted frozen condensate
Figure G.12.2
- depth of frost accumulation is significant

Figure G.12.3
- magnitude of staining on bottom plate indicates severity of condensate rundown on left hand side
G.13  **Test cavity 3N-C**: stucco/2 layers 60 min. Grade D/OSB/ unfaced fiberglass batt/4-mil PE membrane/gypsum/3 coats latex paint

![Image of test cavity 3N-C]

Figure G.13.1
- small amount frost accumulation on sheathing surface along edge of left hand side stud indicating significantly lower vapor bypass than in the adjacent cavity 3N-B
Figure G.13.2
- minor frost accumulation on surface of sheathing in upper right hand corner as well
- insulation frozen to sheathing surface

Figure G.13.3
- staining on stud and bottom plate indicating the presence of melted condensate rundown from left hand side of sheathing
- frost accumulation on surface of sheathing
Figure G.13.4
- detail showing magnitude of frost along left hand side stud
G.14 **Test cavity 3S-A**: stucco/2 layers 60 min. Grade D/OSB/Kraft faced fiberglass batt/gypsum/3 coats latex paint

Figure G.14.1
- left hand Kraft facing tab is air-sealed, right hand side is not
Figure G.14.2
• frost accumulation in upper right hand corner

Figure G.14.3
• frost accumulation in upper left hand corner
  – more severe than in upper right hand corner (Figure G.11.2)
Figure G.14.4

- comparison of sheathing surface staining in cavity 3S-A (right) and 3S-B (left)
- staining in upper left hand side quadrant of 3S-A is larger than that on upper right hand side quadrant despite the presence of the air-sealed Kraft facing tab on the left hand side.
G.15 Test cavity 3S-B: stucco/2 layers 60 min. Grade D/OSB/unsealed 2-mil PA-6 membrane faced fiberglass batt/gypsum/3 coats latex paint

Figure G.15.1
- vapor bypass occurs through gaps at edge of PA-6 facing
Figure G.15.2
- detail of significant gap between PA-6 facing and stud

Figure G.15.3
- frost accumulation, staining and mold on sheathing in upper left and right hand corners
Figure G.15.4
- detail of frost, staining and mold in upper left corner
- mold on top plate

Figure G.15.5
- frost, staining and mold in bottom right hand corner
- staining and mold on bottom plate indicating the presence of condensate rundown
Figure G.15.6
- comparison of upper cavity sheathing surface staining patterns in cavities 3S-B (right) and 3S-C (left)

G.16 **Test cavity 3S-C**: stucco/2 layers 60 min. Grade D/OSB/unfaced fiberglass batt/4-mil PE membrane/gypsum/3 coats latex paint

Figure G.16.1
- PE membrane air-sealed to stud on right hand side only (note absence of staining along right hand side stud in left hand cavity of Figure G.12.6 above)
Yet more indication of the importance of eliminating vapor bypasses at the edges of vapor retarders at the stud interface. The photographic record for test cavities 3-S demonstrates that the common practice of terminating vapor retarders with a stapled seam alone on the stud or plate is inadequate.
G.17 Test cavity 4N-A: fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/4-mil PE membrane/gypsum/3 coats latex paint

Figure G.17.1
- frost accumulation on sheathing surface in upper left hand corner
Figure G.17.2
- frost accumulation in upper left hand corner but none on right hand side illustrates the impact of the left hand side PE not being air-sealed to the stud (right hand side was air-sealed to the stud)

Figure G.17.3
- additional frost accumulation on sheathing along left hand side stud
Figure G.17.4

- Staining on bottom plate indicates condensate rundown from left hand side stud.
Test cavity 4N-B: fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure G.18.1
- pristine – note PA-6 vapor retarder air-sealed on both left and right hand studs
Test cavity 4N-C: fiber cement board/modified asphalt coated membrane/OSB/unfaced fiberglass batt/2-mil PA-6 membrane/gypsum/3 coats latex paint

Figure G.19.1
- surface of sheathing pristine next to left hand side stud pristine (vapor retarder air-sealed) staining and frost accumulation on sheathing surface next to right hand stud (vapor retarder not air-sealed)
Figure G.19.2
- frost accumulation on sheathing surface adjacent to right hand stud

Figure G.19.3
- frost accumulation away from stud pocket edge on sheathing surface
- insulation frozen to sheathing surface
Figure G.19.4

- Staining on surface of bottom plate indicating condensate rundown both towards the center of the cavity as well as down the right hand side edge.
G.22 Test cavities 4S

A: fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/
   4-mil PE membrane/gypsum/3 coats latex paint
B: fiber cement board/spun, bonded polyolefin/OSB/unfaced fiberglass batt/
   2-mil PA-6 membrane/gypsum/3 coats latex paint
C: fiber cement board/modified asphalt coated membrane/OSB/unfaced fiberglass batt/
   2-mil PA-6 membrane/gypsum/3 coats latex paint

Figures G.22
- All cavities pristine.
Commentary

Note that on southern exposure, absence of vapor retarder air-sealing at left hand stud of cavity 4S-C and right hand stud of cavity 4S-A does not produce staining on the sheathing surface or frost accumulation as a result of the solar radiation driven diurnal wetting/drying cycle.

H. UNIVERSAL ENVELOPE HYGROTHERMAL PERFORMANCE STANDARD COMPLIANCE

Applying the requirements of the standard as described in Section B yields the results shown in Table H.1.

It is very important to emphasize that none of the systems tested in the experiment was designed to meet the standard. Thus the assessment of compliance is given with the intention of showing the extent to which the systems tested are nominally deficient in meeting the standards and thereby to provide a direction for future research.

With reference to Table H.1, in order for a system to be assessed an overall passing grade for compliance, it would have to meet all the requirements on both north and south exposures. The experimental data does not enable all the requirements to be evaluated, in particular, conditions exterior to the WSP (or WRB) were not monitored and the annual wetting/drying cycle could not be measured owing to very different interior RH conditions during the first and second heating seasons. Hence, as noted beneath the table, these requirements are not included in the assessment.

Not surprisingly, the results show that none of the tested systems are compliant with the universal performance standard, in the majority of cases, because no WSP was included in the wall system. For those systems that did include a WSP, the test Bay 1 systems failed because of mold growth in either or both the north and south cavities while the system in 4N-C did not meet the 10% SR requirement in the north cavity.

Discounting the WSP requirement, system 4N-A nominally did pass assuming that the absence of visible mold is an adequate indicator of the “no mold” requirement.
### Table H.1  Compliance of experimental test systems with universal building envelope hygrothermal performance standard

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<th>Test Cavity</th>
<th>Requirement</th>
<th>Presence of water separation plane</th>
<th>a. Stable annual wetting/drying cycle</th>
<th>b. No adsorbed water for 4 months</th>
<th>c. 10% saturation ratio limit</th>
<th>d. No mold growth</th>
<th>e. No floor rundown</th>
<th>Water separation plane effective after envelope completion</th>
<th>Overall Rating</th>
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</tr>
<tr>
<td>4S-A</td>
<td>4 – exterior a</td>
<td>fail</td>
<td>not measured</td>
<td>pass</td>
<td>fail</td>
<td>none visible</td>
<td>pass</td>
<td>n/a</td>
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</tr>
<tr>
<td>4N-B</td>
<td>4 – exterior a</td>
<td>fail</td>
<td>not measured</td>
<td>pass</td>
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<td>none visible</td>
<td>pass</td>
<td>n/a</td>
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</tr>
<tr>
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<td>4 – exterior a</td>
<td>fail</td>
<td>not measured</td>
<td>pass</td>
<td>fail</td>
<td>none visible</td>
<td>pass</td>
<td>n/a</td>
<td>pass</td>
</tr>
<tr>
<td>4N-C</td>
<td>4 – exterior a</td>
<td>pass</td>
<td>not measured</td>
<td>pass</td>
<td>fail</td>
<td>none visible</td>
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</tr>
<tr>
<td>4S-C</td>
<td>4 – exterior a</td>
<td>pass</td>
<td>not measured</td>
<td>pass</td>
<td>fail</td>
<td>none visible</td>
<td>pass</td>
<td>pass</td>
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</tr>
</tbody>
</table>

**Notes**

- a. Exterior conditions were not evaluated, so only interior results are reported and are included in overall rating
- b. Not included in overall rating.
- c. Even though no mold was visible, it is highly likely that formal testing would indicate mold where evidence of surface wetness was visible.
- d. Nominal pass only. Fails the 5% SR limit and the current universal performance standard Requirement 1c.
- e. Previous version of standard.
I. CONCLUSIONS

The quantitative experimental data in combination with the photographic record of the dismantling of the test systems allow the conclusions enumerated below to be drawn. These conclusions are strictly relevant to the systems tested in the experiment in a cold northern Minnesota climate for the imposed interior and exterior boundary conditions and for the experimental time period. As such, extrapolation of these conclusions to other interior boundary conditions in different climates for longer time periods should be undertaken with caution.

1. The PA-6 systems in general yielded better performance in terms of sheathing moisture content than the PE systems even though the PA-6 systems tended to produce higher maximum sheathing moisture contents than the PE systems although, in many cases, the difference in performance was relatively small. In the case of cavity 3N-C, the PE system appeared to outperform the Kraft facing and PA-6 systems, however, this was more likely a consequence of the much higher vapor bypass effects in cavities 3N-A and 3N-B compared with 3N-C.

2. Eliminating vapor bypasses at the edges of framing cavities by air-sealing the vapor retarder (if present) to the framing is essential to avoiding significant condensate accumulation on the sheathing. This is particularly relevant to fiberglass batt facing that functions as a vapor retarder. Kraft facing without the tab air-sealing produced a vapor bypass as did unsealed PA-6 and PE. Simply stapling these vapor retarders to the framing is inadequate if the vapor retarder is not continuous between stud cavities across the framing.

3. For the systems tested, northern exposures create a more severe hygrothermal operating environment than southern exposures.

4. Open cell spray-applied polyurethane foam insulation without any interior vapor retarder yielded unacceptably large maximum sheathing moisture contents greater than 33 % on a northern exposure for the imposed boundary conditions. Under the same boundary conditions, all the other systems tested with oriented strand board sheathing yielded maximum moisture contents half this value with the exception of cavity 3N-B where high sheathing moisture contents were a consequence of a severe vapor bypass.

5. The results from the Bay 4 test cavities indicate that it is possible to design wall systems that can function effectively under very high interior humidity conditions. Hence the need to operate wall systems with an uncomfortably low (less than 30%) interior relative humidity during the heating season in cold climates to maintain envelope durability is very questionable.

6. There is no experimental evidence that stucco cladding is unacceptable for use in cold climates or that stucco in isolation is the cause of wall failures produced by mold and rot.

7. On occasion, 2-mil. PA-6 membrane has a tendency to bind to the interior sheathing (drywall) attachment screws.

8. None of the systems tested were in compliance with all the requirements of the universal building envelope hygrothermal performance standard described.
J. REFERENCES


