Characterization of the Moisture Performance of Energy-Efficient and Conventional Light-Frame Wood Wall Systems

November 18, 2013

Prepared For:

Forest Products Laboratory
Under Joint Venture Agreement
12-JV-11111136-070

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November 2013

Report # 3329_11182013

Acknowledgements

This research was supported in part by funds provided by the Forest Products Laboratory, Forest Service, USDA.

The project team included Craig Drumheller, Lance Barta, and Vladimir Kochkin of the Home Innovation Research Labs. Sam Glass of the Forest Products Laboratory is acknowledged for his guidance and review throughout this effort. WUFI simulations referenced in this report were performed by Sam Glass.

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Introduction

The recent changes in the minimum energy codes (2012 IECC) resulted in increased wall insulation levels and reduced wall air leakage for all light-frame wood systems (relative to 2009 IECC). The long-term moisture performance of these new wall systems is not well understood with regard to vapor drive, condensation risk, and drying capability. With moisture performance increasingly becoming a design consideration in the selection of wall systems, home builders and designers need practical guidance for construction of walls that ensure durability of wood buildings. This type of design guidance is particularly needed as various industry groups are advocating specific wall design solutions based on incomplete information.

This project involves monitoring of the moisture performance of wall assemblies with specific design characteristics using the Home Innovation Research Labs outdoor Test Hut facility located in Climate Zone 4. Six (6) configurations of energy efficient walls are studied: four (4) with exterior rigid foam with the study variables including different levels of cavity insulation and types of water resistive barrier, and two (2) with 2x6 framing with different interior vapor retarders (Kraft-facing vs. gypsum with interior paint only). In addition, six conventional 2x4 wood-frame wall systems with varying cladding materials including stucco, manufactured stone, vinyl siding, brick, and fiber cement siding are under continued monitoring as a follow up research to the previous studies (Drumheller and Carll, 2010[1]; NAHB Research Center, 2010[2]; NAHB Research Center, 2011[3]). Specifically, the impact of the interior vapor retarder on the performance of these conventional systems in Climate Zone 4 is studied. Cedar siding has been added in this monitoring phase to expand the library of cladding systems under testing at Home Innovation.

Objectives

The overarching goal of this research is to identify robust design rules and construction practices for durable exterior wood-frame and wood-sheathed walls in a mixed-humid climate. The specific objectives of this phase of monitoring in Climate Zone 4 are to:

1. Characterize the response of the following energy efficient wall systems:
    a. 2x4 walls with exterior XPS foam sheathing installed over OSB structural panel sheathing;
    b. 2x6 walls sheathed with OSB structural panel sheathing; and,
    c. 2x6 walls with exterior XPS foam sheathing installed over OSB structural panel sheathing.

2. Evaluate the impact of interior relative humidity maintained in accordance with the ASHRAE 160 simplified method;

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[1] Drumheller S. C. and Carll C. G. 2010. *Effect of Cladding Systems on Moisture Performance of Wood-Framed Walls in a Mixed-Humid Climate*. Buildings XI Conference Proceedings. Building XI, December 5-9, Clearwater Beach, FL.

[2] NAHB Research Center. 2010. *Moisture Performance of Wood-Based Sheathing on Exterior Walls Clad with Absorptive Materials*. Prepared by the NAHB Research Center for the Forest Products Laboratory.

[3] NAHB Research Center. 2011. *Moisture Performance of Wall Systems with Increased Indoor Relative Humidity (Phase II Analysis)*. Prepared by the NAHB Research Center for the Forest Products Laboratory.

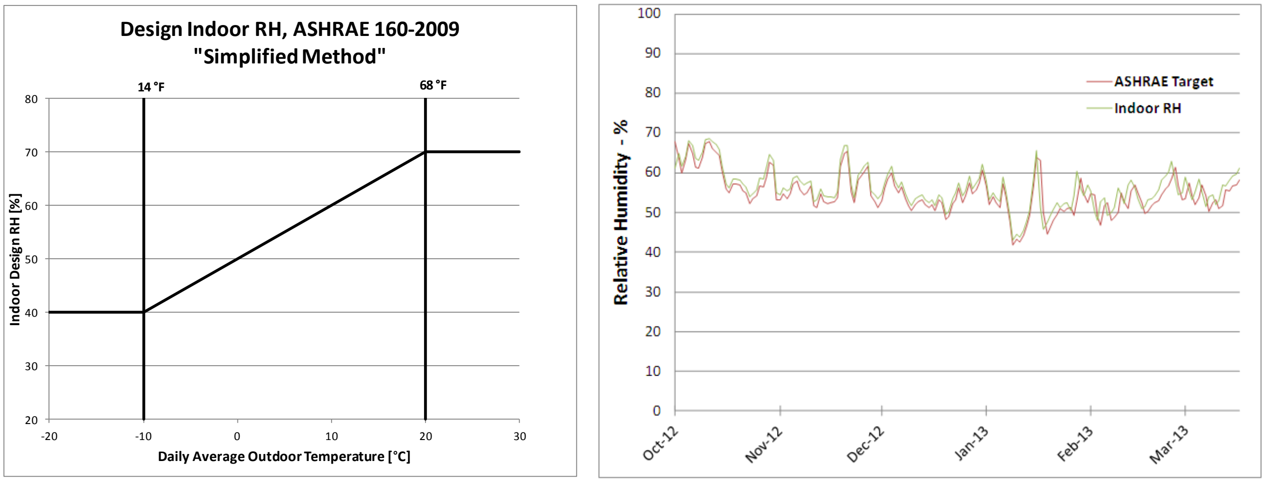
3. Through side by side monitoring, characterize the impact of the interior vapor retarder on the walls' performance under elevated levels of interior relative humidity;
4. As a follow-up to previous research, continue monitoring of conventional 2x4 wall systems with various cladding systems under elevated levels of interior relative humidity and expand the cladding library of tested system to include cedar siding; and
5. Simulate performance of several monitored wall assemblies using hygrothermal modeling software to evaluate the capability of the modeling software to predict the moisture performance of various wall systems under known climatic conditions and interior conditioning loads.

Technical Approach

This research involves detailed monitoring of wall assemblies installed in two test structures near suburban Washington, D.C. Each wall configuration is monitored in a north and south facing exposure. The test structures are temperature and humidity controlled. Within each wall section, temperature, relative humidity, and moisture content of wood framing and sheathing are monitored. Data was gathered over a 16-1/2-month period from the middle of November 2011 through end of March 2013.

The study, either directly or indirectly, addressed the primary drivers of moisture transfer in exterior walls: vapor movement entrained in air movement, vapor diffusion through the wall layer(s), rain water load, and water leakage beyond the cladding system and WRB.

During the heating season, the indoor relative humidity was controlled in accordance with the ASHRAE 160-2009 simplified method (Figure 1). The simplified method establishes the indoor design relative humidity between 40 and 70 percent as a function of the outdoor temperature. The average winter indoor relative humidity for the two winters was 55 percent. The indoor temperature during the heating season was maintained in the 70-72°F range. The outdoor temperature throughout the monitoring period is shown in Figure 2. During the cooling season, the indoor temperature was maintained in the 78-80°F range. Table 1 compares the measured monthly temperatures and precipitation with 30-year average values for this location.



a. Indoor Design RH vs. Outdoor Temperature b. Target vs. measured for 2012-2013 heating season

Figure 1. Indoor Design Relative Humidity, Simplified Method (ASHRAE 160-2009)

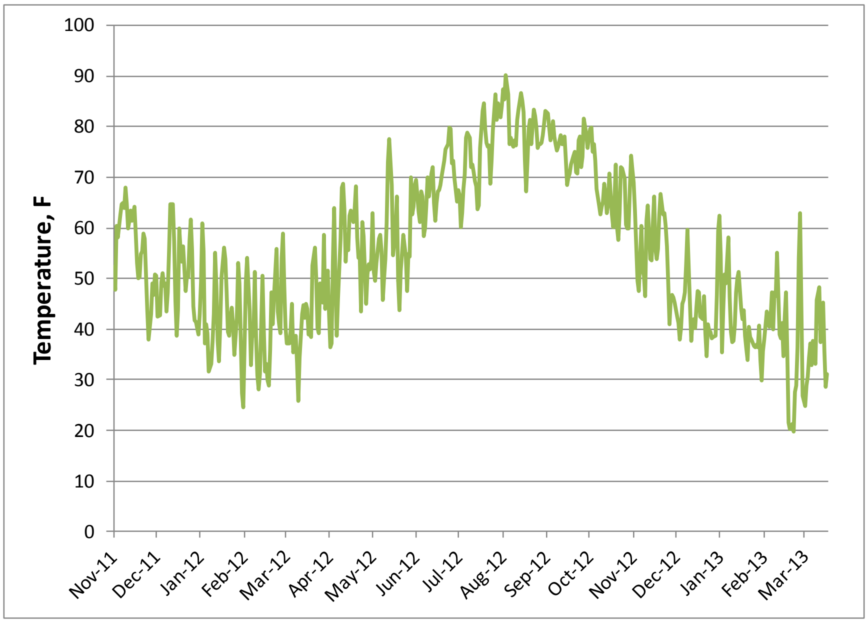


Figure 2. Outdoor T During the Monitoring Period (Daily Average)

Table 1. Monthly Average Temperatures and Precipitation

Year/Month	Monthly Average T, °F		Monthly Precipitation, inch	
	30 year average	Measured	30 year average	Measured
2011 Nov	47.0	51.2	3.5	1.8
2011 Dec	37.5	43.7	3.1	5.0
2012 Jan	33.5	39.8	2.9	2.3
2012 Feb	36.0	42.3	2.8	1.9
2012 Mar	44.5	54.6	3.8	1.8
2012 Apr	54.5	56.1	3.6	1.9
2012 May	63.5	68.6	4.3	2.9
2012 Jun	72.5	72.9	4.1	4.6
2012 Jul	77.5	80.3	4.0	2.1
2012 Aug	75.0	76.2	3.7	1.3
2012 Sep	68.0	68.3	4.0	3.6
2012 Oct	56.0	58.1	3.6	16.7[A]
2012 Nov	47.0	43.3	3.5	0.5
2012 Dec	37.5	43.6	3.1	5.0
2013 Jan	33.5	38.6	2.9	3.4
2013 Feb	36.0	36.2	2.8	4.0
2013 Mar	44.5	41.7	3.8	2.8

[A]. Rainfall in the wake of Hurricane Sandy. Analysis of moisture content results did not reveal any definitive uptick in OSB moisture content following the high rainfall.

Test Hut Construction

Since 2007, Home Innovation Research Labs has been monitoring moisture performance of various wood-framed wall assemblies with a range of siding materials using two outdoor test structures located on the Home Innovation campus in Upper Marlboro, Maryland (Figure 3). Each structure has a nominal footprint of 8' x 48' and each long side features five 8' wide by 9' high bays for installation of wall specimens. The structures are oriented with the long sides facing north and south. Wall assemblies are tested in pairs with each wall configuration in north and south exposure. Wall sections are also monitored for water accumulation in the course of exposure to outside weather conditions and drying capability during controlled wetting events.

Figure 3. Test Structures Showing South-Facing Test Walls

Back building right-to-left: 2x4 w. manufactured stone cladding (#1), [privately funded system], 2x4 w. stucco (#2), 2x4 w. cedar siding (#3), 2x4 w. vinyl siding (#4)

Front building right-to-left: 2x4 w. brick veneer (#5), 2x4 w. fiber cement siding (#6), 2x4 w. 1" XPS sheathing and vinyl siding (#7), 2x6 w. vinyl siding (#8), 2x6 w. 1" XPS sheathing and vinyl siding (#9)

The underside of floor joists is approximately 2-½ feet above grade and insulated with R-19 batts. Attic is insulated with R-38 fiberglass batt. The roof is pitched with minimal overhangs (gutters only) leading to maximum exposure of test bays to rain and sun. One door is installed on the gable end wall of each building with a window on the opposite end wall. Portable air conditioners are used to control temperature in the summer (78-80°F) and resistance heat is used to control indoor temperature in the winter (70-72°F). Humidifiers were used to maintain the indoor relative humidity during the heating season.

Wall Configurations

Table 2 summarizes the test matrix. A total of 9 primary wall configurations were monitored. Each primary configuration included a subcategory designated in the matrix by (a) or (b) to study the specific effect of one of the assembly features: interior vapor retarder, house wrap type, or cladding type. Table 2 includes description of all primary wall layers including cladding, water resistive barrier, exterior insulation, sheathing, framing, cavity insulation, vapor retarder, and interior sheathing. Figure 4 provides cross sections for all wall assemblies.

Table 2. Test Matrix - Wall Configurations

Conf.#		Cladding	Water Resistive Barrier	Exterior Insulation	Framing and Ext. Sheathing	Cavity Insulation/ Kraft Facing	Interior Sheathing and Vapor Retarder
1	a	Manufactured Stone	2 layers felt paper	none	2x4 w/ OSB	**R-13 Kraft faced Batts**	The interior surface of all wall specimens was sheathed with ½-inch gypsum board finished with a primer plus two rolled-on coats of latex paint.
	b					**R-13 Unfaced Batts**	
2	a	Stucco	2 layers felt paper	none	2x4 w/ OSB	**R-13 Kraft faced Batts**	
	b					**R-13 Unfaced Batts**	
3	a	**Cedar Siding Solid Planks** over ¾" furring @ 16" oc	House wrap w drainage plane	none	2x4 w/ OSB	R-13 Kraft Faced Batts	
	b	**Cedar Siding Finger-Jointed Planks** over ¾" furring @ 16" oc					
4	a	Vinyl Siding w/2x4 framing	House wrap	none	2x4 w/ OSB	**R-13 Batts Kraft faced Batts**	
	b					**R-13 Batts Unfaced Batts**	
5	a	Brick	House wrap & 1" Air Gap	none	2x4 w/ OSB	**R-13 Batts Kraft faced Batts**	
	b					**R-13 Batts Unfaced Batts**	
6	a	Fiber Cement Siding	House wrap	none	2x4 w/ OSB	**R-13 Batts Kraft faced Batts**	
	b					**R-13 Batts Unfaced Batts**	
7	a	Vinyl Siding	**House wrap w drain. plane**	1" (R-5) XPS Rigid Foam	2x6 w/ OSB	R-21 Kraft Faced Batts	
	b		**Taped foam joints**				
8	a	Vinyl Siding	House Wrap	none	2x6 w/ OSB	**R-21 Batts Kraft faced Batts**	
	b					**R-21 Batts Unfaced Batts**	
9	a	Vinyl Siding	**House wrap w drain. plane**	1" (R-5) XPS Rigid Foam	2x4 w/ OSB	R-13 Kraft Faced Batts	
	b		**Taped foam joints**				

Note: Bold **type indicates a variation in the wall panel construction between (a) and (b) subcategories.**

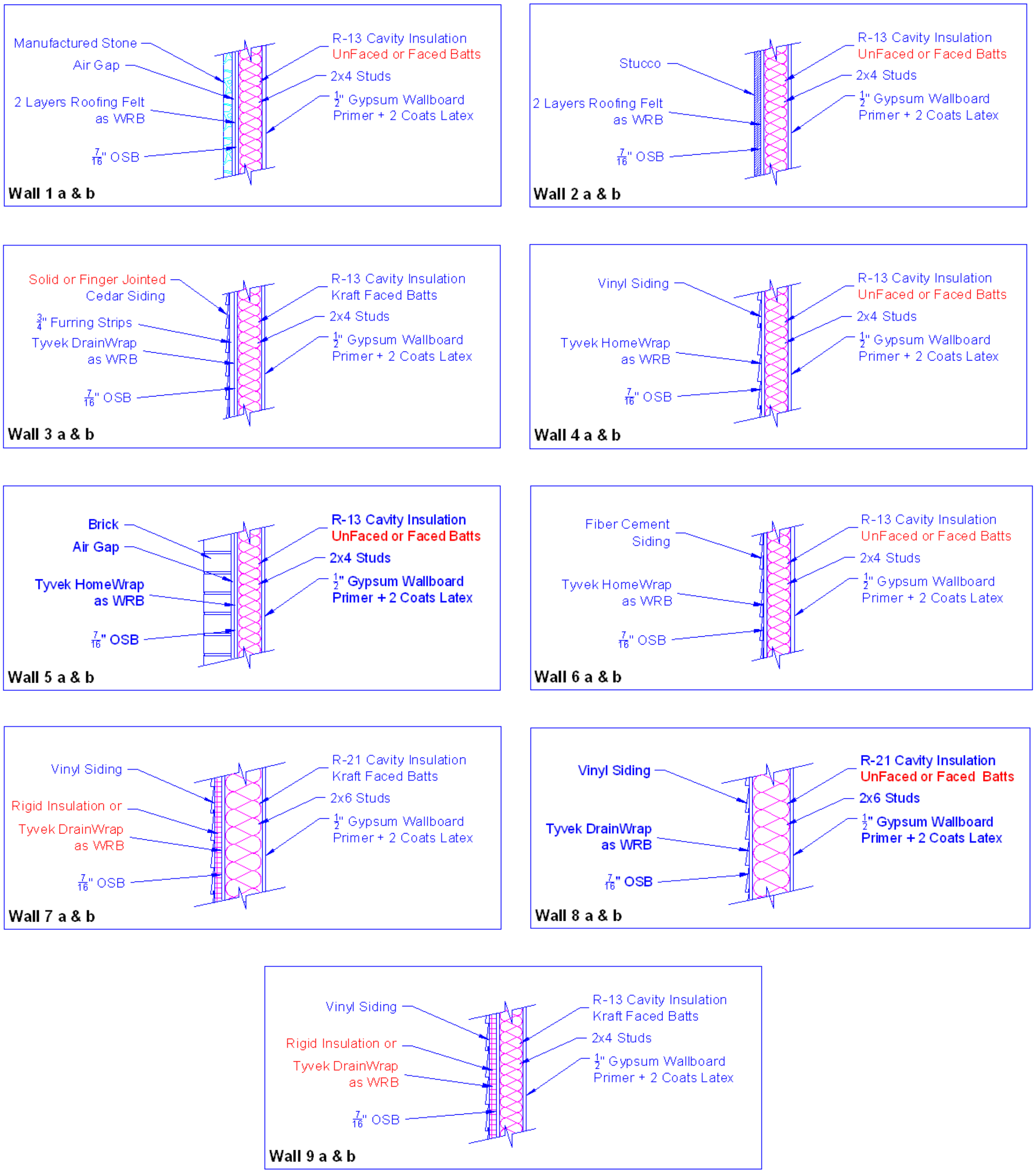


Figure 4. Test Assemblies

Walls were framed using 2"x4" or 2"x6" wood studs spaced 16 inches on center with single bottom and double top plates. Below are specific details for installation of claddings.

Wall Configuration 1: Manufactured Stone Cladding

Manufactured stone exterior cladding is cast concrete composed of Portland cement, aggregate, and pigments. The manufactured stone cladding was installed with two layers of No. 15 felt paper as the WRB. Type S mortar mix was used for the scratch coat and grout. The stone was darker in color than the other four wall claddings and the thickness of the stone varied between 1 and 2 5/8 inches. This cladding system had an installed mass of about 15 lbs/ft^2 and an estimated specific heat of 0.2 Btu/lb°F.

Wall Configuration 2: Stucco Cladding

The stucco cladding was constructed with a Portland cement-based material that was designed to be both a scratch and finish coat material. Final stucco thickness varied between ½-inch and ⅝-inch. The Portland cement-based stucco was placed over ASTM D226 compliant No. 15 felt that was stapled to the sheathing with ⅜-inch length and 1-inch crown staples and wire lath which was stapled using with ½ inch crown and ¾-inch length staples at 16 inches on center.

The stucco-clad wall assembly was not constructed according to Section R703.6.3 of the 2006 IRC, which requires two layers of Grade D paper. However, it did have two layers of ASTM D-226 Type 1 felt (e.g., No. 15 felt paper) under the exterior plaster. The difference between the two WRBs is primarily in the permeability of the materials. Grade D paper has a permeance in excess of 10, whereas No. 15 felt usually has a permeance of around 5. The felt used in the test, however, had a wet cup permeance of over 13. Some jurisdictions have amended Section R703.6.3 to include No.15 felt as being acceptable under Portland cement exterior claddings.[4]

With this construction, the inner layer WRB functions as the drainage plane while the outer WRB bonds to the plaster and thus is unable to function effectively as a drainage plane.

Wall Configuration 3: Cedar Siding

The cedar siding was 6-inch factory-primed planks attached to 3/4-inch-thick by 1-1/2-inch-wide vertical furring strips over Tyvek Drainwrap®. It is noted that the wall specimens were inset into the Test Hut such that there was no ventilation opening at the top or bottom of the cladding interface. The cedar siding was finished with two coats of 100% acrylic flat paint. All site-cut edges were hand-primed prior to installation with Kilz 2 primer. Siding planks were hand-nailed using stainless steel ring-shank nails (the edge nails were installed into pre-drilled holes). The 6-inch planks were overlapped by 1-1/4" inches. Every second row of siding included a butt joint that was not caulked. Flashing was only used below the starter strip, and caulking was only placed on the vertical trim. This exterior cladding was subdivided into two halves: finger jointed planks and solid planks.

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[4] The state of Minnesota has amended section R703.6.3 of the 2006 International Residential Code to also accept 2 layers of #15 felt under plaster wall coverings.

Wall Configurations 4 and 8: Vinyl Siding

Vinyl siding was chosen for comparison because it is the most frequently installed cladding on new houses.[5] Furthermore, due to its non-absorptive properties, its performance was expected to contrast the absorptive cladding systems investigated on the other wall panels. The siding was installed over a single layer of spun-bonded polyolefin (Tyvek HomeWrap®) water resistant barrier, representative of common vinyl siding installation practices in the United States.

Wall Configuration 5: Brick Veneer Cladding

The brick veneer wall was constructed with a one inch air space behind the brick. A 1/2 inch slot at the top of the wall allowed the air space to vent into the attic. The nominal 4 inch bed depth brick was laid in Type N masonry cement mortar. Flashing was installed under the first course of brick and open head joint weep holes were installed at 24 inches on center immediately above the flashing.

Wall Configuration 6: Fiber Cement Siding

The fiber cement cladding included 6-inch factory-primed planks installed over Tyvek Homewrap® with face nails into the framing. Only the vertical trim was caulked. The siding was finished with two coats of Behr premium primer and 100% acrylic latex water based semi-gloss exterior light yellow paint.

Wall Configurations 7 and 9: Vinyl Siding Over 1" XPS (R-5) Exterior Foam

All walls with exterior rigid foam used vinyl siding nailed through the exterior rigid foam into the framing members. For Configuration 7a and 9a, Tyvek DrainWrap® was installed between the OSB sheathing and exterior foam. For configuration 7b and 9b, house wrap was not installed and the exterior foam joints were taped to provide the WRB.

Water Intrusion Testing

All wall sections were subjected to four separate simulated water intrusion events, once during each season. The purpose of the water intrusion events was to assess the drying capability of the wall system due to a potentially leaky window. The wall framing at the location of the injection included a window sill plate to simulate a typical window framing layout.

Water intrusion events were simulated by injecting water behind the cladding system through two ¼-inch plastic tubes installed in the wall specimens during construction. The two tubes terminated on opposite sides of the WRB: one tube terminated between the WRB and the cladding (or between the WRBs when two WRB layers were present) and the other tube terminated between the WRB and the sheathing. Thirty milliliters of water was injected into each tube for five consecutive days. Additional moisture sensors were installed in the vicinity of the injection location to detect accumulation water and the drying rate following the water intrusion events.

No significant increases in moisture content were observed as a result of the injections. The peak fluctuations in OSB moisture content were limited to less than 2 percent and followed by a rapid return to the base moisture levels. Therefore, no additional discussion on the injections is included in this report.

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[5] www.census.gov/const/C25Ann/sftotalexwallmat.pdf

Instrumentation and Monitoring

Wall Sensors

To monitor the performance of test walls, 42-47 sensors were installed in each wall section (Figure 5). Each sensor measured temperature, relative humidity, and wood moisture content (OSB or framing) at programmed time intervals. A sensor (Figure 6) includes two 2-inch stainless steel screws that penetrate the wood member by ⅜-inch to obtain a conductance reading related to substrate moisture content. The sensors are capable of measuring moisture content between 7 percent and the fiber saturation point, temperature between negative 40°F and 185°F, and relative humidity from 0 to 100 percent. Data is transmitted wirelessly from the sensors every 30 minutes to a local gateway which transmits the data over the internet to a server.

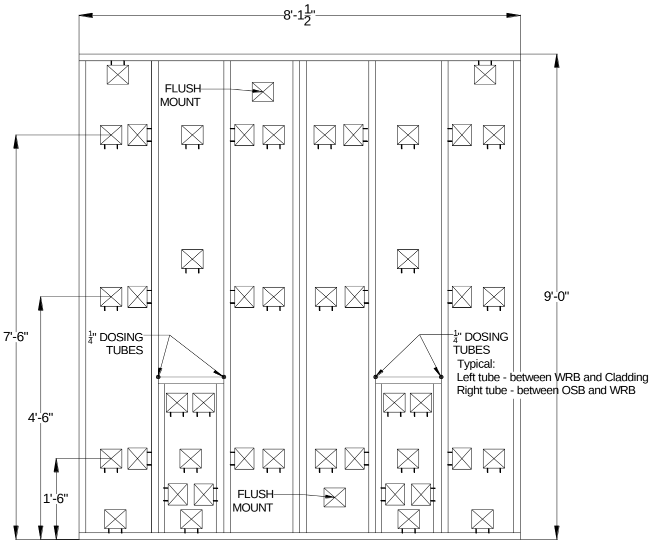

Figure 5. Wireless Sensor Layout (typ.)

Figure 6. Wireless Temperature, Humidity & Wood Moisture Sensor

Indoor Temperature and Humidity Measurements

Each Test Hut included six type-T thermocouples and two temperature and humidity probes measuring the temperature and relative humidity. The temperature and humidity probes contained capacitance-type humidity sensors, accurate within 2 percent from 0 to 98 percent relative humidity, and RTD type temperature sensors, accurate within 1°F over the range of 14°F to 140°F.

Weather Data

A weather station was mounted on the test hut roof to measure ambient weather conditions. The station included an anemometer to measure wind speed and direction, a temperature and humidity sensor, a tipping bucket rain gauge, and a horizontally installed spectral pyranometer to measure solar radiation.

A custom designed, wind-driven rain gauge and a vertically positioned spectral pyranometer were installed on the north and south walls of the test hut to better understand the conditions at the wall surface. The wind-driven rain gauge consisted of a standard tipping bucket rain gauge with a custom built attachment that only allows rain moving horizontally to enter.

Material Properties

Laboratory tests were conducted to measure water vapor permeance and density of the materials used in construction of the test wall sections. The measured properties were also used as input to the hygrothermal models in WUFI to improve the accuracy of the computer simulations for comparison with the measured walls' performance.

Table 3 summarizes test results. All materials were taken from the same batch of the product that was used in wall specimen construction. Test methods for determining permeability included the desiccant method (dry cup test) and the water method (wet cup test) (ASTM E 96/E 96M - 10 – Standard Test Method for Water Vapor Transmission of Materials). For both tests, the atmospheric chamber was set at 23°C and 50 percent relative humidity. The 7"x7" test specimens rested on a custom metal dish and the perimeter between sample and dish was sealed with bee's wax to prevent moisture from getting into or out of the sample through the edge. The ends of each specimen were sealed with foil tape, prior to being sealed to the dish, in order to control the area of possible moisture transmission. Three specimens of each material were tested. Density of each material was measured gravimetrically (based on Test Method A ASTM D2395-07 Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials).

Table 3. Material Properties

Material	Thickness (in)	Density (lb/ft^3)	Permeance (Perms)	
			Dry Cup	Wet Cup
Drywall	0.489	31.1	49	45
Drywall with primer and 2 coats of paint	0.493	37.4	35	35
OSB	0.435	42.4	2.0	1.4
1" XPS Foam	0.979	1.7	1.1	1.0
Spun bonded polyolefin	0.004	33.9	52	44
Spun bonded polyolefin crinkle	0.004	42.9	53	45
Asphalt-coated Kraft paper	0.007	36.2	0.6	1.0
Cedar	0.182	21.0	0.6	3.2

A notable discrepancy with published data was observed for a primer plus two layers of latex paint. The 2013 ASHRAE Handbook of Fundamentals (pg. 26.17) lists an expected permeance at or below 11.3 perms for two or three layers of paint – a significantly lower value compared to 35 perms measured in this testing program.

WUFI Simulations

WUFI simulations were performed to evaluate WUFI's ability to predict moisture response for the range of walls tested in this study. Appendix A documents the methodology used to perform WUFI simulations and provides detailed simulation results. The results are also used for comparative analyses in the body of this report.

The simulation software program selected for this study was WUFI® Pro version 5.2,[6] which calculates one-dimensional transient heat and moisture transport in multilayer building assemblies. WUFI was developed based on recent building research for vapor diffusion and liquid transport, and its results have been validated in laboratory and outdoor testing.

Results and Data Analysis

Performance of Walls with Kraft-Faced Batts vs. Unfaced Batts

Figure 7 compares OSB moisture content for the wall configurations with and without Class II vapor retarder (i.e., batts with and without Kraft-facing) for the North and South exposure. This experiment was conducted to evaluate the 2009 IRC provisions that allow wall construction without an interior vapor retarder in Climate Zone 4. The evaluation was performed in combination with the ASHRAE 160 interior moisture load. The graphs show a significant impact of Kraft facing on the moisture performance, with the OSB moisture content near or at the fiber saturation point for all six wall systems without Kraft facing in the North exposure during the heating season. (Note that sensors do not read above the fiber saturation point and any difference in moisture content levels above the fiber saturation point that could be caused by presence of liquid water does not get detected.)

For the South exposure, only the wall with stucco cladding (#2) showed MC levels similar to the North exposure and the wall with vinyl siding (#4) peaked at a comparable level for a short time in the second winter. This performance is consistent with the winter drying to the outside that was slowed down by the stucco cladding for Configuration #2. The remaining assemblies in the South Exposure stayed close to or below 20 percent moisture content. All wall assemblies, with and without interior vapor retarder, dried out rapidly over the spring months to MC levels below 15 percent.

The observed behavior for walls without Kraft facing should be evaluated in light of the elevated levels of interior relative humidity that are set to represent a conservative upper bound design value and in light of the drywall permeance of 35 perm (significantly higher than the code-implied 10 perm for painted drywall.) Also there were no air-sealing measures implemented at the bottom of the drywall with potential for a greater air leakage in the wall cavities where Kraft facing was not installed.

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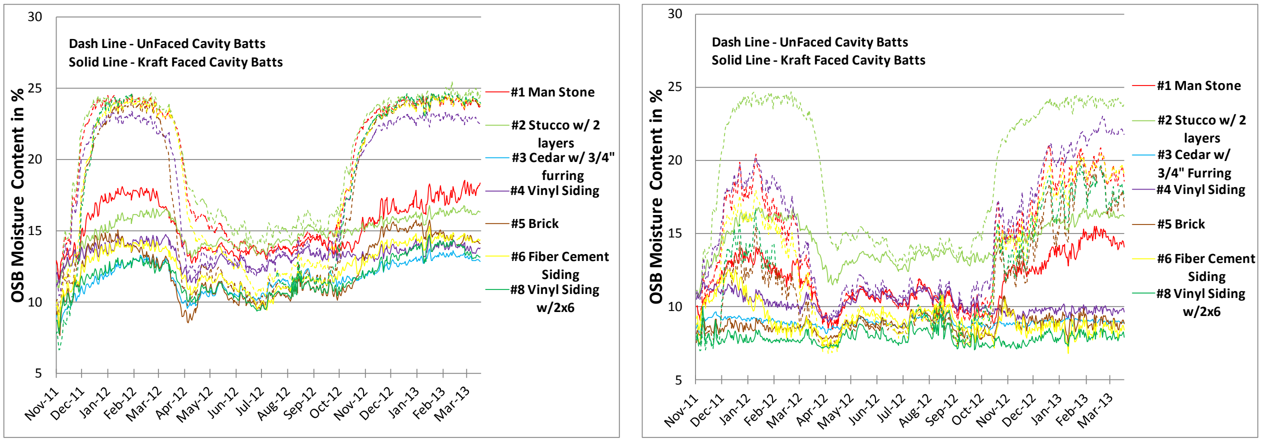
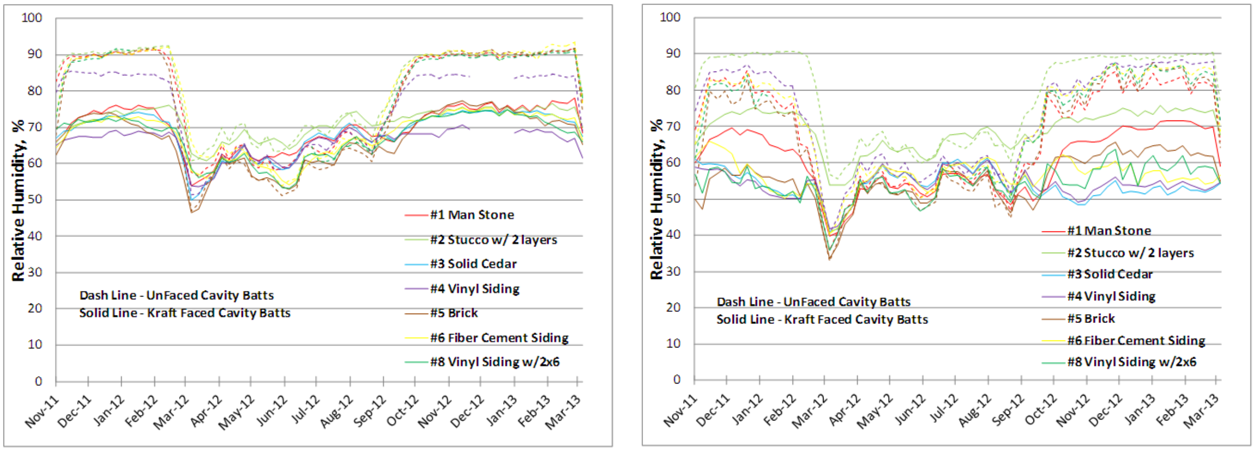
[6] IBP. 2013. WUFI® Pro version 5.2. Holzkirchen, Germany: Fraunhofer Institute for Building Physics. www.wufi.de/index_e.html. (23 October 2013).



a. North Exposure b. South Exposure

Figure 7. OSB Moisture Content: Kraft-Faced Batt vs. Unfaced Batts (North Exposure)

To show the underlying drivers for the OSB moisture content, Figure 8 compares cavity relative humidity for the wall sections with and without Class II vapor retarder (i.e., batts with and without Kraft-facing) for the North and South exposure. As consistent with the moisture content trends, walls without Kraft facing exhibit significantly higher cavity relative humidity. (It should be noted that because the sensors included stand-off legs, the temperature and relative humidity measurements were taken approximately 1-1/4 inch away from the interior surface of the OSB sheathing. The fiberglass batt insulation was installed over the sensor such that there was an air pocket between the sensor and the OSB sheathing.)



a. North Exposure b. South Exposure

Figure 8. Cavity Relative Humidity: Kraft-Faced Batt vs. Unfaced Batts (North Exposure)

Failure of some of the moisture sensors during the 2011-2012 winter in Configuration #8b prompted inspection of the interior cavity of that wall section. The drywall and insulation were removed from the #8b wall in the summer of 2012. Inspection of the OSB and the framing members revealed water stains, mold, and rusted nails (Figure 9). The observed damage suggest water condensation, high levels of relative humidity for an extended period of time, and high levels of moisture content. Because the sensors do not detect moisture levels above the fiber saturation point, the actual moisture content in this wall configuration is unknown. The water damage and the fact that the sensors' batteries shorted out suggest presence of liquid water and high moisture content levels. Sensors did not fail in any other walls.

a. Mold b. Mold

c. Staining d. Corrosion

e. Mold

Figure 9. Moisture Damage: Mold, Corrosion, Staining

As another point of reference over the same time period, Home Innovation has been monitoring 2x6 walls without Kraft facing in five homes in Climate Zone 4 with four of the homes less than 20 miles from the test hut site. The drywall was well air sealed at the top and bottom plates. The average winter interior RH varied between 33 and 47 percent (compared to 55 percent average RH in the test huts). The walls' OSB moisture content over the heating seasoned averaged below 15 percent with one of the homes peaking at 22 percent for a shorter period of time. Inspection of wall cavities in one of the homes that included removal of drywall and insulation to access the sheathing and framing showed no sign of damage or high moisture levels. It is noteworthy that the house with the highest interior RH (47 percent) was the one where the 22 percent peak was observed.

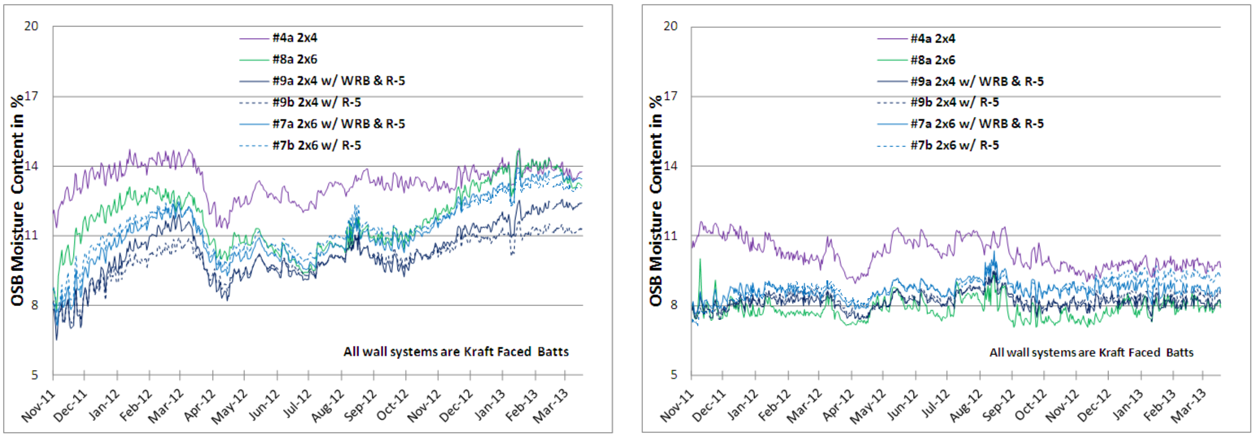
To evaluate the impact of the high moisture content levels on the OSB mechanical properties, a series of comparative simply-supported small bending tests was conducted on specimens cut out from the OSB panels used in 2x6 walls with and without Kraft facing (Configurations 8a and 8b - 10 specimens each). Panels only from the North orientation were tested. Specimens were 4.5 inches wide by 14 inches long with a test span of 10.5 inches. The specimens from the wall without Kraft facing showed an average 9 percent thickness increase compared to the specimens from the wall with Kraft facing. A 19 percent average decrease in the bending strength was observed for the specimens from the wall without Kraft facing relative to the wall with Kraft facing. Based on the T-test statistics, the observed decrease was statistically significant.

As a conclusion, the combination of three variables – (1) high interior RH, (2) high permeance of the interior vapor retarder, and (3) air leakage path into the cavity – have a potential for causing high MC of the exterior OSB sheathing in Climate Zone 4. Further study is needed to uncouple the impact of air leakage from vapor diffusion and to complete the assessment of the appropriateness of the ASHRAE 160 simplified method for evaluating performance of enclosures. The results of this study suggest that the ASHRAE 160 Simplified Method leads to wall moisture levels higher than those observed in the field. The effectiveness of primer and paint to serve as Class III vapor retarder also needs reevaluation.

Performance of Walls with Exterior Rigid Foam

Figure 10 shows the OSB moisture content for walls with exterior foam and without exterior foam (baseline). All walls in this comparison used Kraft facing as interior vapor retarder. To enable direct comparison, the difference between Configuration pairs #4a & #9 (2x4 studs) and #8a & #7 (2x6 studs) is the use of one-inch exterior rigid XPS foam. For the North exposure, the results indicate that the 2x4 wall with foam (#9) consistently has the lowest moisture content. However, all six walls exhibit OSB moisture content below 15% percent and the difference between the walls is typically within a 3 percent range. While Configuration #4 starts at a higher moisture content level and consistently remains at 2-3 percent higher than the other walls for nearly a year, during the second heating season the gap between the lines becomes smaller and the performance of 2x4 and 2x6 walls without foam becomes nearly identical. All six wall configurations showed a drying trend in the spring months. Interestingly, all walls showed a very similar drying rate as evidenced by the slopes of the moisture content lines. This behavior can be explained by sharp drop of relative humidity in the cavity as a result of increasing cavity temperatures in the spring. It does not mean that all that water left the wall assembly at the same rapid rate. Rather, the assembly's capacity for water vapor storage increased with elevated temperature and any drying occurred over time either to the inside or outside.

For the South exposure, with exception of Configuration 4a (2x4 wall) that had a higher initial moisture content, all walls oscillate within a 1-2 percent range of each other and below 10 percent. Configuration 4a oscillates 3 percent higher on average compared to other walls during the first 12 months of the study. During the second heating season, Configuration 4a oscillated closer to the range observed for other walls.



a. North Exposure

b. South Exposure

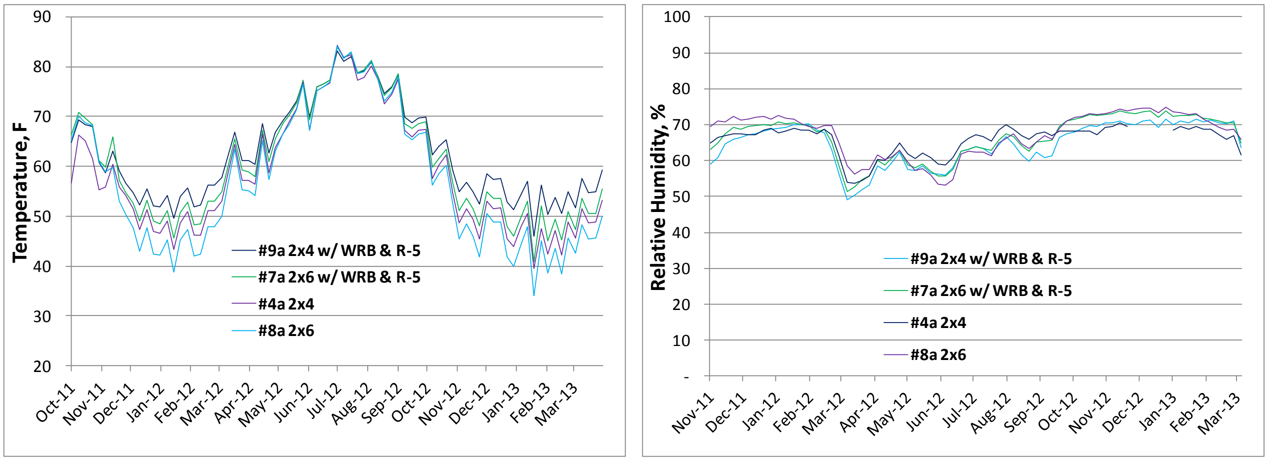
Figure 10. OSB MC for Walls with and without Exterior Rigid Foam (North Exposure)

A comparison of WRB function using housewrap with a drainage plane vs. taping foam sheathing joints (#7a vs. #7b and #9a vs. #9b) shows a moisture content difference of less than 2 percent in the winter months and less than 1 percent in the summer months. The slight increase in divergence over the winter months may be associated with a more effective insulative performance of foam sheathing in direct contact with the OSB. Overall, the differences are not signifcant. It should be noted that this study does not address longterm performance of materials and effects of installation practices.

Figure 11 shows the impact of exterior foam on cavity temperature and cavity relative humidity for north exposure walls (weekly averages are shown to reduce noise due to daily flactuations). There is a distinct separation of cavity temperature lines between all four walls in the winter months in a logical sequence from coldest to warmest:

1. 2x6 studs without exterior foam (#8a)
2. 2x4 studs without exterior foam (#4a)
3. 2x6 studs with 1-inch exterior foam (#7a)
4. 2x4 studs with 1-inch exterior foam (#9a)

The difference in cavity temperatures is the highest during the month of January for both heathing seasons with the maximum difference of 10°F. In the observed temperature range (35-50°F) and average relative humidity range (less than 75%), the difference of 10°F can lead to a change of moisture content of 4 percent or less, consistent with the reported measurements. The difference in observed levels of cavity relative humidity does not follow a consistent trend. These results can partially be expalined by the large expected relative humidity gradient across the wall cavity and the large daily fluctuations of temperatures leading to fluctuaions in relative humidity. Moisture content is a more stable moisture parameter for monitoring and drawing conclusions. The average relative humidity measurements serve a more informative function in terms of the overall range observed – showing an approximate 20 percent increase during the winter months relative to the summer months.



a. Cavity Temperature

b. Cavity Relative Humidity

Figure 11. Cavity Temperature and Relative Humidity in Walls with and without Exterior Foam (North Exposure)

In summary, 1-inch XPS exterior rigid sheathing (R5) has a marginal impact on the moisture content of the OSB sheathing in walls with vinyl siding and interior Kraft vapor retarder in Climate Zone 4. The lowest outside temperature recorded during the two winter seasons was 20°F (Figure 2). All walls – with and without exterior foam – showed OSB drying in the spring at a similar rate regardless of use of foam on the exterior.

Multi-Year Performance of Walls with Kraft-Faced Batts

To evaluate the impact of winter interior relative humidity, Figure 12 shows average winter OSB moisture content for walls that were part of the monitoring program for multiple heating seasons (North orientation only). A range of interior relative humility has been studied over six heating seasons (Table 4). Five wall configurations spanned all three target interior relative humidity levels with each of the walls using cavity batt insulation with Kraft paper facing and 2x4 framing. Only cladding/drainage system varied between the five configurations: #1a (manufactured stone), #2a (stucco), #4a (vinyl siding), #5a (brick veneer), and #6a (fiber cement siding).

Although all walls exhibited an increase in OSB moisture content during the 2009-2011 heating seasons relative to the 2007-2009 heating seasons, there is no consistent trend for the 2011-2013 heating seasons. Configurations #1a (manufactured stone), #5a (brick veneer), and #6a (fiber cement siding) exhibited either a slight increase in OSB moisture content in 2011-2013 or remained essentially at the 2009-2011 season levels. Configurations #2a (stucco) and #4a (vinyl siding) exhibited a drop in OSB moisture content during the 2011-2013 seasons despite an increase in interior relative humidity. One of the possible contributing reasons for this OSB performance is slightly milder winters in 2011-2013 (Table 5). A more important observation is that walls with Kraft paper interior vapor retarder are much less sensitive to interior relative humidity conditions than walls without it. Other factors such as annual weather fluctuations and a wall's ability to dry to the outside become more important variables than the level of interior relative humidity for walls with Kraft facing. On the other hand, interior relative humidity is a critical factor for design and performance of walls with an interior vapor retarder other than Class I or II.

Table 4. Seasonal Interior Relative Humidity

Heating Season	Target RH, %	Actual Season Average RH, % (Dec 15 – Mar 15)
2007-2008	30%	30
2008-2009		26
2009-2010	40%	41
2010-2011		42
2011-2012	ASHRAE Simplified Method	56
2012-2013		54

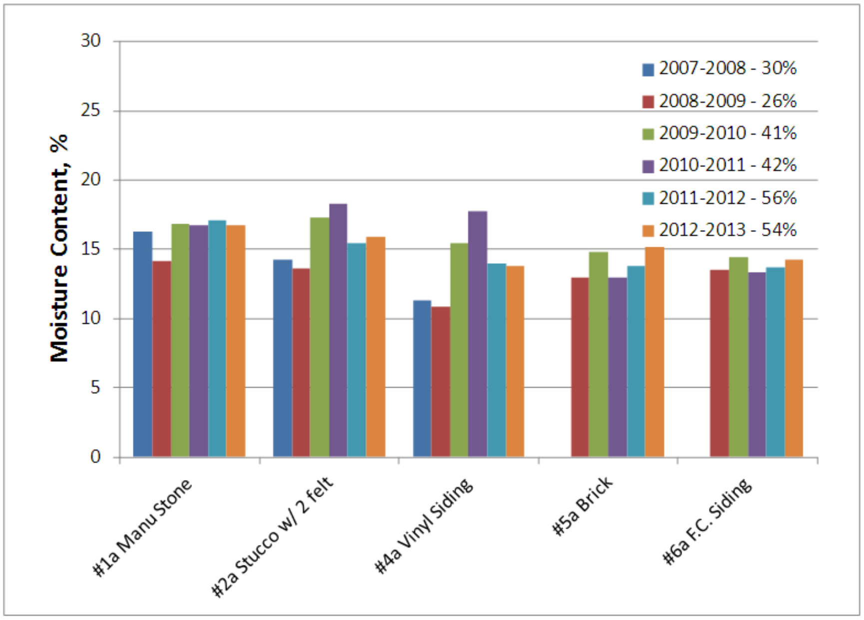


Figure 12. Multi-Year Performance of Walls with Kraft-Faced Batts (North Orientation)

Table 5. Seasonal Outdoor Winter Temperatures

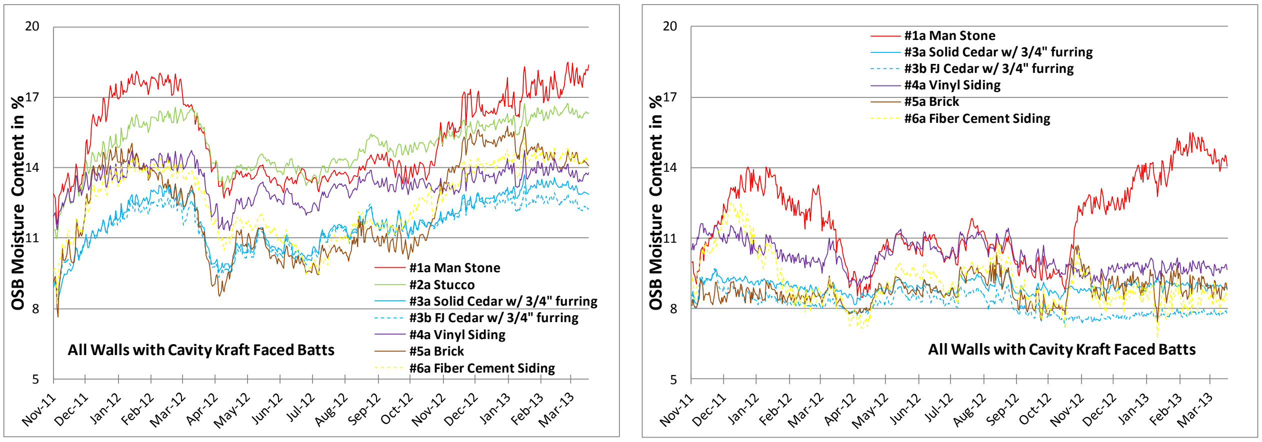
Heating Season	Season Average T°F (Dec 15 – Mar 15)
2008	39.7[A]
2008 - 2009	37.5
2009 - 2010	35.3
2010 - 2011	36.3
2011-2012	43.5
2012-2013	38.8

[A] Monitoring period from Jan 1 to Mar 15

Performance of Walls with Cedar Siding

For the 2011-2013 seasons, cedar siding was added to expand the library of cladding systems monitored at the Home Innovation test huts since 2007. Figure 13 shows OSB moisture content for Configurations 3a and 3b (cedar siding over ¾-inch furring) along with five other walls for direct moisture performance comparison. All walls used 2x4 construction and fiberglass batt cavity insulation with Kraft facing. Only cladding/drainage system varied between the configurations: #1a (manufactured stone), #2a (stucco), #4a (vinyl siding), #5a (brick veneer), and #6a (fiber cement siding).

In the north exposure, the wall with cedar siding consistently had one of the lowest moisture contents trending in the 10-13 percent range and at the bottom of the overall spread between the different wall configurations throughout the 2011-2013 monitoring period. In the south exposure, the wall with cedar siding consistently trended in the 8-9 percent range over the same period clustering with other lap siding systems (vinyl and fiber cement) and brick veneer. There is no detectable difference in OSB moisture content between walls with solid and finger-jointed cedar siding.



a. North Exposure

b. South Exposure

Figure 13. OSB Moisture Content – Comparison of Cedar Siding with Other Claddings

In addition to sensors in the wall cavity, the cedar siding planks were also instrumented with moisture content sensors (Figure 14). Moisture content of cedar siding ranged between 9 and 14 percent depending on season, orientation, and plank type (solid vs. finger jointed). Finger-jointed siding in the north walls consistently had the higher moisture content likely due to the reduced drying potential as a result of reduced moisture flow in the parallel-to-grain direction. The plank type did not make a distinguishable difference in the south wall.

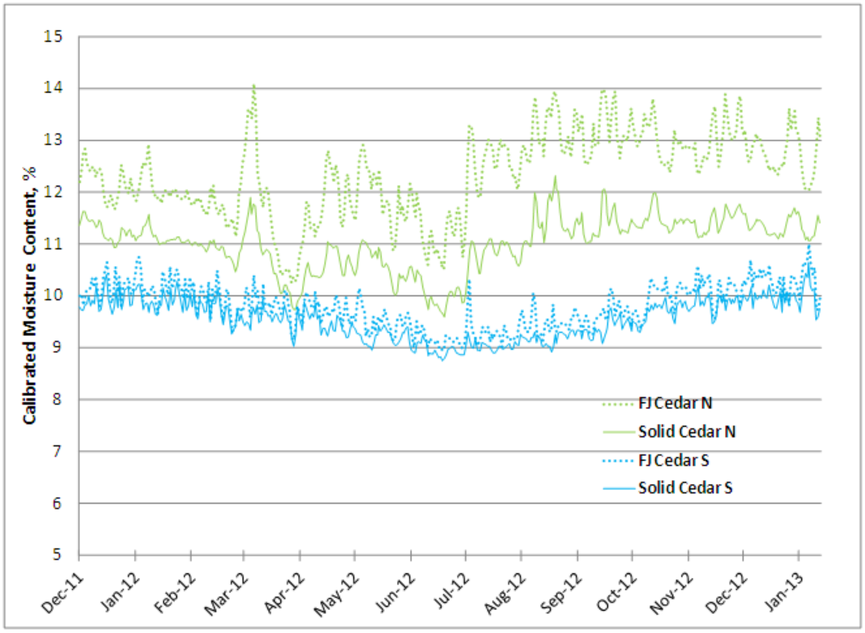


Figure 14. Moisture Content of Cedar Siding Planks

In summary, the wall with cedar siding installed over ¾-inch furring strips showed good moisture performance over the 16-month monitoring period with the OSB moisture content at or below 13 percent and the cedar moisture content at or below 14 percent. Inspection of the cedar siding material in the summer of 2013 did not reveal any damage or deterioration of the wood material.

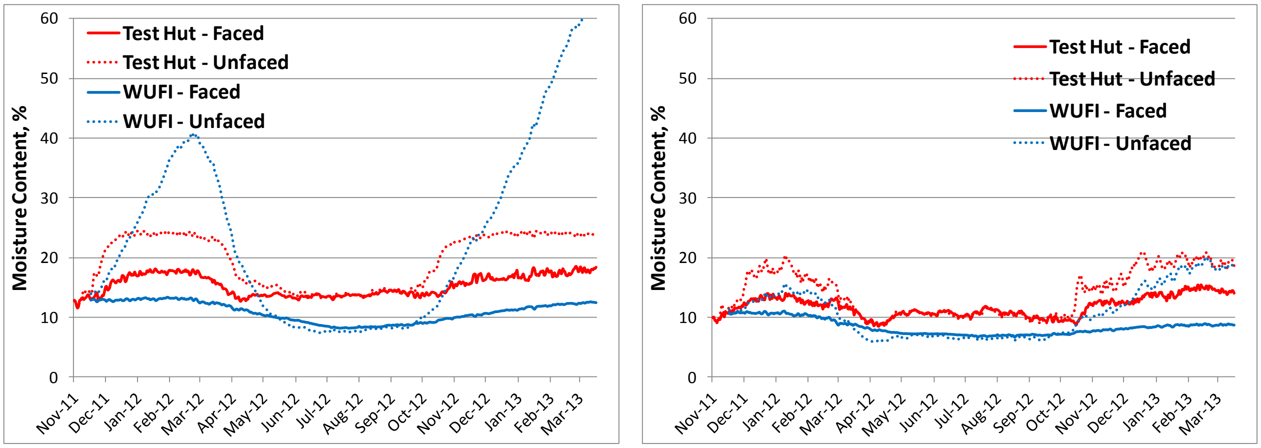
WUFI Modeling of the Monitored Walls

To evaluate the ability of WUFI software to accurately predict the moisture performance of various wall systems, the configurations monitored in the test huts during the 2011-2013 period were modeled using WUFI. Appendix A summarizes the details of the analysis. Figure 15 through Figure 23 compare the monitoring results from the test huts with the results of the WUFI simulation. (Note that charts use two different vertical scales based on the range of the moisture content levels for wall pairs to enable meaningful evaluation of the results.) In general, WUFI's predicting power varies for different wall systems. The software is capable of predicting the ranges and the trends, but not always the absolute magnitude of the moisture content at the time of the occurrence. General observations based on the review of the comparison charts include:

1. The biggest discrepancies are observed for walls without Kraft facing. However, because the sensors are not capable of determining moisture content above the fiber saturation point (e.g.,

fiber saturation is asymptotic for the sensors and the readings level off even if the actual moisture content climbs above the fiber saturation point), the differences in the moisture content levels above the fiber saturation points are not known and would be far less than those shown in the figures.

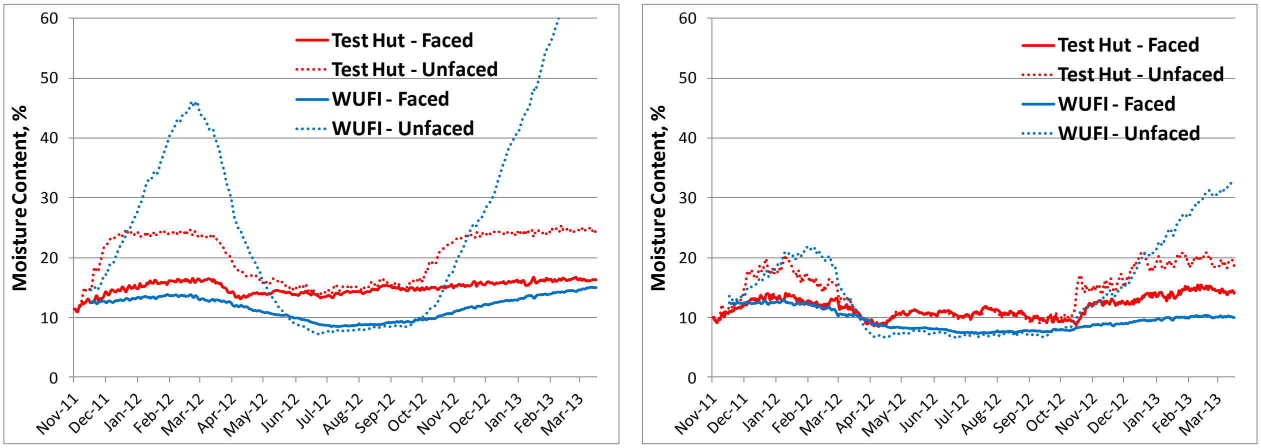
2. Because the peak moisture content for walls without Kraft facings cannot be directly compared, the parameter that can be evaluated is the duration of the moisture content above the fiber saturation point. WUFI simulations show the increase and decrease trends occurring at the same time as observed in the structure.
3. For walls without Kraft facing, the difference between modeled and measured results are higher for the north exposure compared to the south exposure. Similarly for walls with Kraft facing, there is a slightly better agreement between field and simulated results for South orientation than for North orientation, with the South walls also having a narrower fluctuation range overall.
4. For walls with absorptive claddings (Configurations #1 and #2), WUFI under predicts summer moisture content for specimens with and without Kraft facing and under predicts winter moisture content for walls with Kraft facing. This observation suggests that WUFI over predicts the drying capability of walls systems with exterior cladding that have water storage capacity.
5. Although to a smaller degree, WUFI under predicts moisture levels of several other wall systems (#3 North, #4, #6, #7, #8 North, #9 North). These differences may be driven by mechanisms not captured by WUFI such as bulk air flow.
6. Overall, WUFI provides a good level of agreement with observed trends in moisture levels. .



a. North

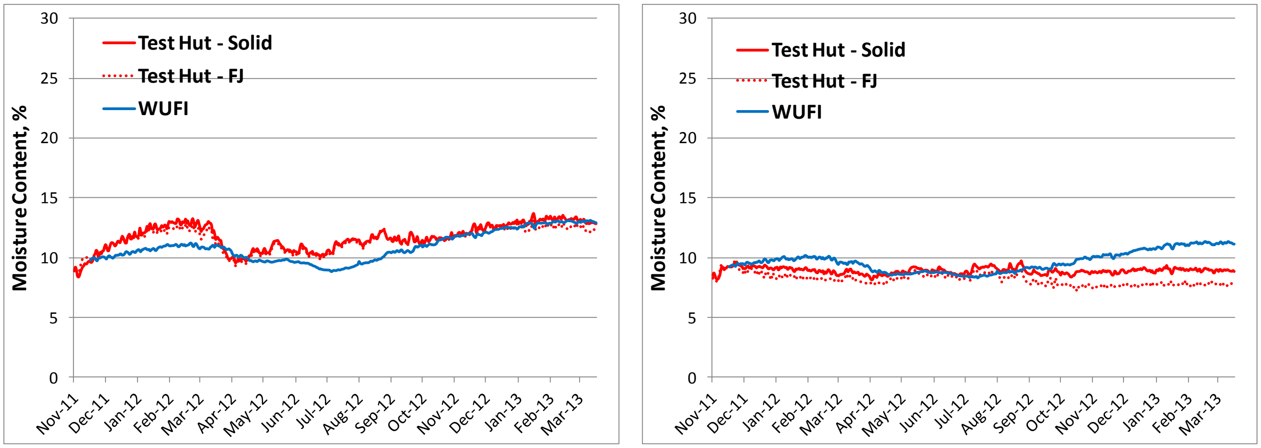
b. South

Figure 15. #1 Manufactured Stone



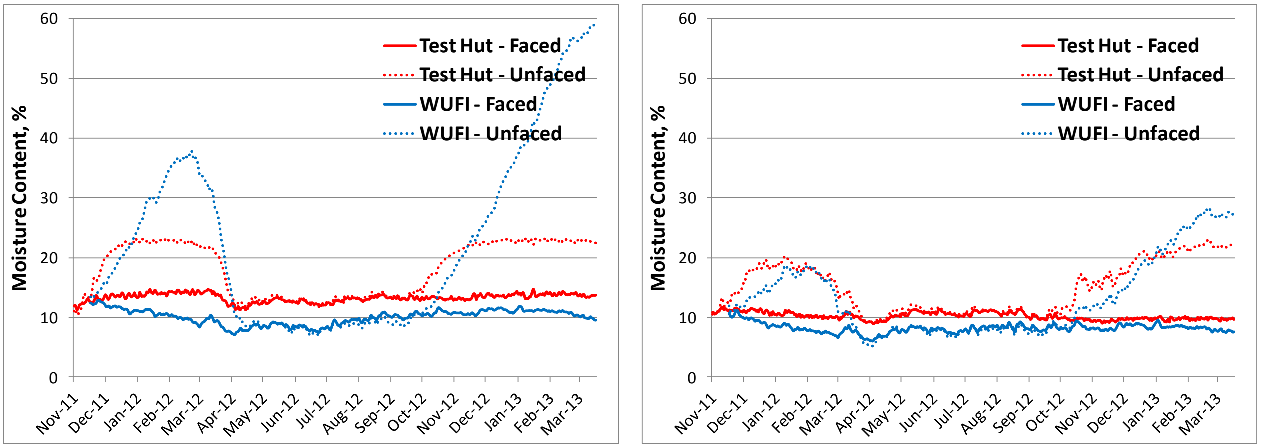
a. North b. South

Figure 16. #2 Stucco



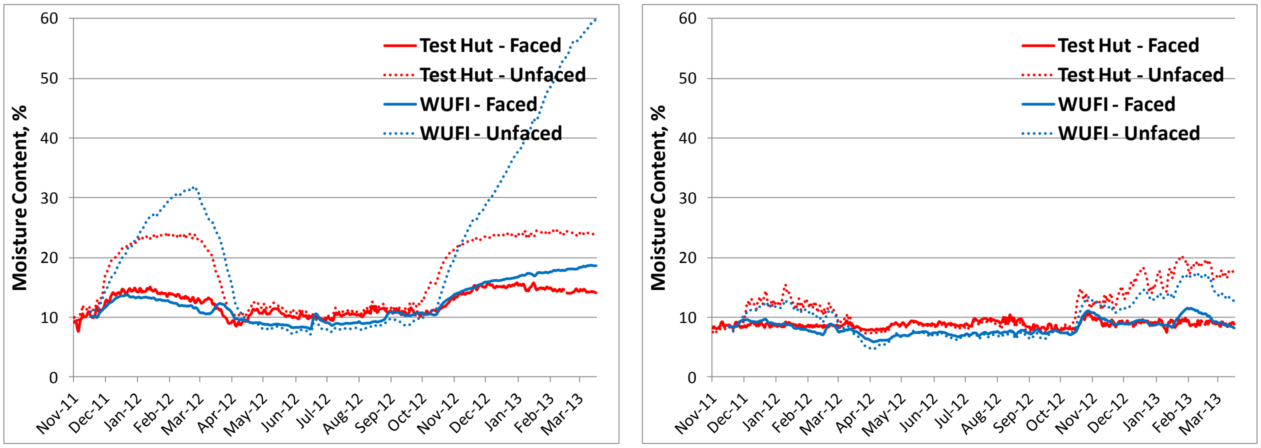
a. North b. South

Figure 17. #3 Cedar Siding over ¾" Furring



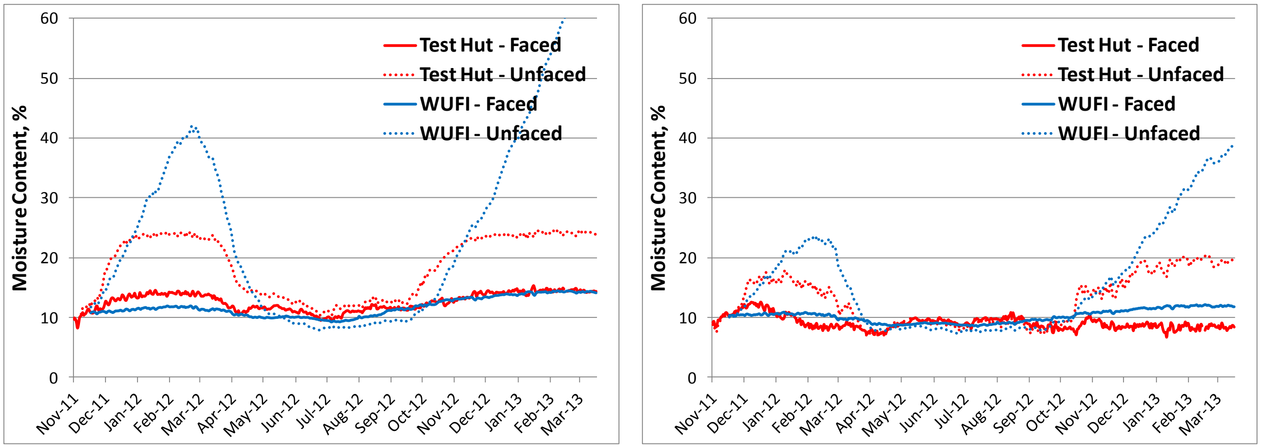
a. North b. South

Figure 18. #4 Vinyl Siding



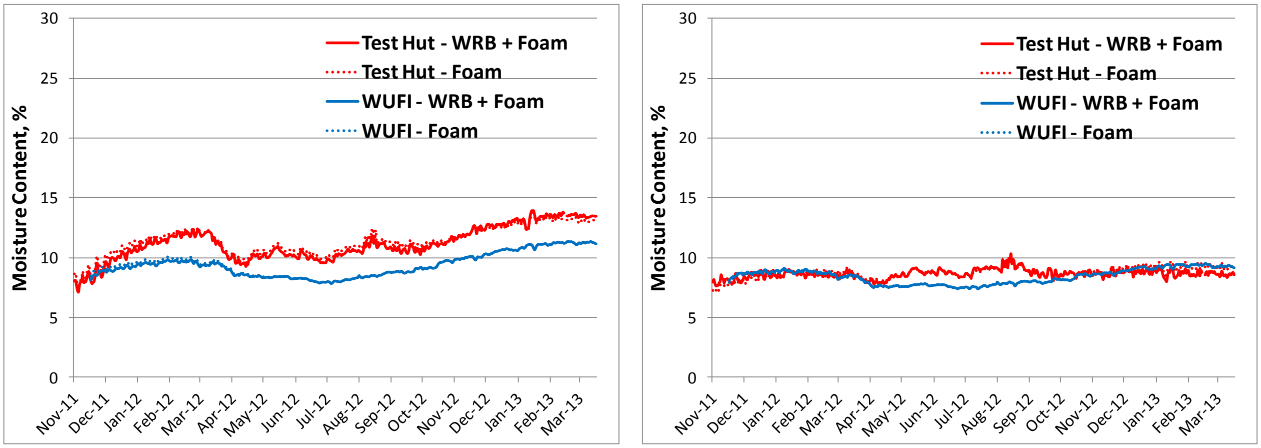
a. North b. South

Figure 19. #5 Brick Veneer



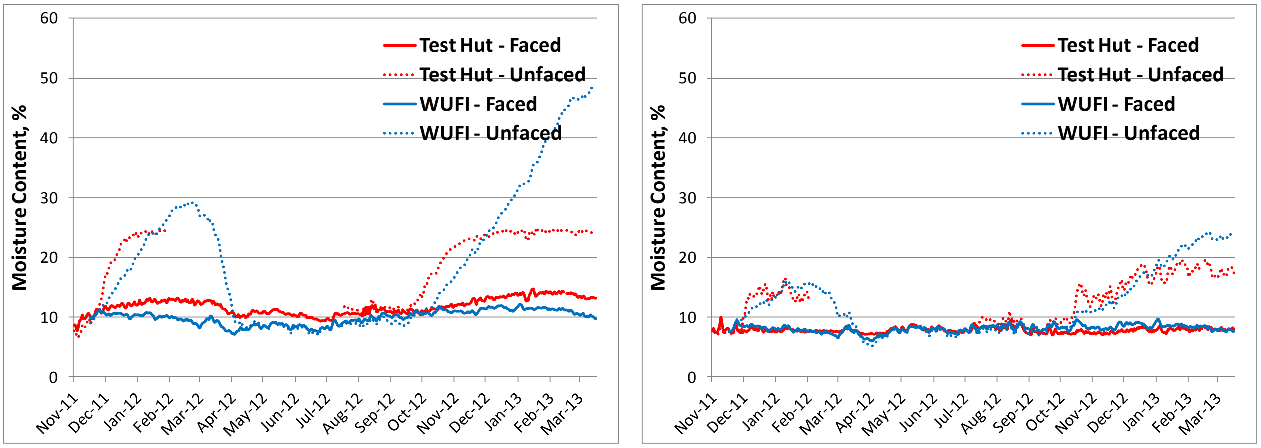
a. North b. South

Figure 20. #6 Fiber Cement



a. North b. South

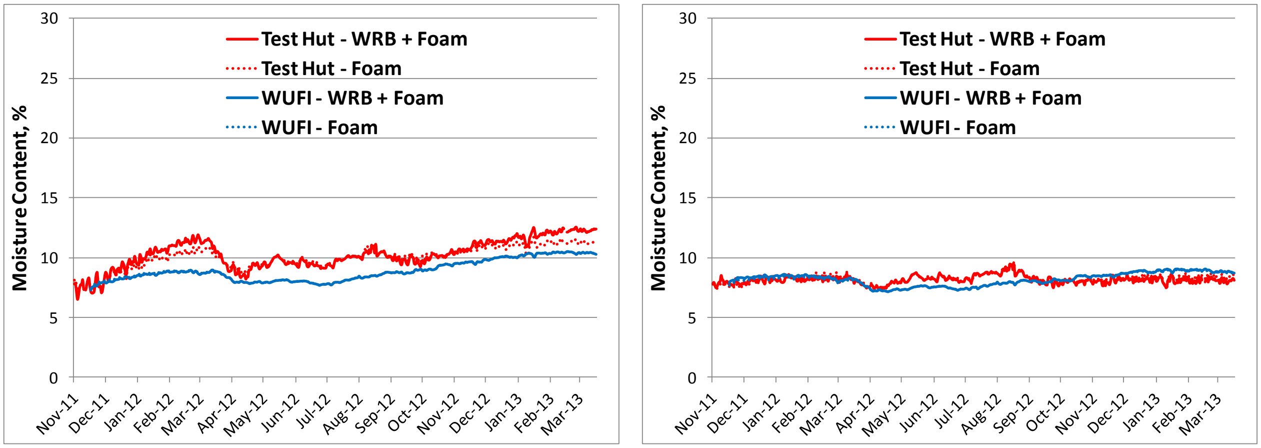
Figure 21. #7 Vinyl Siding Over 1" XPS w/2x6 Framing



a. North

b. South

Figure 22. #8 Vinyl Siding w/ 2x6 Framing



a. North

b. South

Figure 23. #9 Vinyl Siding Over 1" XPS

Summary and Conclusions

This study provides moisture performance data for a range of walls systems including energy efficient configurations required by new building codes in Climate Zone 4. The results of this study provide the basis for developing design and specification guidance for durable wood-frame wall systems. The key observations and conclusions are summarized below:

1. The combination of three variables – (1) high interior RH, (2) high permeance of the interior vapor retarder, and (3) air leakage path into the cavity – have a potential for causing high moisture content of the exterior OSB sheathing in Climate Zone 4. Further study is needed to uncouple the impact of air leakage from the effect of vapor diffusion and to complete the assessment of the appropriateness of the ASHRAE 160 simplified method for evaluating performance of enclosures. The results of this study suggest that the ASHRAE 160 Simplified

Method leads to wall moisture levels higher than those observed in the field. The effectiveness of primer and paint to serve as Class III vapor retarder also needs reevaluation.

2. 1-inch XPS exterior rigid sheathing (R5) has a marginal impact on the moisture content of the OSB sheathing in walls with vinyl siding and interior Kraft vapor retarder in Climate Zone 4. Walls with and without exterior foam showed OSB drying in the spring at a similar rate regardless of use of foam on the exterior.

3. Walls with Kraft paper interior vapor retarder are less sensitive to interior relative humidity conditions than walls without Kraft facing. On the other hand, interior relative humidity is a critical factor for design and performance of walls with painted gypsum as the only interior vapor retarder.

4. The wall with cedar siding installed over ¾-inch furring strips (with interior Kraft vapor retarder) showed good moisture performance over the 16-month monitoring period with the OSB moisture content at or below 13 percent and the cedar moisture content at or below 14 percent. Inspection of the cedar siding material following the monitoring did not reveal any damage or deterioration of the wood material.

5. Overall, WUFI provides a good level of agreement with observed trends in moisture levels. For walls without Kraft facing, direct comparison with test results was not possible during certain winter periods due to the sensors' limitation to read moisture content above the fiber saturation point.

APPENDIX A:
Computer Hygrothermal Modeling

Samuel V. Glass, Research Physical Scientist, USDA Forest Products Laboratory, Madison, Wisconsin

This summary describes the modeling approach for WUFI 5.2 simulations of test hut walls monitored at Home Innovation Research Labs in Upper Marlboro, Maryland.

Modeling Approach and Input Parameters

Simulations were run using WUFI® Pro 5.2 software for one-dimensional transient heat and moisture transfer (IBP 2013).[7] Model input parameters include the following:

- Wall configuration and geometry of components
- Material properties of each component
- Wall orientation
- Wind-driven rain exposure
- Surface heat and mass transfer coefficients
- Initial temperature and moisture content in each component
- Calculation period (start and end dates and time step)
- Numerical calculation parameters
- Outdoor environment
- Indoor environment

Wall Configurations

All wall assemblies have 11 mm (7/16 in) Oriented Strand Board (OSB) sheathing and 12.5 mm (1/2 in) gypsum drywall with primer and two coats of latex paint. Cavity insulation is either R-13 for nominal 2x4 framing or R-21 for nominal 2x6 framing. Table A1 summarizes the different wall configurations simulated.

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[7] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the United States Department of Agriculture (USDA) of any product or service.

Table A1. Wall Assembly Details

ID	Cladding	Air space	Exterior XPS	WRB	Framing	Kraft VR
1a	Manufactured stone	---	---	2 layers felt	2x4	Yes
1b	Manufactured stone	---	---	2 layers felt	2x4	No
2a	Stucco	---	---	2 layers felt	2x4	Yes
2b	Stucco	---	---	2 layers felt	2x4	No
3	Cedar siding	¾ in not vented	---	DrainWrap	2x4	Yes
4a	Vinyl siding	---	---	HomeWrap	2x4	Yes
4b	Vinyl siding	---	---	HomeWrap	2x4	No
5a	Brick Veneer	1 in vented	---	HomeWrap	2x4	Yes
5b	Brick Veneer	1 in vented	---	HomeWrap	2x4	No
6a	Fiber cement siding	---	---	HomeWrap	2x4	Yes
6b	Fiber cement siding	---	---	HomeWrap	2x4	No
7a	Vinyl siding	---	R-5	DrainWrap	2x6	Yes
7b	Vinyl siding	---	R-5	Taped XPS	2x6	Yes
8a	Vinyl siding	---	---	HomeWrap	2x6	Yes
8b	Vinyl siding	---	---	HomeWrap	2x6	No
9a	Vinyl siding	---	R-5	DrainWrap	2x4	Yes
9b	Vinyl siding	---	R-5	Taped XPS	2x4	Yes

Material Properties

Manufactured Stone. Thickness was selected as 46 mm (1.8 in) based on the average of the thickness range reported by NAHB Research Center (2010). The vapor permeance curve was a user-defined function of RH based on measured dry cup and wet cup tests from that report (see Figure A1). Note that the figure below shows permeance values at the tested thickness of 0.767 in (specimens were trimmed); permeability values (which correct for thickness) were entered in WUFI.

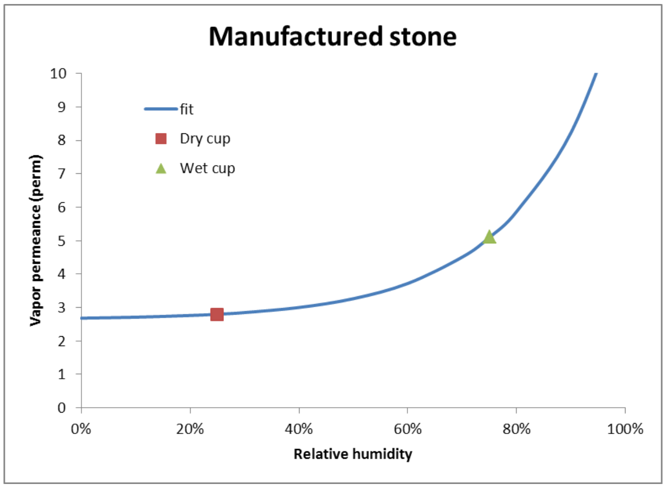

Figure A1.

Stucco. The properties were those of "Regular Portland Stucco" from the WUFI North America Database. A thickness of 19 mm (3/4 in) was used.

Cedar Siding. Thickness: 11 mm (0.5 in).The vapor permeance curve was a user-defined function of RH based on measured dry cup and wet cup tests (see Figure A2). The trend of increasing permeance with increasing RH agrees with literature values for wood. The measured wet cup values are intermediate between literature values for Eastern white cedar and Western red cedar (Kumaran et al. 2002). The siding was modeled with paint layers on each side; the vapor permeance of the paint layers was based on measured dry cup and wet cup tests.

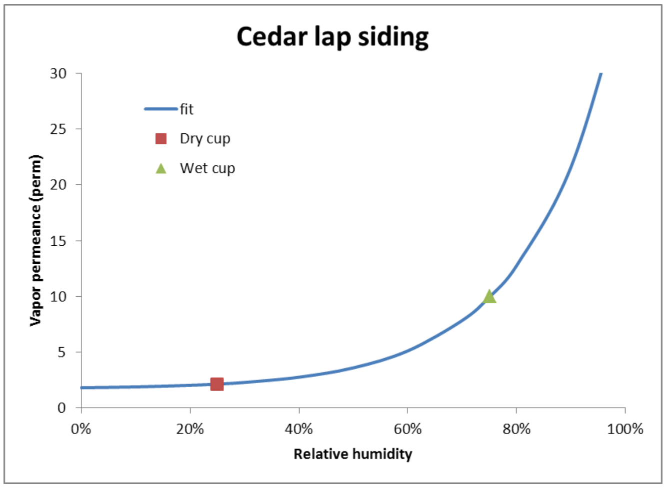

Figure A2.

Vinyl Siding. Modeled with an equivalent vapor permeance of 40 perms based on BSC (2010). This is a method of modeling a cladding that is vapor impermeable but is back-ventilated by airflow. The alternative, which is modeling an air space between the siding and house wrap, requires the selection of an air change rate, and determining proper values was beyond the scope of this study.

Brick Veneer. The properties were those of “Brick (old)” from the WUFI North America Database. A thickness of 102 mm (4 in) was used.

Fiber Cement Siding. The properties were those of “Fibre Cement Sheathing Board” from the WUFI North America Database. A thickness of 8 mm (5/16 in) was used. The vapor permeance value at 75% RH is 12.7 perms, which agrees well with the measured wet cup value of 13.2 perms (NAHB Research Center 2010). The siding was modeled with paint layers on each side, with the same paint vapor permeance as was used for cedar lap siding.

Air Spaces. The properties were those of air layers of the appropriate thickness (without additional moisture capacity) from the WUFI Generic Materials database.

Extruded Polystyrene (XPS). Thickness: 25 mm (0.98 in). R-value at 24°C (75°F) is 5 h·ft^2·°F/Btu. Vapor permeance was taken as 1.03 perms (the average of measured dry cup and wet cup tests) and was assumed to be independent of RH.

Felt WRB. The properties were those of “Bituminous Paper (#15 Felt)” from the WUFI North America Database.

Tyvek DrainWrap. The properties were those of "Spun Bonded Polyolefine Membrane with Crinkled Surface" from the WUFI North America Database. The vapor permeance is 52 perms (independent of RH), which is within the range of the measured dry cup and wet cup tests.

Tyvek HomeWrap. The properties were those of "Spun Bonded Polyolefine Membrane" from the WUFI North America Database. The vapor permeance is 49 perms (independent of RH), which is within the range of the measured dry cup and wet cup tests.

Oriented Strand Board (OSB). Thickness: 11 mm (7/16 in). The properties were those of "Oriented Strand Board" from the WUFI North America Database. Literature data show a wide variation in values, generally showing an increase in vapor permeance with increasing RH; the WUFI vapor permeance curve appears to be a reasonable fit (Glass 2013). The value at 25% RH is 0.7 perm (compare with current dry cup test value of 1.95 perms and previous value of 4.1 perms); the value at 75% RH is 3.8 perms (compare with current wet cup test value of 1.35 perms and previous value of 4.5 perms).

Glass Fiber Insulation. The properties were those of "Fibre Glass" from the WUFI North America Database. R-value at 24°C (75°F) is 13 h·ft^2·°F/Btu for 2x4 construction (89 mm) and 21 h·ft^2·°F/Btu for 2x6 construction (140 mm).

Asphalt-Coated Kraft Paper. The vapor permeance curve was a user-defined function of RH based on measured dry cup and wet cup tests (see Figure A3). The trend of increasing permeance with increasing RH agrees with literature values (Glass 2013). The measured values are intermediate between those of Gatland (2005) and Burch et al. (1992).

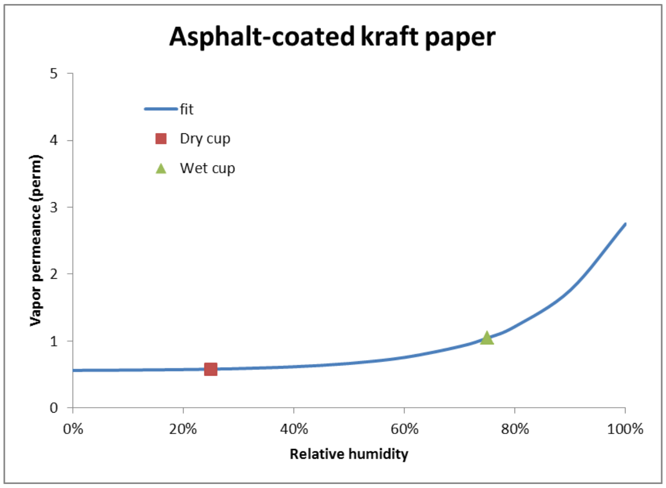

Figure A3.

Gypsum Board/Primer/Paint. Thickness: 12.5 mm (0.493 in). Vapor permeance of gypsum board itself was taken as 47 perms (the average of measured dry cup and wet cup tests) and was assumed to be independent of RH (reasonable assumption for the range of interior RH values in the test hut). Vapor permeance of gypsum board with primer and two coats of latex paint was found to be 35 perms (dry cup and wet cup values agree). The interior primer/paint coating was modeled as an interior surface permeance of 140 perms (which in combination with 47 perm gypsum board results in 35 perms).

Wall Orientation

Each wall was simulated in both the north-facing and south-facing orientation.

Wind-Driven Rain Coefficients

Wind-driven rain on the walls was calculated according to ASHRAE Standard 160 (ASHRAE 2009), using measured horizontal rainfall, wind speed, and wind direction. A rain exposure factor of 1.0 (medium exposure for buildings less than 10 m (33 ft)) and a rain deposition factor of 0.35 (walls below a steep-slope roof) were assumed.

Surface Transfer Coefficients

The exterior surface heat transfer coefficient was set to be wind-dependent using default parameters. Standard values were used for short-wave radiation absorptivity and long-wave radiation emissivity (depending on the cladding type). Standard values were used for the adhering fraction of rain and the interior heat transfer coefficient.

Initial Conditions

The initial moisture content of OSB was set to correspond with measured values in each of the wall assemblies. For materials other than OSB, the initial moisture content was set at equilibrium with 65% RH. Initial temperature in all materials was set to 21°C (70°F).

Calculation Period

Simulations were started on December 1, 2011, with a one-hour time step and were concluded on December 31, 2012.

Numerics

Default values were used for numerical calculation parameters except that adaptive time step control was enabled, which in combination with a fine numerical grid minimized convergence failures.

Outdoor Environment

Outdoor conditions were obtained from a weather station mounted on one of the test huts. These measurements included dry-bulb temperature, relative humidity, wind speed, wind direction, and solar radiation (on both north and south-facing orientations). The data were collected at half-hour intervals and were averaged to obtain hourly values. Hourly rainfall data were obtained from the nearest weather station, Andrews Air Force Base.

Indoor Environment

Indoor conditions were measured in the test huts at half-hour intervals and were averaged to obtain hourly values.

Appendix A References

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