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# Measured and Predicted Moisture Performance of High-R Wall Assemblies in Cold Climates

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## ABSTRACT

*The wall system is a key component of an energy-efficient building. Incremental increases in building enclosure insulation levels have resulted in reduced heat loss and space heating loads. However, there are challenges that arise, including changes in the construction process and concerns about the long-term durability of these new assemblies. Of primary concern are the effects of higher insulation levels on the overall moisture performance and durability of the building enclosure. In the past, some practitioners and designers have resisted the use of low permeability exterior insulation as part of a high R-value wall system because of the concern that it will reduce drying and result in moisture accumulation within the wall system. An alternative approach to achieving high R-values is to use thick (20–50 cm [8–20 in.]) cavity spaces filled with insulation. A field study was conducted of four full-scale high-R (approximately R-30 effective) wall assemblies and one standard wall (for comparison), on both the north and south orientation, using both exterior insulation construction and thick insulation-filled wall systems. The study was performed in Waterloo, Ontario, which is on the border of IECC Climate Zones 5 and 6. The measured moisture performance data from the full-scale test walls along with interior and exterior boundary conditions was used to validate a hygrothermal model for the testing location. The model was then used to predict performance in Climate Zones 4 through 8. Both the field measurements and hygrothermal modeling demonstrated that exterior-insulated walls were much more tolerant to cold weather moisture accumulation as a result of interior air leakage into the assembly than thick cavity-insulated walls. There was also correlation between measurements and hygrothermal modeling on the slow drying of the wood sheathing following a rain leak with low permeance exterior insulation and interior vapor barrier. However, when the interior vapor barrier layer was removed, the assembly dried much more quickly. Both the field measurements and hygrothermal analysis from this study showed that the least risky wall with respect to moisture-related durability issues was an exterior-insulated wall with sufficient exterior insulation to allow a Class II or Class III vapor control layer to be used on the interior.*

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## INTRODUCTION

Like all components of a building enclosure, above-grade wall systems must fulfill four important functions: to support, distribute (goods, people, and utilities), finish, and control. The most critical control layers, in order of importance, are as follows (Straube and Burnett 2005):

- Rain control layer
- Air control layer
- Vapor control layer

- Thermal control layer

Durability depends on the interaction between these layers. For example, increasing the thermal control layer (i.e., increasing insulation R-value) without considering the material properties and placement of other layers could lead to moisture accumulation and durability risks. In the development of high-R wall designs for cold climates, several approaches have been used, each with advantages and limitations.

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The *thick wall approach* relies on traditional methods of installing insulation between framing members and installing sheathing on the exterior. To allow for more insulation, the thickness of the framing is expanded. Double-stud walls, truss walls, and I-joist walls are all examples of the thick wall approach. The most critical performance concern with these thick wall systems is interstitial condensation. Because of the increased thermal resistance of the thick insulation layer, the outer wall sheathing will be colder than standard construction in winter and any construction moisture, air exfiltration, or vapor flow may result in sheathing condensation and higher moisture contents than typical  $2 \times 4$  or  $2 \times 6$  wood-framed assemblies (Arena et. al 2013; Ueno 2015). Because of the susceptibility of thick wall designs to condensation, an effective air barrier and good vapor control are especially critical in this type of wall system.

The *exterior insulation approach* involves the addition of a continuous insulation layer exterior to the building's structure. The benefits of the exterior insulation approach were first documented in North America in the early 1960s for masonry wall assemblies (Hutcheon 1964) and have more recently been analyzed by Kane and Titley (1987); Proskiw (1995); Maref et al. (2010); and Straube (2011). By locating insulation outboard of the sheathing, this strategy shelters an assembly's structural elements and control layers from temperature cycling and (assuming sufficient insulation is used) eliminates condensation on the inner surface of the wall sheathing. Both of these benefits can result in increased durability of the wall system. Designs that use exterior insulation also allow higher R-values to be achieved, especially when used in conjunction with a traditional insulation strategy with batt insulation between the studs. Some of the more common examples of the exterior insulation approach include insulated sheathing, Exterior Insulation Finish Systems (EIFS), and exterior spray foam.

Despite these advantages, some practitioners have resisted the use of exterior-insulated designs, out of concern that low permeability insulation outboard of the sheathing could trap moisture and result in moisture accumulation within the wall system.

This paper describes research that compared a commonly constructed  $2 \times 6$  stud-bay insulated design to several different exterior-insulated R-30 (effective) wall assemblies and an R-34 (effective) double-stud wall design. Field measurements of full-scale wall assemblies were used to validate a hygrothermal model for a specific location in Southwestern Ontario (Climate Zone 5/6). The model was then used to predict performance for the field-tested assemblies (as well as an additional exterior-insulated assembly) in Climate Zones 4 to 8. The relative durability and thermal performance of high-R wall designs have implications for future research, practice, and code development.

## Experimental Method

This experiment measured the performance of the test walls under ideal construction conditions (dry during construction, perfect airtightness and watertightness) and natural environmental exposure conditions. The experiment also measured the consequences of the two most important wetting mechanisms at different times: air leakage condensation and rain penetration.

Field measurements for this study were obtained from the University of Waterloo's natural exposure test facility, which is on the border of Climate Zones 5 and 6 (4200 heating degree days [HDD] °C / 7500 HDD °F [MMAH 2012]). Data were originally gathered as part of a larger collaboration between the Natural Sciences and Research Council of Canada (NSERC), the Network of Wood-Based Building Systems (NEWBuildS), the University of Waterloo Building Engineering Group, and Ryerson University's Department of Civil Engineering. The data from this study starts in October 2012, and ends August 2013.

## Test Facility and Apparatus

The Building Engineering Group's outdoor full-scale permanent natural exposure test facility (the BEGHUT) is located on the University of Waterloo campus in Southwestern Ontario, Canada. It is approximately  $34 \times 34$  ft. ( $10.5 \times 10.5$  m) in plan and 9.8 ft. (3.0 m) high floor to ceiling, with walls oriented in the four cardinal directions. The interior conditions were maintained at approximately 70°F (21°C) and 40% rh during this experiment. A ceiling-mounted air distribution system was used to distribute the conditioned air evenly. The roof overhang (8 in. [200 mm]) is sized to prevent shading from the sun under most conditions. The small overhang and the drip-edge in lieu of eavestrough, provide very little direct protection from rainfall. The test hut is sited on relatively flat land and is fully exposed to winds from most directions. The weather station on top of the BEGHUT measures exterior temperature, exterior relative humidity, horizontal incident solar radiation, and rainfall.

Two methods of introducing moisture into the wall systems were employed at different phases of the study: one to simulate air leakage from the interior and one to simulate rain leakage from the exterior.

To simulate an interior air leak from a point source such as an electrical outlet box, interior air (70°F [21°C], 40% rh) was pumped into the center test bay of each test wall. The injection of interior air acts as a potential wetting system during the coldest months of the year. When interior air flows past any surface within the wall assembly that is below its dew point, condensation will occur on that surface. The air injection system is composed of a high-pressure blower motor and fan, attached to a distribution system of 3/4 in. (19 mm) diameter polyethylene pipe. Manifolds are used to distribute air to each wall and airflow rotameters with integral needle valves are used to control and measure the flow entering each test wall panel. The air is introduced to the center of the test bay,

at a height of 12 in. (305 mm) from the bottom of the wall through a 1 1/2 in. (38 mm) diameter plumbing cleanout. A flow rate of 0.24 L/s (30 cfh) was chosen based on air leakage rates expected in new residential construction during winter conditions (Trainor 2014). An air relief path was provided at each top plate to direct air back into the interior of the BEGHUT, as the exterior sheathing membrane acted as a reasonably effective air barrier in these test walls.

To simulate an exterior rain leak, wetting mats were applied to the exterior surface of the oriented strand board (OSB) sheathing board, interior to the sheathing membrane. Water was applied via plastic tubing with carefully punctured exit holes. The exit holes release water between a folded sheet of plastic-mesh-reinforced paper towel. This allows a controlled volume of water to be injected to a known area of the wall assembly and prevents liquid water from draining away from the site of application.

### Assembly Design and Instrumentation

The datum wall for this study was a standard 2 × 6 assembly with R-24 fiberglass batt insulation, OSB sheathing, and an interior polyethylene sheet to provide air and vapor control. This type of wall has been used for almost 30 years in much of Canada and parts of the United States and is well accepted by the industry. Such a wall system provides an effective thermal resistance of approximately R-16 when accounting for the thermal bridging of the framing members (Smegal and Straube 2009).

The other four walls in the field study represent realistic construction techniques to reach higher wall R-values. A target R-value of approximately R-30 (effective) was chosen. For the high-R walls, exterior insulation was added to the 2 × 6 insulated (datum) wall design. Different insulation types with a range of vapor permeance (from very low to very high) were selected. The fourth wall used a thick wall approach with approximately 11 1/4 in. (286 mm) cellulose insulation cavity fill and double 2 × 4 framing.

Experimental variables included insulation strategy, framing thickness, vapor control strategy and air barrier strategy (Table 1). Elements common to all assemblies are listed in Table 2. The assemblies were tested on the north and south orientations of the BEGHUT in order to represent the most differentiated temperature conditions. Solar exposure on the south results in significantly higher peak and slightly higher average annual wall temperatures, while the north has the lowest winter and annual average temperature.

Each test wall was fitted with five resistance-based moisture content and temperature (MC/T) sensors: at the top and bottom plates and at three positions in the OSB sheathing. All MC/T sensors were installed along the center line of the test panels, within the test bay. As well, two relative humidity and temperature (RH/T) sensors were installed in each test wall, within the insulation at the center point of the test wall (midway through the depth of cavity), and in the air gap behind the siding. Two thermistor temperature (T) sensors were used to monitor temperature at two other positions in the assembly. All penetrations were air sealed with caulking or spray foam. Details of the instrumentation for this project and for similar

**Table 1. Test Wall Variables**

| Test Wall                     | Insulation Strategy                                                                                                                 | Air/Vapor Control                                 | Framing Thickness                                                                                                                                                                                                                                                          |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1: Datum                      | Standard R-24 (RSI- 4.2) fiberglass batt insulation between studs                                                                   | Air/vapor:<br>6 mil. polyethylene on the interior | Standard 2 × 6 wood studs, 24 in. (610 mm) on center                                                                                                                                                                                                                       |
| 2: Mineral wool (MW)          | Datum + 3 in. (76 mm) high-density MW (installed in two layers) exterior to the water control membrane                              | Air/Vapor:<br>6 mil. polyethylene on the interior | Standard 2 × 6 wood studs, 24 in. (610 mm) on center                                                                                                                                                                                                                       |
| 3: Extruded polystyrene (XPS) | Datum + 2 1/2 in. (63.5 mm) of XPS (installed in two layers) exterior to the water control membrane                                 | Vapor: XPS<br>Air: airtight drywall               | Standard 2 × 6 wood studs, 24 in. (610 mm) on center                                                                                                                                                                                                                       |
| 4: Polyisocyanurate (PIC)     | Datum + 2 in. (50 mm) foil-faced PIC (installed in two layers) exterior to the water control membrane                               | Vapor: PIC<br>Air: airtight drywall               | Standard 2 × 6 wood studs, 24 in. (610 mm) on center                                                                                                                                                                                                                       |
| 5: Double stud                | Cavity filled with dense-packed cellulose insulation at a density of approximately .4 pounds per cubic foot (65 kg per cubic meter) | Air/vapor:<br>6 mil. polyethylene on the interior | Outer wall: 2 × 6 wood stud with a double top plate<br>Inner wall: 2 × 4 wood stud with a single top plate<br>Walls attached using 3/8 in. (9.5 mm) thick plywood gusset plates creating a 2 1/4 in. gap between inner and outer studs<br>Total: 11 1/4 in. (286 mm) thick |

monitoring projects can be found in the works by Trainor (2014) and Straube et al. (2002).

### Field Measurement Results

**Moisture Content Measurements.** Moisture content (MC) sensors provide a direct measurement of moisture accumulation at the OSB sheathing and wood framing members. This moisture includes the built-in moisture, the absorption of condensation or bulk water, as well as the adsorption of mois-

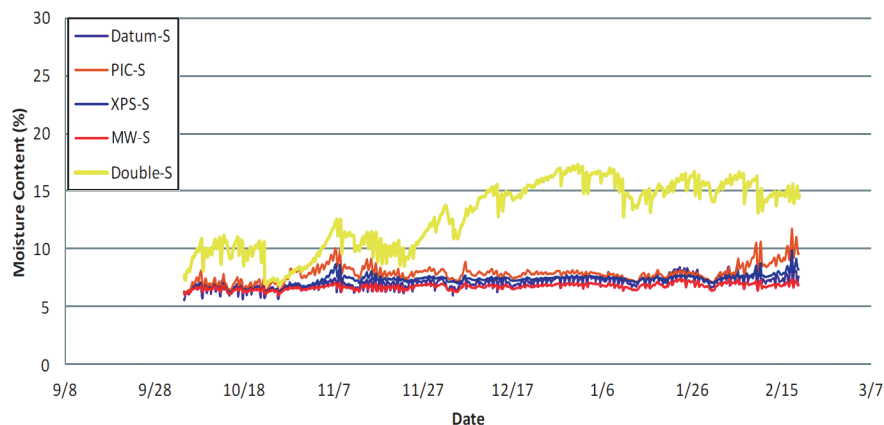
ture in the air and redistribution of moisture from surrounding materials. It is also important to consider that measured moisture content is the net effect of both wetting and drying mechanisms. Moisture content is reported as a percentage by mass. Wood moisture content measurements were used as the analysis criteria in this research to demonstrate the measured performance differences between the test walls and to correlate the measured performance to the hygrothermal analysis.

As shown in Figure 1, under the as-built conditions (Phase 1), the OSB sheathing moisture content remained primarily between 6% and 8% for the datum wall and the exterior-insulated walls, with a few brief peaks of 10% to 12% for the PIC wall during extended wet weather. The OSB moisture content for the double-stud wall was measurably higher than the other test walls, especially near the top of the walls on the south side. Moisture content readings at the upper sheathing position began to increase as the weather turned colder reaching as high as 17% without any intentional defects in construction. These results are likely because of the concentration of built-in moisture within the cellulose because of the buoyancy of the air within the solar heated (south side) double-stud wall. Many other sensor measurements are available in the work by Trainor (2014).

During Phase 2 (air injection phase), the air injection had little effect on the measured moisture content of any of the test walls at the top plate or upper sheathing positions. On the lower half of the walls near the air injection site, however, the air injection resulted in significant increases in moisture content in the double-stud and datum walls, as seen in Figure 2. The sheathing on the double-stud wall picked up moisture consistently over the air injection period and was not significantly affected by the exterior temperature variations over that time. This is likely due to the hygric buffering effects of the cellulose in the cavity. The sheathing of the datum wall, however, picked up moisture very quickly during the cold periods and dried down during periods of warmer weather. The sheathing moisture content of the exterior-insulated walls even with the injection of interior air did not exceed 10% MC.

**Table 2. Test Wall Common Elements**

| Element                    | Description                                                                                                                                                                 |
|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Framing layout             | Double top plates, single bottom plate; inner two studs of standard 2 × 6 framing lumber 16 in. on center                                                                   |
| End studs                  | End studs of 3/8 in. (9.5 mm) thick plywood, attached to OSB sheathing and drywall with sheet metal L-brackets                                                              |
| Cladding                   | Prepainted fiber cement lap siding, applied continuously and sealed at the top edge                                                                                         |
| Air gap                    | To form a drainage and ventilation gap, the cladding was installed on vertical pine furring strips, 2 1/2 in. (64 mm) wide and 3/4 in. (19 mm) thick                        |
| Water-air control membrane | Spun bonded polyolefin, stapled to the OSB sheathing and sealed to the perimeter of the OSB and to the wall buck using 2 1/2 in. (60 mm) wide technical tape                |
| Structural sheathing       | 7/16 in. (11 mm) thick OSB, attached to the wall framing using 1 1/2 in. (38 mm) wood screws at 16 in. (406 mm) on center                                                   |
| Interior finish            | 1/2 in. (12.7 mm) thick gypsum wallboard (drywall) installed with 1 1/4 in. (32 mm) drywall screws at 16 in. (406 mm) on center. and painted with two layers of latex paint |



**Figure 1** Measured moisture content at upper sheathing during as-built Phase 1, south elevation.

**Rain Leaks and Drying Capability.** The intentional wetting events were used to apply a controlled amount of water directly to the exterior surface of the OSB sheathing, simulating a rainwater leak at the corner of a window or other area of water concentration. It's important to note that the intentional wetting events simulated a construction failure in the water control layer of the enclosure. With a large enough failure of the water control layer, few walls are safe from durability-related issues such as mold and rot. However, drying potential can often manage small imperfections in moisture control. The primary method of quantifying drying capability in this study was to track the change in the measured sheathing MC during and following the wetting mat water application. The lower sheathing position was the focus of the assessment since it was within the field of the wetting mat.

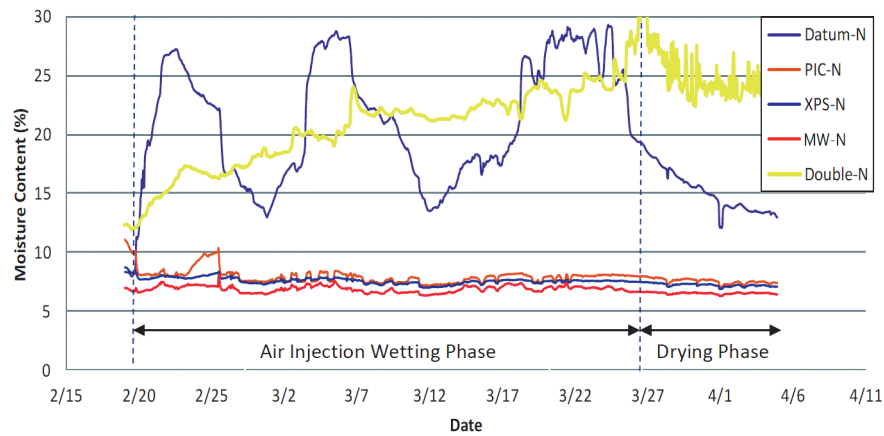
Figure 3 shows the accumulation of moisture during and immediately following the wetting mat water injections and the subsequent drying phase (with the dashed line for each wall on the graph) at the lower sheathing position (immediately in line with the wetting mat). This graph shows that the datum and double-stud walls were the quickest to dry

down to prewetting moisture content levels, requiring approximately a week and a half. The mineral wool (MW) exterior-insulated wall also dried down very quickly requiring only 2 weeks. The extruded polystyrene (XPS) and the polyisocyanurate exterior-insulated walls required 8 to 10 weeks to dry down to prewetting moisture content levels.

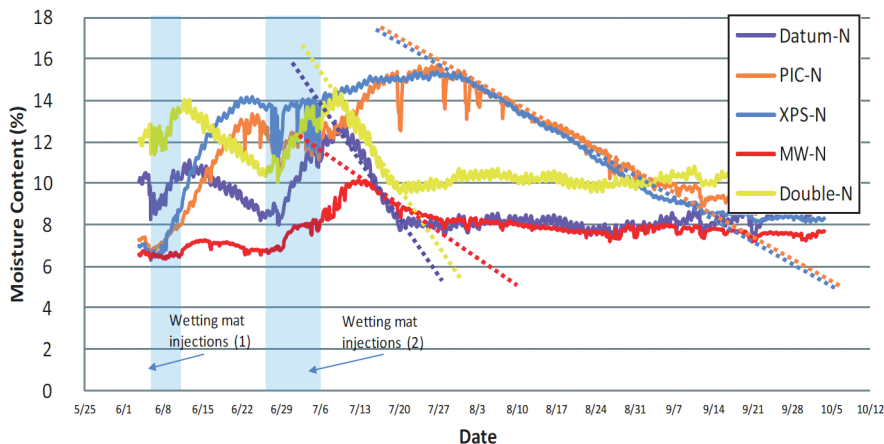
Clearly, the largest factor affecting time to dry is the vapor flow resistance of the assembly layers exterior to the sheathing. The XPS and PIC walls were only able to effectively dry to the interior and required approximately five times longer to dry down after wetting compared to the other test walls. These walls have not yet been dismantled to assess moisture damage visually.

### HYGROTHERMAL MODELING

Combining measured data with hygrothermal modeling adds value to both research methods; measured data significantly improves the predictive validity of models, while well-designed and validated models can cost-effectively predict performance across a wide range of locations and other variables. In the current study, measured moisture performance



**Figure 2** Measured moisture content at lower sheathing during air injection Phase 2, north elevation.



**Figure 3** Measured moisture content at lower sheathing during wetting mat and subsequent drying phase, south side.

data from the full-scale test walls along with interior and exterior boundary conditions were used to validate a hygrothermal model for the testing location in Climate Zone 5/6. The model was then used to predict performance in Climate Zones 4 to 8.

### Approach

Before hygrothermal simulations were conducted, simulations were set up in WUFI® Pro (Fraunhofer IBP 2011) for existing wall assemblies, using measured boundary conditions, to determine if the predicted moisture performance of the assemblies closely matched measured performance.

**Model Validation.** Measured data from the University of Waterloo NSERC-NewBuilds High-R Wall Study (Trainer 2014) was used to correlate the measured performance to the predicted performance. North-orientation wall data from November 1, 2012 through October 31, 2014 was used for this validation. The north orientation was selected because it experiences very little direct solar energy, which complicates the correlation. As well, elevated moisture content levels were required in the test walls to be able to correlate the predicted moisture content performance, and the north orientation provides the worst-case scenario for sheathing moisture content, due to cold weather moisture accumulation.

Each of the modeled assemblies was run with a custom two-year Waterloo, Ontario outdoor weather file and an interior conditions file which matched the time-frame of the monitoring data. The results from each simulation were then compared to monitoring data. Specifically, comparisons were made between measured and predicted cladding temperature, sheathing temperature, and sheathing moisture content. As an additional check of the models, a sensitivity analysis was performed for the following three variables most relevant to the predicted hygrothermal performance of these wall systems in cold climates:

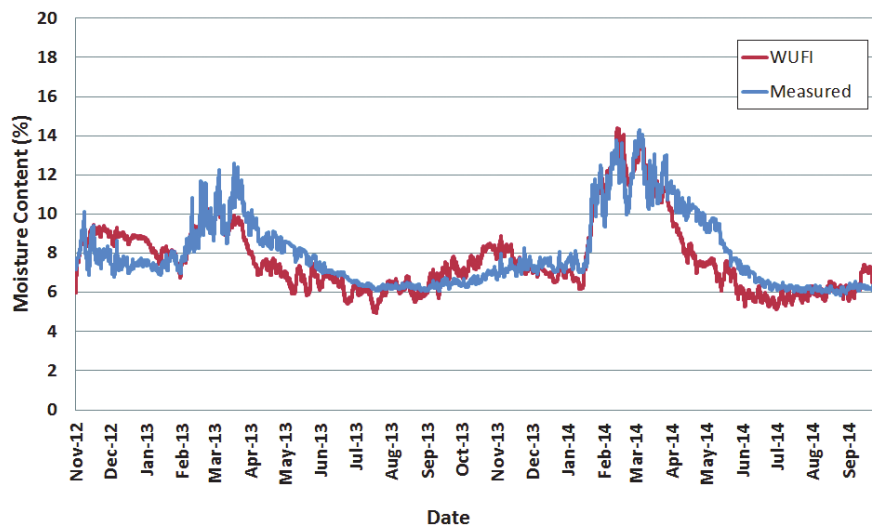
- Exterior insulation level

- Climate zone
- Interior RH

The WUFI models were found to provide results that were consistent with field monitoring data and appropriately sensitive to critical modeling parameters. Figure 4 shows one example of the agreement of the WUFI predicted sheathing moisture content and the actual measured sheathing moisture content for the PIC wall over a two-year period.

Following the validation of the modeled wall assemblies, three rounds of simulations were conducted for the datum wall, the double-stud wall, and the three types of exterior-insulated wall systems (PIC, XPS, and MW exterior insulation). An additional exterior-insulated wall was also modeled using expanded polystyrene (EPS). Standard WUFI material data were used where available. Where standard data were unavailable, custom material files were created. The three rounds of hygrothermal simulations were conducted as follows:

1. Baseline simulations were first performed for each geographic location with the datum wall, the double-stud wall, and the exterior-insulated walls with approximately RSI 2.1 (R-12) of exterior insulation. These simulations assumed a perfect air barrier and no rain penetration and were used to determine the effect of climate on peak sheathing moisture content for these assemblies.
2. Simulations were then performed on the exterior-insulated wall systems with higher levels of exterior insulation in select cold climates and lower levels of exterior insulation in select warmer climates. These simulations also assumed a perfect air barrier and no rain penetration and were used to determine the interactive effect of climate and the exterior/interior insulation ratio on peak sheathing moisture content.
3. Finally, a third round of simulations was performed using the models from the baseline testing at select locations



**Figure 4** Upper OSB moisture content: measured versus WUFI model for the PIC wall over a 2-year period.

with the addition of air exfiltration or rain leakage to determine the effects of these conditions on peak sheathing moisture content.

**Experimental Model Parameters.** The parameters for the WUFI modeling runs were chosen to support the main objectives of the study: to evaluate the performance of wood-framed, high-R wall systems under a variety of realistic conditions. The eight locations in Canada that were chosen for WUFI modeling are shown in Table 3, along with some of the relevant climate parameters for each location.

The north orientation was used for all simulations that did not involve rain leakage. As mentioned above, the north orientation has the lowest drying capacity and is often the worst-case for cold weather moisture accumulation and elevated sheathing moisture content. For simulations that included rain leakage, the elevation with the highest driving rain exposure was used. There were two levels of interior RH used for simulations in all locations:

- Low: Sine curve function with 30% wintertime RH to represent an air-leaky house with low moisture generation and/or adequate mechanical ventilation.
- Medium: Sine curve function with 40% wintertime RH to represent a more airtight house with more moisture generation and/or less than adequate ventilation.

A third, lower RH level (20%) was used for simulations in Winnipeg and Yellowknife because of the extreme cold winter conditions. To compare the moisture durability of the wall assemblies, the MC of a thin slice (1/8 in. [3 mm]) of the structural sheathing on the interior and exterior faces was obtained from the simulations on an hourly basis. OSB sheathing moisture content was used as the performance criteria because this is generally where moisture will accumulate and wood sheathing is a moisture-susceptible material. The peak

annual OSB sheathing MC was determined and the risk was assessed based on the following criteria:

- Low Risk: Peak OSB sheathing MC <20%, no mold growth.
- Moderate Risk: Peak OSB sheathing MC 20%–28%; potential for mold growth eventually, depending on frequency, length of wetting, and temperatures during wetting. This design can be successful, but conservative durability assessments usually require corrective action.
- High Risk: Peak OSB sheathing MC >28%; moisture-related problems are expected and this design is not recommended.

To test the effect of changing the ratio of exterior insulation to total R-value on sheathing moisture content, the simulations for the exterior-insulated walls were repeated with the same cavity insulation (R-24) and varying amounts of exterior insulation. In the very cold climates of Winnipeg and Yellowknife, exterior insulation values were increased to approx. RSI 3.1 (R-18) (43% insulation ratio) and RSI 4.2 (R-24) (50% insulation ratio). In the warmer climates of Vancouver, Toronto, and Ottawa, exterior insulation levels were reduced to approximately RSI 1.0 (R-6) (20% insulation ratio).

To test the effect of exterior insulation on the drying capacity of the wall systems, the simulations were repeated with two levels of simulated rain leakage. This was accomplished by creating a moisture source on the exterior surface of the sheathing layer. Simulations were performed with this moisture source at 1% and 2% of driving rain in Vancouver, Toronto, and St. John's. For these simulations, the elevation with highest driving rain exposure was used (east for Vancouver, south-east for Toronto, and south for St. John's).

To test the resistance of the wall systems to air leakage condensation, two levels of air leakage were tested: 0.02 L/s/m<sup>2</sup> (0.04 cfm/ft<sup>2</sup>) and 0.08 L/s/m<sup>2</sup> (0.16 cfm/ft<sup>2</sup>). These values represent the approximate natural air leakage rate for a very

**Table 3. Locations and Relevant Climate Parameters in WUFI Analysis**

| Location         | 2.5% Design Temperature, °C | Heating Degree Days, HDD18 | Annual Precipitation, mm | Annual Driving Rain, mm | IECC Climate Zone |
|------------------|-----------------------------|----------------------------|--------------------------|-------------------------|-------------------|
| Vancouver, BC    | -7                          | 2910                       | 1169                     | 950                     | 4                 |
| St. John's, NL   | -15                         | 4881                       | 914                      | 900                     | 6                 |
| Toronto, ON      | -20                         | 3800                       | 606                      | 225                     | 5                 |
| Ottawa, ON       | -25                         | 4440                       | 586                      | 400                     | 6                 |
| Quebec City, QC  | -25                         | 5080                       | 807                      | 375                     | 6/7               |
| Calgary, AL      | -30                         | 5000                       | 304                      | 250                     | 6/7               |
| Winnipeg, MB     | -33                         | 5670                       | 309                      | 200                     | 7                 |
| Yellowknife, NWT | -41                         | 8170                       | 289                      | N/A                     | 8                 |

Note: 2.5% Design temperature and heating degree days data are from NRC (2012). Precipitation and driving rain are from WUFI Pro Standard Weather Files (Fraunhofer IBP 2011).



airtight building (approximately 0.6 ACH<sub>50</sub> as required for Passive House certification [Passive House Institute 2014]) and a moderately airtight building (approx. 2.5 ACH<sub>50</sub>, as required for ENERGY STAR<sup>®</sup> certification) respectively. These models were tested on all simulated wall assemblies under the climatic conditions of Vancouver, Toronto, and St. John's.

### MODELING RESULTS

The results of the calibrated hygrothermal modeling study show the same general trends as the measured data. Figures 5–8 assume the following parameters:

- Walls are residential wood frame with light-colored thin cladding facing north. This is a worst-case scenario for cold-weather diffusion wetting.
- Results are for OSB sheathing. Plywood sheathing values will be equal or lower. OSB permeance is always over 60 ng/Pa·s·m<sup>2</sup> in exterior sheathing applications.

- Effective air barrier is assumed to be installed, as is proper rain control.
- MC values are for inner 0.12 in. (3 mm) OSB sheathing.

As shown in Figure 5, in the absence of air exfiltration and rain leakage, the double-stud wall consistently showed sheathing moisture content higher than the standard (datum) wall, but remained within the low-risk zone in all locations without air or water leakage. The results for the exterior-insulated walls demonstrate the importance of the exterior/total insulation ratio and its relationship with both climate and interior relative humidity. When the level of exterior insulation was not adequate for the climate and/or interior RH, sheathing moisture contents exceeded safe levels without sufficient interior vapor control. As shown in Figure 6, however, when a sufficient insulation ratio was used, the exterior-insulated walls remained within the low risk zone, even without an interior polyethylene vapor barrier. More specifically, results showed that:

■ = MC < 20%, no mold growth    
 ■ = MC is 20 to 28%, potential for mold growth    
 ■ = MC > 28%, moisture problems expected, this design is NOT recommended

| Wall Construction |                   |              |                                  |                       |                    | Vancouver      |                | St. John's      |                | Toronto         |                | Ottawa          |                | Quebec City     |                | Calgary         |                |                   | Winnipeg        |                |                   | Yellowknife     |                |    |
|-------------------|-------------------|--------------|----------------------------------|-----------------------|--------------------|----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-------------------|-----------------|----------------|-------------------|-----------------|----------------|----|
|                   |                   |              |                                  |                       |                    | 2.5% Temp = -7 |                | 2.5% Temp = -15 |                | 2.5% Temp = -20 |                | 2.5% Temp = -25 |                | 2.5% Temp = -25 |                | 2.5% Temp = -30 |                |                   | 2.5% Temp = -33 |                |                   | 2.5% Temp = -41 |                |    |
|                   |                   |              |                                  |                       |                    | HDD 2910       |                | HDD 4881        |                | HDD 3800        |                | HDD 4440        |                | 5080            |                | HDD 5000        |                |                   | HDD 5670        |                |                   | HDD 8170        |                |    |
| Wall              | Cavity Insulation | Cavity Depth | Exterior Insulation              | Ext. Insul. Thickness | Vapour Control     | Low RH 30/55%  | Med. RH 40/60% | Low RH 30/55%   | Med. RH 40/60% | Low RH 30/55%   | Med. RH 40/60% | Low RH 30/55%   | Med. RH 40/60% | Low RH 30/55%   | Med. RH 40/60% | Low RH 30/55%   | Med. RH 40/60% | Ex. Low RH 20/50% | Low RH 30/55%   | Med. RH 40/60% | Ex. Low RH 20/50% | Low RH 30/55%   | Med. RH 40/60% |    |
| Datum             | Fiberglass        | 5.5"         | none                             | 0                     | Polyethylene sheet | 10%            | 11%            | 11%             | 11%            | 11%             | 11%            | 10%             | 10%            | 11%             | 11%            | 8%              | 8%             | 10%               | 10%             | 10%            | 11%               | 11%             | 12%            |    |
| PIC               | Fiberglass        | 5.5"         | polyisocyanurate                 | 2"                    | Latex paint-primer | 10%            | 11%            | 12%             | 15%            | 11%             | 13%            | 12%             | 18%            | 13%             | 19%            | 14%             | 21%            | 12%               | 20%             | 30%            | 15%               | 30%             | 35+%           |    |
|                   |                   |              |                                  |                       | Polyethylene sheet |                |                |                 |                |                 |                |                 |                | 7%              |                |                 |                |                   |                 |                |                   |                 |                |    |
| XPS               | Fiberglass        | 5.5"         | extruded polystyrene             | 2.5"                  | Latex paint-primer | 10%            | 11%            | 12%             | 15%            | 11%             | 13%            | 12%             | 14%            | 13%             | 19%            | 14%             | 21%            | 12%               | 20%             | 30%            | 15%               | 30%             | 35+%           |    |
|                   |                   |              |                                  |                       | Polyethylene sheet |                |                |                 |                |                 |                |                 |                |                 | 7%             |                 |                |                   |                 |                |                   |                 |                |    |
| EPS               | Fiberglass        | 5.5"         | expanded polystyrene             | 3.0"                  | Latex paint-primer | 10%            | 11%            | 12%             | 17%            | 11%             | 14%            | 13%             | 20%            | 14%             | 20%            | 15%             | 24%            | 12%               | 21%             | 34%            | 17%               | 34%             | 35+%           |    |
|                   |                   |              |                                  |                       | Polyethylene sheet |                |                |                 |                |                 |                |                 |                | 8%              |                |                 | 8%             |                   |                 |                |                   |                 |                |    |
| MW                | Fiberglass        | 5.5"         | mineral wool insulated sheathing | 3.0"                  | Latex paint-primer |                | 12%            |                 |                |                 |                |                 | 12%            |                 | 15%            |                 | 16%            | 12%               | 17%             | 25%            | 13%               | 25%             | 35+%           |    |
|                   |                   |              |                                  |                       | Polyethylene sheet | 8%             | 9%             | 8%              | 8%             | 9%              | 9%             | 8%              | 8%             | 9%              | 9%             | 7%              | 7%             | 7%                | 8%              | 8%             | 8%                | 7%              | 7%             | 8% |
| Double Stud       | Cellulose         | 11.25"       | none                             | 0                     | Polyethylene sheet | 12%            | 13%            | 13%             | 14%            | 13%             | 13%            | 14%             | 14%            | 14%             | 14%            | 13%             | 13%            | 15%               | 15%             | 14%            | 16%               | 16%             | 16%            |    |

Figure 5 Modeling results: maximum sheathing moisture content for baseline conditions (no rain or air leakage).

■ = MC < 20%, no mold growth    
 ■ = MC is 20 to 28%, potential for mold growth    
 ■ = MC > 28%, moisture problems expected, this design is NOT recommended

| Wall Construction |                   |              |                                  |                       |                    | Winnipeg       |                | Winnipeg       |                | Winnipeg       |                | Yellowknife    |                | Yellowknife    |                | Yellowknife    |                | Vancouver     |                | Toronto       |                | Ottawa        |                |
|-------------------|-------------------|--------------|----------------------------------|-----------------------|--------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|
|                   |                   |              |                                  |                       |                    | R-12 (RSI 2.1) |                | R-18 (RSI 3.1) |                | R-24 (RSI 4.2) |                | R-12 (RSI 2.1) |                | R-18 (RSI 3.1) |                | R-24 (RSI 4.2) |                | R-6 (RSI 1.0) |                | R-6 (RSI 1.0) |                | R-6 (RSI 1.0) |                |
|                   |                   |              |                                  |                       |                    | HDD 5777       |                | HDD 5777       |                | HDD 5777       |                | HDD 8166       |                | HDD 8166       |                | HDD 8166       |                | HDD 2910      |                | HDD 3800      |                | HDD 4440      |                |
| Wall              | Cavity Insulation | Cavity Depth | Exterior Insulation              | Ext. Insul. Thickness | Vapour Control     | Low RH 30/55%  | Med. RH 40/60% | Low RH 30/55%  | Med. RH 40/60% | Low RH 30/55%  | Med. RH 40/60% | Low RH 30/55%  | Med. RH 40/60% | Low RH 30/55%  | Med. RH 40/60% | Low RH 30/55%  | Med. RH 40/60% | Low RH 30/55% | Med. RH 40/60% | Low RH 30/55% | Med. RH 40/60% | Low RH 30/55% | Med. RH 40/60% |
| PIC               | Fiberglass        | 5.5"         | polyisocyanurate                 | 2.0"                  | Latex paint-primer | 20%            | 30%            | 15%            | 23%            |                | 18%            | 30%            | 35+%           | 15%            | 30%            | 12%            | 15%            | 12%           | 14%            | 13%           | 19%            | 16%           | 26%            |
|                   |                   |              |                                  | 3.0"                  | Polyethylene sheet |                |                | 8%             |                | 8%             |                | 8%             |                | 7%             |                | 7%             |                | 7%            |                |               |                | 9%            |                |
| XPS               | Fiberglass        | 5.5"         | extruded polystyrene             | 2.5"                  | Latex paint-primer | 20%            | 30%            | 15%            | 23%            |                | 18%            | 30%            | 35+%           | 15%            | 30%            | 12%            | 15%            | 12%           | 12%            | 13%           | 20%            | 18%           | 28%            |
|                   |                   |              |                                  | 3.5"                  | Polyethylene sheet |                |                | 8%             |                | 8%             |                | 8%             |                | 7%             |                | 7%             |                | 7%            |                |               |                | 9%            |                |
| EPS               | Fiberglass        | 5.5"         | expanded polystyrene             | 3.0"                  | Latex paint-primer | 21%            | 34%            | 17%            | 24%            |                | 19%            | 34%            | 35+%           | 17%            | 34%            | 12%            | 17%            | 12%           | 12%            | 13%           | 20%            | 18%           | 28%            |
|                   |                   |              |                                  | 4.5"                  | Polyethylene sheet |                |                | 8%             |                | 8%             |                | 8%             |                | 7%             |                | 7%             |                | 7%            |                |               |                | 9%            |                |
| MW                | Fiberglass        | 5.5"         | mineral wool insulated sheathing | 3.0"                  | Latex paint-primer | 17%            | 25%            | 12%            | 19%            |                | 14%            | 25%            | 35+%           | 13%            | 25%            | 10%            | 13%            | 9%            | 12%            | 12%           | 16%            | 15%           | 24%            |
|                   |                   |              |                                  | 4.5"                  | Polyethylene sheet | 8%             | 8%             | 8%             |                | 8%             |                | 7%             | 8%             | 7%             | 7%             | 7%             | 7%             |               |                |               |                | 9%            | 8%             |

Figure 6 Modeling results: maximum sheathing moisture content for higher and lower levels of exterior insulation.



- When an interior vapor barrier was present, and there was no air exfiltration or rain leakage, all of the walls tested were in the low-risk zone for sheathing MC. The sheathing MC for the exterior-insulated walls remained very low at 8% or below, while the datum wall remained at 11% or lower and the double-stud wall ranged from 12% in warmer climates to 16% in the colder climates.
- The interior RH had very little effect on sheathing moisture content for walls with interior polyethylene. In the walls with low-permeance exterior insulation and no interior polyethylene (only latex paint) in colder climates (Ottawa and colder), the increase of interior RH from the low to the medium level resulted in a significant increase in sheathing moisture content, in some cases to risky levels. This shows that the durability of the wall system is closely related to the interior relative humidity, exterior climate, and vapor control performance.
- Higher levels of exterior insulation resulted in decreased sheathing moisture content. The addition of an inadequate level of exterior insulation without a polyethylene vapor barrier was found to result in increased sheathing moisture content risk levels compared to the standard (datum) wall in several cases.

The results of the simulations that included rain leakage can be seen in Figure 7. When rain leakage is included in the model, sheathing moisture content appears to be a function of the amount of rain exposure, the annual climatic temperature conditions, and the drying capacity of the wall system. The drying capacity of the wall system is significantly reduced with the addition of low-permeance exterior insulation; however, much of that reduction can be mitigated by removing the interior polyethylene vapor barrier to allow inward drying.

Removal of the interior polyethylene vapor barrier should only be done when a sufficient amount of exterior insulation is used.

The results of the simulations that included air leakage can be seen in Figure 8. When air leakage was included in the simulation, the walls with adequate levels of exterior insulation were not significantly affected by the air leakage. Conversely, the datum wall and double-stud wall showed a significant increase in sheathing moisture content under the air leakage conditions. Air exfiltration at lower rate resulted in moisture contents at or near the moderate risk level, while air leakage at the higher rate resulted in moisture content levels at or near the high risk levels for these walls. A more thorough analysis of the modeling results including graphs can be found in the work by Trainor and Smegal (2015).

### CONCLUSIONS

As building and energy codes continue to call for higher thermal performance, and move toward using effective R-values as the standard for construction, assembly designs with more insulation will be required. Abundant previous field research, dew point analysis calculations, moisture physics calculations, and hygrothermal simulations support the use of insulation to the exterior of the structure and control layers. Yet there are still moisture-related durability concerns about continuous exterior insulation from some practitioners and designers in the industry.

This study compared measured data from standard wood-framed walls without exterior insulation, high-R exterior-insulated walls, and a thick high-R wall design. Measured and modeled data showed that the thick high-R wall (with a high level of insulation between the sheathing and drywall) had significantly more risk and higher measured sheathing moisture content than the standard 2 × 6 wood-framed wall, both

= MC < 20%, no mold growth
  = MC is 20 to 28%, potential for mold growth
  = MC > 28%, moisture problems expected, this design is NOT recommended

| Wall              | Wall Construction |                     |                                  |                |                    | Vancouver                     |              |            | Toronto                      |              |              |            | St. Johns                     |              |      |
|-------------------|-------------------|---------------------|----------------------------------|----------------|--------------------|-------------------------------|--------------|------------|------------------------------|--------------|--------------|------------|-------------------------------|--------------|------|
|                   |                   |                     |                                  |                |                    | Ave. Annual Temp 9 °C         |              |            | Ave. Annual Temp 7 °C        |              |              |            | Ave. Annual Temp 4 °C         |              |      |
|                   |                   |                     |                                  |                |                    | HDD 2910, 304 mm Driving Rain |              |            | HDD 3800, 77 mm Driving Rain |              |              |            | HDD 4881, 291 mm Driving Rain |              |      |
| Cavity Insulation | Cavity Depth      | Exterior Insulation | Ext. Insul. Thickness            | Vapour Control | No Leakage         | 1% Rain leak                  | 2% Rain leak | No Leakage | 1% Rain leak                 | 2% Rain leak | 5% Rain leak | No Leakage | 1% Rain leak                  | 2% Rain leak |      |
| Datum             | Fiberglass        | 5.5"                | none                             | 0              | Polyethylene sheet | 11%                           | 15%          | 22%        | 11%                          | 11%          | 12%          | 15%        | 11%                           | 15%          | 22%  |
| PIC               | Fiberglass        | 5.5"                | polyisocyanurate                 | 2"             | Latex paint+primer | 11%                           | 16%          | 24%        | 13%                          | 13%          | 17%          | 23%        | 15%                           | 25%          | 35+% |
|                   |                   |                     |                                  |                | Polyethylene sheet |                               | 35+%         | 35+%       |                              | 11%          | 15%          | 35+%       |                               | 35+%         | 35+% |
| XPS               | Fiberglass        | 5.5"                | extruded polystyrene             | 2.5"           | Latex paint+primer | 11%                           | 16%          | 24%        | 13%                          | 13%          | 17%          | 23%        | 15%                           | 25%          | 35+% |
|                   |                   |                     |                                  |                | Polyethylene sheet |                               | 35+%         | 35+%       |                              |              | 15%          | 35+%       |                               | 35+%         | 35+% |
| EPS               | Fiberglass        | 5.5"                | expanded polystyrene             | 3.0"           | Latex paint+primer | 11%                           | 17%          | 27%        | 14%                          | 15%          | 18%          | 25%        | 17%                           | 26%          | 35+% |
|                   |                   |                     |                                  |                | Polyethylene sheet |                               | 35+%         | 35+%       |                              |              | 20%          | 35+%       |                               | 35+%         | 35+% |
| MW                | Fiberglass        | 5.5"                | mineral wool insulated sheathing | 3.0"           | Latex paint+primer |                               | 13%          | 18%        |                              |              | 12%          | 16%        |                               | 13%          | 20%  |
|                   |                   |                     |                                  |                | Polyethylene sheet | 9%                            | 12%          | 18%        | 9%                           | 9%           | 9%           | 13%        | 8%                            |              | 20%  |
| Double Stud       | Cellulose         | 11.25"              | none                             | 0              | Polyethylene sheet | 13%                           | 15%          | 20%        | 13%                          | 13%          | 16%          | 19%        | 14%                           | 17%          | 20%  |

Figure 7 Modeling results: maximum sheathing moisture content including rain leakage.

= MC < 20%. no mold growth
  = MC is 20 to 28%, potential for mold growth
  = MC > 28%, moisture problems expected, this design is NOT recommended

| Wall Construction |                   |              |                                  |                       |                    | Vancouver                     |                    |                    | Toronto                      |                    |                    | St. Johns                     |                    |                    |
|-------------------|-------------------|--------------|----------------------------------|-----------------------|--------------------|-------------------------------|--------------------|--------------------|------------------------------|--------------------|--------------------|-------------------------------|--------------------|--------------------|
|                   |                   |              |                                  |                       |                    | 2.5% Temp. = -7               |                    |                    | 2.5% Temp. = -20             |                    |                    | 2.5% Temp. = -15              |                    |                    |
|                   |                   |              |                                  |                       |                    | HDD 2926, 304 mm Driving Rain |                    |                    | HDD 4065, 77 mm Driving Rain |                    |                    | HDD 5777, 291 mm Driving Rain |                    |                    |
| Wall              | Cavity Insulation | Cavity Depth | Exterior Insulation              | Ext. Insul. Thickness | Vapour Control     | No Exfiltration               | Air Exfil. 0.5 ACH | Air Exfil. 2.0 ACH | No Exfiltration              | Air Exfil. 0.5 ACH | Air Exfil. 2.0 ACH | No Exfiltration               | Air Exfil. 0.5 ACH | Air Exfil. 2.0 ACH |
| Datum             | Fiberglass        | 5.5"         | none                             | 0                     | Polyethylene sheet | 11%                           | 17%                | 29%                | 11%                          | 22%                | 35+%               | 11%                           | 24%                | 35+%               |
| PIC               | Fiberglass        | 5.5"         | polyiso-cyanurate                | 2"                    | Latex paint+primer | 11%                           | 12%                | 13%                | 13%                          | 15%                | 17%                | 15%                           | 18%                | 20%                |
|                   |                   |              |                                  |                       | Polyethylene sheet |                               |                    | 13%                |                              |                    | 16%                |                               |                    |                    |
| XPS               | Fiberglass        | 5.5"         | extruded polystyrene             | 2.5"                  | Latex paint+primer | 11%                           | 12%                | 13%                | 13%                          | 14%                | 16%                | 15%                           | 18%                | 20%                |
|                   |                   |              |                                  |                       | Polyethylene sheet |                               |                    |                    |                              |                    |                    |                               |                    |                    |
| EPS               | Fiberglass        | 5.5"         | expanded polystyrene             | 3.0"                  | Latex paint+primer | 11%                           | 12%                | 13%                | 14%                          | 18%                | 19%                | 17%                           | 20%                | 22%                |
|                   |                   |              |                                  |                       | Polyethylene sheet |                               |                    |                    |                              |                    |                    |                               |                    |                    |
| MW                | Fiberglass        | 5.5"         | mineral wool insulated sheathing | 3.0"                  | Latex paint+primer |                               |                    |                    |                              |                    |                    |                               |                    | 15%                |
|                   |                   |              |                                  |                       | Polyethylene sheet | 9%                            | 10%                | 12%                | 9%                           | 10%                | 13%                | 8%                            | 11%                | 13%                |
| Double Stud       | Cellulose         | 11.25"       | none                             | 0                     | Polyethylene sheet | 13%                           | 25%                | 28%                | 13%                          | 25%                | 29%                | 14%                           | 31%                | 35+%               |

**Figure 8** Modeling results: maximum sheathing moisture content including air leakage.

under normal operating conditions and when there was a source of interior air leakage into the assembly. The exterior-insulated wall assemblies had the lowest sheathing moisture content under normal operating conditions and the lowest sheathing moisture content levels when exposed to intentional air leakage from the interior. During simulated rain leakage, the standard 2 × 6 wall, the double-stud wall, and the wall with permeable MW exterior insulation had the highest drying rates and maintained the lowest sheathing moisture content, showing the importance of vapor movement to the exterior for rapid drying of sheathing moisture. The walls with low-permeance exterior insulation were significantly slower to dry and showed higher sheathing moisture levels as the moisture movement to the exterior was dramatically reduced. When an interior polyethylene vapor barrier was present, sheathing moisture content levels increased quickly to dangerous levels; however, when the interior polyethylene was removed, these walls were able to dry to the interior and could tolerate some level of rain leakage.

In both measured field testing and modeled hygrothermal simulations, using continuous exterior insulation was shown to be a more moisture-durable option than either standard 2 × 6 construction or thick high-R value wall assemblies, both under normal operating conditions and when subjected to an interior air leak of warm moist air at a failure in the interior air control layer. When sufficient exterior continuous insulation is installed, it is recommended to decrease the vapor resistance of the interior vapor control layer to allow the possibility of moisture redistribution to the interior if necessary.

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