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Characterization of Moisture Performance of Energy-Efficient Light-Frame Wood Wall Systems – Phase II

Prepared For

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TABLE OF CONTENTS

TABLES

FIGURES

EXECUTIVE SUMMARY

A field investigation of wood-framed wall assemblies was conducted to monitor the moisture performance of various exterior wall constructions with intentional air leakage and seasonal moisture injections between the cladding and sheathing over a 20-month period from November 2013 to June 2015. The research focused on four specific studies: moisture performance of Extended Plate and Beam (EP&B) walls, walls with air leakage versus air sealing, 2x4 walls with various types of exterior insulation, and baseline walls insulated with kraft-faced batts and unfaced batts. This report covers the field monitoring results and compares the performance of the 10 wall pairs.

The field study was conducted in a mixed-humid climate located in Upper Marlboro, Md., on the campus of Home Innovation Research Labs, located 20 miles east of Washington, D.C. Wall sections with each of the cladding systems were investigated in North and South orientations. Over the test period, indoor humidity conditions were controlled to 30 to 60 percent RH during the winter heating period. Stud bay temperature and humidity conditions were monitored, as was moisture content in the exterior sheathings and studs. During this winter portion of the testing, the wood-based components of the wall sections indicated moisture levels significantly higher for the stucco, stone, brick, and fiber cement walls relative to the walls with vinyl siding with or without exterior insulations. The winter peak moisture content in the sheathing for these walls ranged from 20 to 24 percent; higher than the generally accepted 20 percent Moisture Content (MC) level for wood products (Drumheller and Carll, 2010). Thus, they might have been at risk for moisture problems such as rot and mold growth.

In this study, the advanced EP&B wall system demonstrated satisfactory moisture performance with 14 percent as the maximum MC recorded for the OSB sheathing. Also, air sealing did not show significant improvement in moisture performance over the EP&B wall assembly. The walls with controlled 2 cfm air leakage to the cavity performed significantly worse than the air sealed walls. The walls with intentional air leakage also showed greater increases of sheathing MC in year 2 than in year 1. The vinyl sided walls with exterior insulation performed better than the walls with unfaced batt insulation, no exterior insulation, and a variety of different claddings. But the wall with polyisocyanurate (PIC) exterior insulation performed worse than the other walls with expanded polystyrene (EPS), extruded polystyrene (XPS), and rockwool exterior insulations. The PIC wall had 21 percent MC in the OSB sheathing, which had mold growth potential. Therefore, it's important to use exterior insulation with medium to high water vapor permeance to avoid potential moisture problems if there is no water vapor management on the interior side of the wall. With kraft-faced batt insulation in the cavities the vinyl sided walls achieved significantly better moisture performance than the similar wall with unfaced batt insulation, which had 24 percent MC in the OSB sheathing in the winter.

Portions of six wall systems – two vinyl baseline walls and four walls with exterior insulations –were subjected to moisture injections on each side of the sheathing at the window sill area. Injections of water were performed in four discrete week-long experiments spread out over the entire monitoring period. Water injections were performed daily at noon over a five-day period. All south facing walls had higher moisture increases within the window sills and adjacent OSB sheathing, and quicker drying (below 15 percent) than those in north facing walls. Among all six pairs of walls, the walls with PIC exterior insulations had the longest drying time in winter due to the low water vapor permeance of the PIC material.

INTRODUCTION

Energy-efficient walls built in recent years have higher level of insulation than conventional walls. To achieve even higher thermal performance, the walls are air sealed for tightness to avoid air leakage and thus reduce undesired heat loss or gain through the walls. The 2012 IECC has been the driving force behind this significant shift to creating highly insulated building envelope systems. However, the long-term moisture performance of these energy-efficient wall systems is not well understood. Moisture may accumulate on the wood sheathing and framing due to surface condensation of water vapor and rain events. Some wall designs may not have sufficient drying capacity for the condensed water to dissipate. The moisture performance of these highly insulated, air-tight walls has increasingly become a concern to home builders, owners, designers, architects, and engineers. To alleviate these industry concerns and create a reliable pathway for building high performing, air-tight, durable walls without moisture issues, it is imperative to have practical design guidance based upon long-term moisture research.

Climate must always be considered during the wall system design process since every climate has its own unique characteristics that impact moisture performance. The mixed-humid climate is defined as a region that receives more than 20 inches of precipitation and has less than 5,400 heating degree days (base 65°F) annually. In this climate, the average monthly winter temperature is below 45°F. This combination of conditions creates a situation where moisture typically migrates from the inside of a wall system to the exterior side during the winter. The moisture migration is reversed during the summer. These dynamic hygrothermal processes can create significant moisture loads on wall materials and lead to durability problems unless the systems are intentionally designed to manage these loads. In addition, several new insulation and air sealing techniques have been introduced into the market to meet the new demand for energy-efficient walls. These innovative materials and techniques have vastly different moisture characteristics. The long-term impact of these materials used in various climates, and their combinations on the durability of wood products in walls is often not well understood. Therefore, the design of walls constructed to current specifications and in a specific climate needs to include consideration of the ability to manage moisture, in addition to energy efficiency requirements.

Moisture performance of building envelope systems is not only dependent on design, but also on the indoor conditions. The indoor conditions are mostly affected by building occupant behavior, mechanical systems performance, and settings. For example, humidifier set-points, plants, standing water, occupant density, and their interaction with building tightness all contribute to the moisture load on the building structure and consequently the wall systems. However, research on the impact of indoor conditions on wall system moisture performance is needed to provide further guidance to achieve robust designs that tolerate variabilities in climates.

The research summarized in this report involved intensive monitoring of two climate controlled test huts located in Upper Marlboro, Md. Each test hut was constructed with five pairs of walls (one north- and one south-facing), and most of these panels were divided into two sub panels. These test hut walls were modular and designed to be removable without destroying the structure. Each wall contained multiple sensors to measure the MC of the wood framing or OSB and the temperature and relative humidity in the cavity. Both the interior conditions and exterior conditions were also monitored. Among the outdoor conditions monitored were temperature, relative humidity, speed and direction of wind, rainfall, solar radiation on the roof, driving rain against the walls, and solar radiation on the walls.

This research required installation of energy-efficient wall configurations (R20 or R13+R5 exterior continuous insulation or higher), with the primary study variables including 2x6 wood framing, exterior rigid foam, weather resistive barrier, and bulk air movement through the wall cavity. A new conventional 2x4 wall (R13) provided a baseline for analysis of the observed performance of the high-R wall systems.

The remaining walls in the test huts had their drywall, insulation, and sensors removed. These walls were examined for damage and, if deemed acceptable for continued observation, re-instrumented with sensors and had new fiberglass cavity batt insulation and interior drywall installed

OBJECTIVE

The objective of this research was to quantify the field performance of 16 wood-frame wall designs at variable indoor winter relative humidity levels. The indoor winter relative humidity maintained between 30 and 60 percent is similar to the design indoor RH as calculated by the DIN EN 15026 (EN 2007), roughly 5 percent RH lower than the standard profile.

To evaluate the wall performance, MC of the sheathing was measured at multiple locations on a half-hour basis. The study considered the primary drivers for moisture accumulation in wall assemblies: vapor diffusion through the wall layer(s); vapor movement entrained in air movement; and bulk water (rain) leakage past the cladding system and the WRB.

The main objectives of this research were to identify moisture-tolerant design and construction practices for high-R wood-frame exterior walls with different types of insulation and air sealing methods.

The specific objectives of this phase of research included:

1. To conduct a comparative evaluation of the performance of walls constructed with four types of exterior insulation materials with a wide range of vapor permeance characteristics;
2. To quantify the relative impact of vapor diffusion versus air leakage on the MC of the OSB sheathing in 2x6 walls during the heating season;
3. To evaluate the performance of the innovative Extended Plate and Beam (EP&B) wall system with two different air sealing configurations; and
4. To evaluate the impact of reduced interior relative humidity levels on the performance of walls without a kraft vapor retarder in Climate Zone 4.

TECHNICAL APPROACH

A pair of 4'x9' sub-panel walls for each of the 16 designs was installed in a test hut constructed on the Home Innovation Research Labs campus. The interior of the hut was climate-controlled to simulate indoor conditions, while the exterior cladding was exposed to ambient conditions. Detailed measurements of indoor and outdoor environmental conditions and the MC of studs and sheathing were used to determine hygrothermal performance of each assembly.

Six wall sections were subjected to four (seasonal) simulated water intrusion events. Water intrusion events were simulated by injecting 30 milliliters of water behind the cladding system through each of two ¼-inch hoses each day for five consecutive days. The hoses terminated on opposite sides of the OSB; one terminated on the window sill along a cut in the OSB, and the other terminated between the WRB and the sheathing into a bladder. The moisture sensors in the OSB detected any accumulation of water in the sheathing; readings over time indicated the wall assemblies' ability to dissipate moisture.

TEST STRUCTURE CONSTRUCTION

The test structures were constructed on the grounds of Home Innovation Research Labs in Upper Marlboro, Md., approximately 20 miles east of Washington, D.C. The structures are a post-and-beam design, with a nominal footprint of 8'x48' (Figure 1). The hut design allowed for five pairs of 8'x9' wall test panels to be installed as exterior wall sections, with one panel of each pair having southern exposure and the other panel of the pair having northern exposure. The 8'x9' test panels were typically framed with 2x4 studs, sheathed with wood structural panels. The panels included various combinations of cladding, exterior insulation, and drainage strategies, which are described in the following section of this report. A window is located on the west end of the hut and an entrance door is located on the east end. Eight-foot on-center post spacing allows for insertion and removal of test specimens for subsequent testing. The huts' interiors were finished with ½-inch drywall and wall cavities were insulated with fiberglass batts. The perimeter of each wall panel was sealed to minimize extraneous air infiltration.

Figure 1. South Facing Walls of Test Structures 1 (right) and 2 (left)

The floors are located approximately 30 inches above grade and insulated with R-19 fiberglass batt insulation. The roof is shingled on 4/12 pitch trusses and insulated to R-30 at the attic ceiling interface.

Roof overhang was limited to the 4-inch gutter; test panel exteriors therefore had appreciable exposure to the weather. Gable end walls were clad with horizontal lap vinyl siding over a WRB and OSB. All products were installed in accordance with manufacturer recommendations or, if recommendations were unavailable, in accordance with the prevailing building code (2003 IRC).

Two portable air conditioners limited the maximum interior summer temperature to 78°F and resistance heat maintained indoor temperature in the winter at 70°F. A humidifier maintained indoor relative humidity between 30 and 60 percent in the winter months, based on European Standard DIN EN 15026 (EN 2007).

FIELD TEST WALL ASSEMBLIES

The nominal dimensions of the specimens are 9 feet tall by 4 feet wide. Walls were constructed with 2x4, 2x6, or a combination of both with studs spaced 16" o.c. The lumber was SPF grade 2. All specimens used fiberglass batt cavity insulation and several specimens also included R5 or R10 insulation exterior to the wall cavity and installed over or behind the OSB sheathing. A typical framing layout for two adjacent specimens is shown in Figure 2. The 4'x9' segments were framed in an identical manner containing three stud bays and the lower framing of a false window in the center bay. To simplify the construction, adjacent test specimens of identical thickness were constructed as a single 8'x9' wall with continuous top and bottom plates and a double center stud.

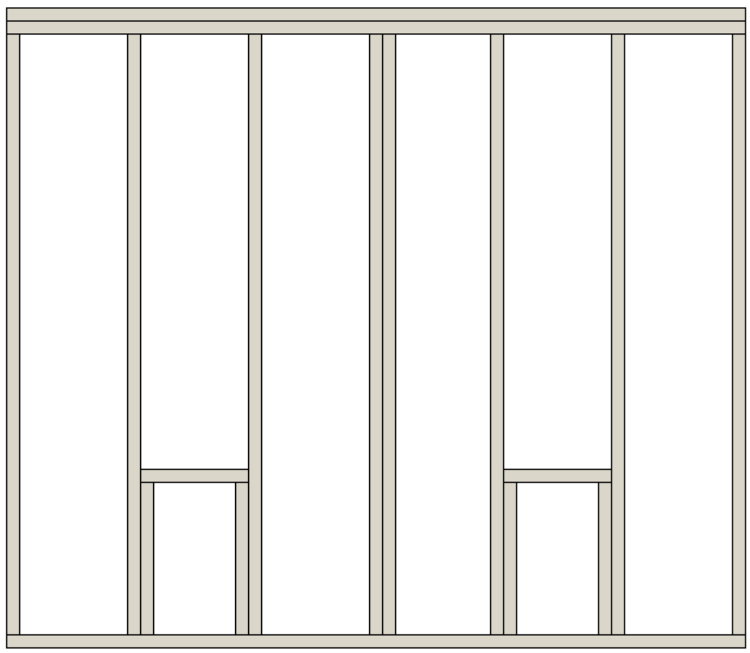

Figure 2. Typical Construction of Two Adjacent Test Wall Specimens

The perimeter edges between the specimens in the test huts for each of the 10 pairs of walls installed were sealed with spray foam and caulk. The vertical joints between the two abutting studs in adjacent test specimens were also sealed. All vertical seams between the OSB sheathing and the wall framing were sealed so that air movement could occur only at plates (unless sealed for a specific configuration in accordance with the test matrix).

The 16 wall panel designs evaluated in the study are outlined in Table 1. The (4'x9') panels included vinyl siding, synthetic stone cladding, stucco, fiber cement siding, and brick.

Table 1. Detailed Test Wall Configurations

	Hut 1									
Wall Number	**1A**	**1B**	**2A**	**2B**	**3A**	**3B**	**4A**	**4B**	**5A**	**5B**
Wall Identifier	2x4 w/ Vinyl		2x6 Leakage Wall 1		2x4 w/ Stucco		2x6 Leakage Wall 2		2x4 w/ Manufactured Stone	
Cladding	Vinyl		Vinyl		Stucco		Vinyl		Manufactured Stone	
Insulated Sheathing	NA		NA		NA		NA		NA	
Weather Barrier	HouseWrap		HouseWrap		2 layer felt		HouseWrap		2 layer felt	
Structural Sheathing	OSB		OSB		OSB		OSB		OSB	
Framing	2x4		2x6		2x4		2x6		2x4	
Cavity Insulation	R13		R21		R13		R21		R13	
Interior Vapor Retarder	UnFaced	KFB	Kraft Paper		UnFaced		Kraft Paper		UnFaced	
Drywall	yes		yes		yes		yes		yes	
Primer (standard)	yes		yes		yes		yes		yes	
Paint	2 coats latex		2 coats latex		2 coats latex		2 coats latex		2 coats latex	
Air sealing										
Controlled Air Leakage	NA		Control (fully sealed)	Controlled Leak 1	NA		Un-controled Leak	Controlled Leak 2	NA	
Water Injections	yes		no		no		no		no	
Purpose	Provide baseline and continued monitoring for reduced interior RH		Air leakage vs. diffusion study		Continued monitoring with reduced interior RH		Air leakage vs. diffusion study		Continued monitoring with reduced interior RH	

Table 1. Detailed Test Wall Configurations (Continued)

Hut 2										
Wall Number	**1A**	**1B**	**2A**	**2B**	**3A**	**3B**	**4A**	**4B**	**5A**	**5B**
Wall Identifier	Extended Plate and Beam		2x4 w/ R-5 EPS	2x4 w/ R-5 Rockwool	2x4 w/ R-5 PolyISO	2x4 w/ R-5 XPS	2x4 w/ Fiber Cement		2x4 w/ Brick	
Cladding	Vinyl		Vinyl		Vinyl		Fiber Cement		Brick	
Insulated Sheathing	NA		R-5 EPS (1.25") No Tape	R-5 Rockwool (1.25") No Tape	R-5 PolyISO (.75") Tape Joints	R-5 XPS (1") Tape Joints	NA		NA	
Weather Barrier	HouseWrap		HouseWrap	HouseWrap	NA	NA	HouseWrap		HouseWrap	
Structural Sheathing	OSB		OSB		OSB		OSB		OSB	
Alternate Ins Location	2" XPS (No Tape)		NA		NA		NA		NA	
Framing	2x6 plates w/ 2x4 studs		2x4		2x4		2x4		2x4	
Cavity Insulation	R13		R13		R13		R13		R13	
Interior Vapor Retarder	UnFaced		UnFaced		UnFaced		UnFaced		UnFaced	
Drywall	yes		yes		yes		yes		yes	
Primer (standard)	yes		yes		yes		yes		yes	
Paint	2 coats latex		2 coats latex		2 coats latex		2 coats latex		2 coats latex	
Air sealing	Standard	Picture Frame								
Air Leakage Testing	NA		NA		NA		NA		NA	
Water Injections	no		yes	yes	yes	yes	no		no	
Purpose	Evaluate EP&B with two levels of air sealing		Evaluate the performance of OSB sheathing behind four different types of exterior insulation in walls without interior vapor retarder				Continued monitoring with reduced interior RH		Continued monitoring with reduced interior RH	

RESEARCH FOCUS

There were four areas of focus for this research.

1. Extended Plate and Beam Wall (EP&B)

The EP&B advanced wall design, diagramed in Figure 3, relies on common construction methods and materials. However, this unique design integrates the foam sheathing into a conventional walls system in a manner that provides continuous structural backing for siding attachment and relies on wood structural panels nailed directly to framing for shear resistance.

The design features include:

- Reduced thermal shorts due to framing members
- Rigid foam insulation is set to the inside of the structural sheathing for ease of siding attachment and nailed directly to extended top and bottom plates to provide shear load resistance
- Clear drainage plane and flashing surface for window and door openings
- Cold surface exterior sheathing capable of drying to exterior and limited exposure from interior moisture diffusion
- Flexible in the selection of wall cavity and foam sheathing materials
- Flexible in the use of framing combinations for optimum overall wall thermal resistance

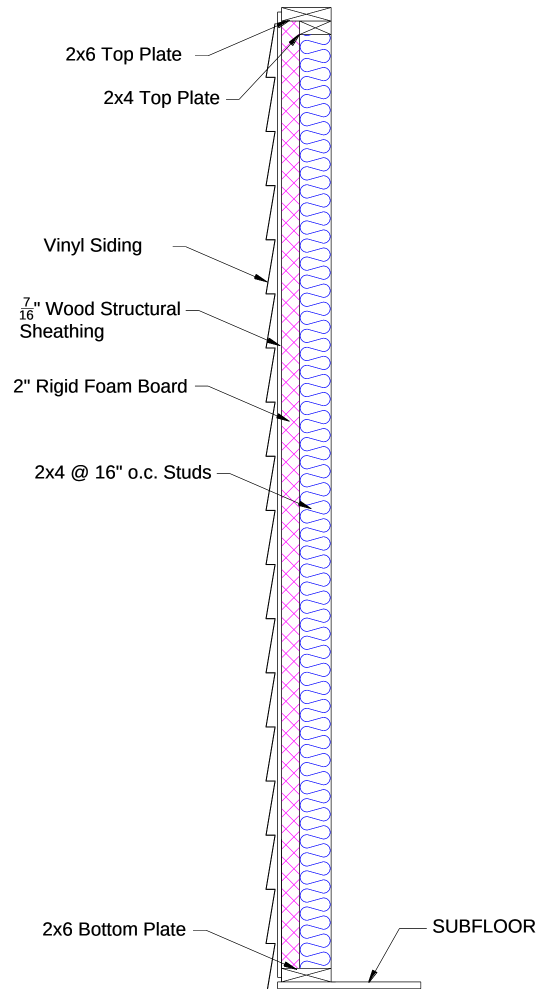

Figure 3. Extended Plate and Beam Wall Detail

- In both pairs of test wall panels in Hut 2, panel 1B had air sealing using spray foam sealant between the exterior surfaces of 2x4 studs/top plate and the foam sheathing material. Panel 1A did not have spray foam sealing between the 2x4 wood members and the foam sheathing.

Because the MC sensors (by Omnisense) were installed on the interior face of the OSB, which in the case of the EP&B wall were flush with the face of the 2” XPS foam, small pockets were carved out in the foam to accommodate the sensors. The pockets were approximately 1-inch deep. To make up for the lack of insulation at the area where the sensors were located, a 1-inch thick foam block extending beyond the pocket one inch in all directions was attached to the back side of the foam board centered on the sensor locations. The 1-inch blocks were glued to the foam panel only at the block’s perimeter edges such that there was no air leakage between the foam block and the foam and panel, yet there was additional vapor diffusion resistance introduced between the foam block and the foam panel.

2. Air Leakage versus Vapor Diffusion

The walls for air leakage versus water vapor diffusion (no air leakage) were sealed with spray foam and caulk to control the air flow through the cavities. The control specimen (Hut 1-Wall 2A) was sealed to prevent any air from either entering or escaping the cavity. Both the drywall and the OSB were sealed to the framing members.

For the specimens with controlled leakage levels (Hut 1-Walls 2B and 4B), the wall had tubes penetrating through the drywall at the top of each of the three stud bays as shown in Figure 4. Three 1/4-inch tubes were combined into a single tube exhausting the cavity air to the outside through the floor of the test hut. This tube was equipped with an orifice plate to measure air flow rate and a fan with a speed control to draw air through the wall cavity at a specific rate. The pressure drop across the orifice plate was continuously monitored in order to record the flow rate through the wall cavities at all times. Air was only allowed to enter the cavity through the unsealed bottom edge of the drywall which was gapped with a 1/32-inch shim and only allowed to exit through the tube at the top of each stud bay. Any other potential entry or exit points for air were sealed. A hole simulating a wire chase was drilled through the two interior studs to alleviate any pressure difference across the three bays. The fourth scenario (Hut 1-Wall 4A) was created similar to the controlled leakage with an air gap at bottom of the drywall and fully air sealed on the other three sides. It was not controlled mechanically.

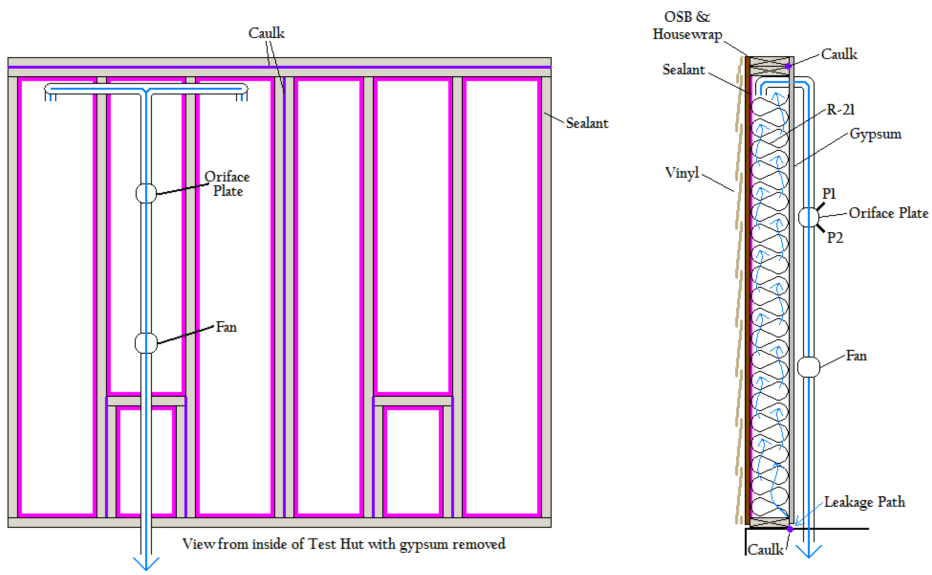

Figure 4. Controlled Air Leakage Diagram

The air flow rates were calibrated to two target house tightness levels – 3 ACH50 and 5 ACH50 for a 2,000 ft^2 house. The resulting air flow rates were 1 cfm or 2 cfm per 4' by 9' specimen framed with a 2x6 cavity. The total volume of exhausted air was 6 cfm (less than 1 percent of the hut volume). The intentional air flow rates remained the same as originally calibrated during the 20-month monitoring period.

3. Exterior Insulation

Four different types of continuous insulation were compared. The thickness of the insulation was selected to ensure that the R-Value was 5, so that the biggest difference between the insulating properties of these four walls was the permeance of the insulation and the location or existence of an additional WRB. The perm values for the different insulation type can be seen in Table 2.

Table 2. Exterior Insulation Perm Ratings

Material	Perms	Additional WRB Locations
EPS	~ 2.8	Exterior of OSB
RockWool	~ 30	Exterior of OSB
PolyISO	~ 0.03	Tape Seams
XPS	~ 1.0	Tape Seams

4. Impact of Kraft Facing on Batt Insulation

In the previous study, walls that had kraft-faced batt insulations performed better than walls insulated with unfaced batts in regard to OSB MC. The combination of unfaced batts and high indoor relative humidity in the last phase led to wall moisture problems. Walls with similar construction but with kraft-faced batts did not experience these moisture problems.

For this study the relative humidity in the test huts was kept at a lower level than the previous study. The walls that contained unfaced batts in the last study are considered moisture damaged and only have a minimal number of sensors installed. The walls that were previously insulated with kraft-faced batts had unfaced batts installed in this study. The moisture performance of walls with kraft-faced batt insulations was compared to the moisture performance of the walls with unfaced batts at a lower relative humidity level.

FIELD TEST PROCEDURE

Field testing continued for a total of 20 months. This duration covered two winters and all four seasons of weather exposure and a reasonable duration to monitor accumulation and drying moisture cycles of all walls on the two test huts. The indoor conditions of the test huts, both temperature and relative humidity, were controlled. The indoor relative humidity (RH) followed the European standard DIN EN 15026 normal occupancy protocol, which is lower than the indoor RH for the previous study (ANSI/ASHRAE Standard 160-2009, Home Innovation Research Labs 2013 and Glass, et al. 2015) that followed a higher moisture load curve as shown in Figure 5. The test huts were instrumented to measure MC of the OSB sheathing and wood framing, relative humidity, and temperature in each bay.

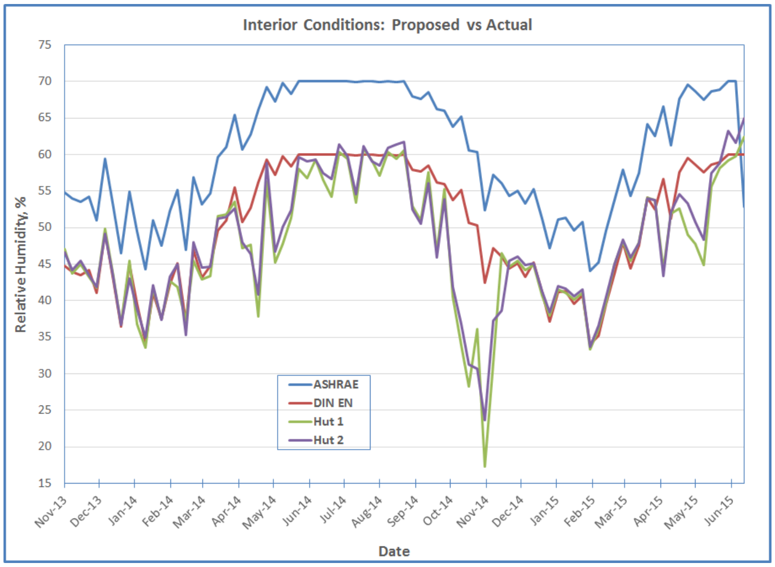

Figure 5. Test Hut Indoor Relative Humidity

1. Test Wall Instrumentation

Each field wall sensor, as shown in Figure 6, includes two stainless steel screws that secure the device to either wood framing or sheathing and penetrate ⅜-inch into the substrate to obtain a conductance reading related to substrate MC. The sensors are capable of measuring MC between 7 and 40 percent, temperature between -40°F and 185°F, and relative humidity from 0 to 100 percent at programmable time intervals. Sensors were gravimetrically calibrated to the SPF studs and OSB sheathing.

Figure 6. Wireless Temperature, Humidity and Wood Moisture Sensor

Approximately 19 sensors (shown in Figure 7) were installed in each 4'x9' test wall panel. Data was transmitted wirelessly from the sensors to a local gateway which transmitted the data to the internet. Measurements were conducted on sufficiently short intervals (30 minutes) to allow the correlation between the MC in the wall, weather conditions monitored externally, and interior conditions. Standing fans were operating inside the hut to minimize temperature stratification.

2. Data Acquisition System

In addition to the net-connected wireless sensors installed in the walls, a separate data acquisition/controller system (as shown in Figure 8) was installed in each test hut. The datalogger was programmed to take readings from indoor temperature and humidity and outdoor weather conditions every five seconds. This data was averaged or summed, as appropriate, every 30 minutes and recorded. The datalogger also had control capabilities, and was used to control indoor conditions.

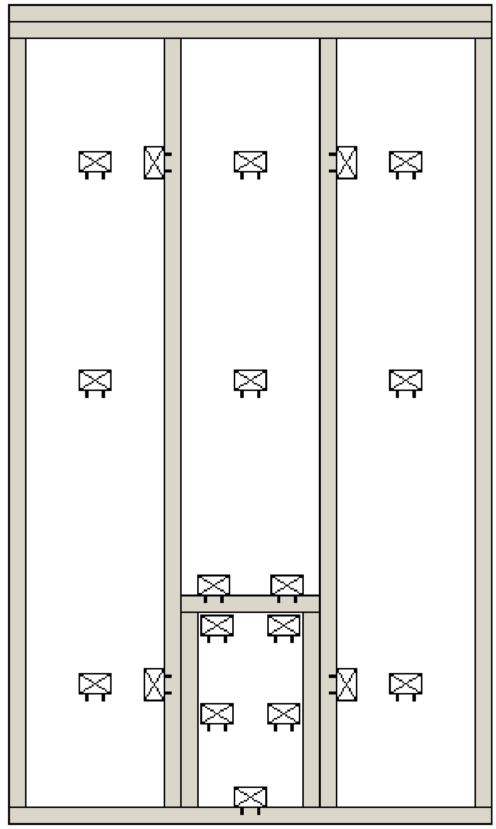

Figure 7. Typical Sensor Locations for the Test Wall

3. Indoor Temperature and Humidity Measurements

Six type-T thermocouples and two temperature and humidity probes measured the temperature and relative humidity in the test hut. The temperature and humidity probes contained capacitance-type humidity sensors, accurate within 2 percent from 0 to 98 percent relative humidity, and thermistor-type temperature sensors, accurate within 1°F over the range of 14°F to 140°F.

4. Weather Station

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.

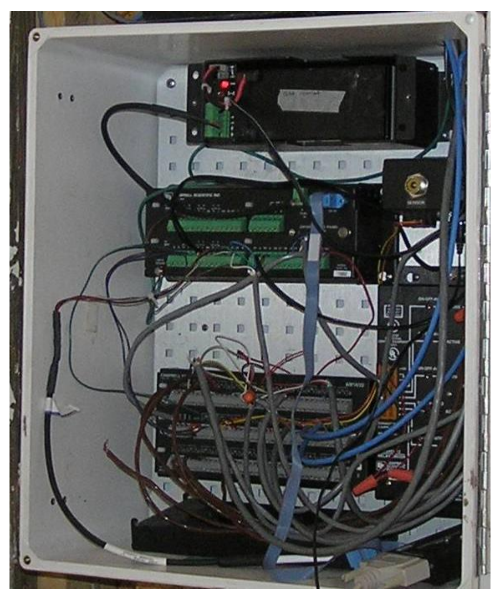

Figure 8. Data Acquisition System

5. Water Injection

Plastic tubes were installed into walls 1A and 1B in Hut 1 and walls 2A, 2B, 3A, and 3B in Hut 2 during construction to facilitate the ability to inject bulk water to a certain layer in the wall simulating a leaking window. By injecting bulk water in the cavities of the walls to be tested, the ability of each wall section to cope with bulk moisture could be determined. For this study an updated approach was adopted, as the previous water injections typically showed that the majority of the water injected tended to run off the exterior face of the OSB or the WRB rather than being absorbed, effectively eliminating the point of the injections. The new walls still had water injected, however the locations and techniques were different.

For the injections on the exterior of the OSB, a pocket made of Tyvek was sealed to the exterior face of the OSB with caulk and was filled with cotton. The cotton was used to help hold the water in the injection location and expose the OSB to moisture for a greater period of time facilitating its absorption. The top of the Tyvek pocket remained unsealed so the water was able to evaporate if not absorbed by the wall. The other injection location was on the interior face of the OSB at the intersection of the window sill plate and OSB. A notch was cut in the OSB at the injection location approximately half the thickness of the OSB. It is believed that the OSB was able to absorb more water if the surface finish was disturbed. Cotton was inserted into the slit to facilitate water absorption. A bead of caulk was installed on top of the window sill plate around the slit to ensure the water was not able to flow in any direction on the window sill plate away from the slit. A diagram of these designs can be seen in Figure 9 while Figure 10 shows the tubes.

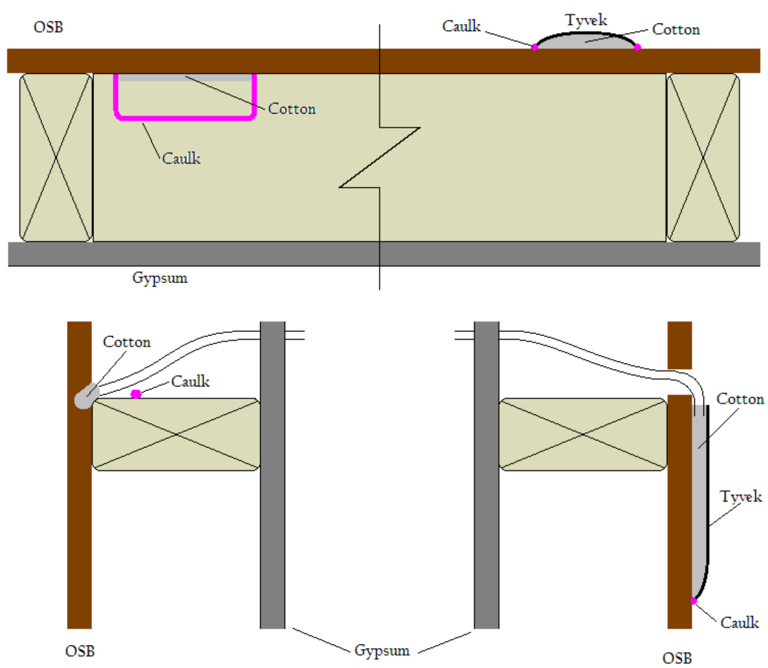

Figure 9. Setup of Wall Water Injection

Figure 10. Water Injection Tubes in Test Walls

RESULTS AND DATA ANALYSIS

The field test data was gathered over a 20-month period from November 1, 2013, through the end of June 2015. The field test data for both test huts were analyzed for moisture performance of test walls. Comparison analyses of specific walls were also conducted for the focused research area.

Weather Conditions

The 2014 winter was the coldest during the test period as it had the most heating days compared to other years and the normal winter average for the area (approximately 7 percent higher). The summer had 1,070 Cooling Degree Days (CDD), which was considerably lower than the historical average (ASHRAE 2009) with 42 inches total rainfall recorded (as shown in Table 3).

Table 3. Weather Data

	Average Outdoor Temp	Average Outdoor RH	Heating Degree Days	Colling Degree Days	Rainfall
Dec 2013	40.7	75	754	0	16.2
Jan 2014	29.5	67	1101	0	2.4
Feb	34.5	67	854	0	3.5
Mar	40.1	64	773	0	9.9
Apr	54.3	65	333	11	6.1
May	65.9	72	62	90	4.4
Jun	73.6	77	1	259	1.7
Jul	75.5	77	0	325	3.6
Aug	72.6	83	0	234	4.9
Sep	68.4	84	31	133	1.1
Oct	59.2	78	197	16	2.3
Nov	44.8	65	607	1	2.8
Dec	40.7	77	753	0	3.1
Jan 2015	32.0	71	1022	0	4.7
Feb	26.9	62	1066	0	12.7
Mar	41.4	66	733	0	3.8
Apr	56.3	63	266	6	3.4
May	69.1	73	48	174	2.7
Jun	74.0	83	19	288	8.0
2015 Yearly Total (to date)			3154	468	35
2014 Yearly Total			4713	1070	46
2013 Yearly Total			3978	1203	52
Andrews AFB Avg.			4421	1241	42

Figure 11 and Figure 12 show the indoor and outdoor field test conditions for the two test huts between November 2013 and June 2015.

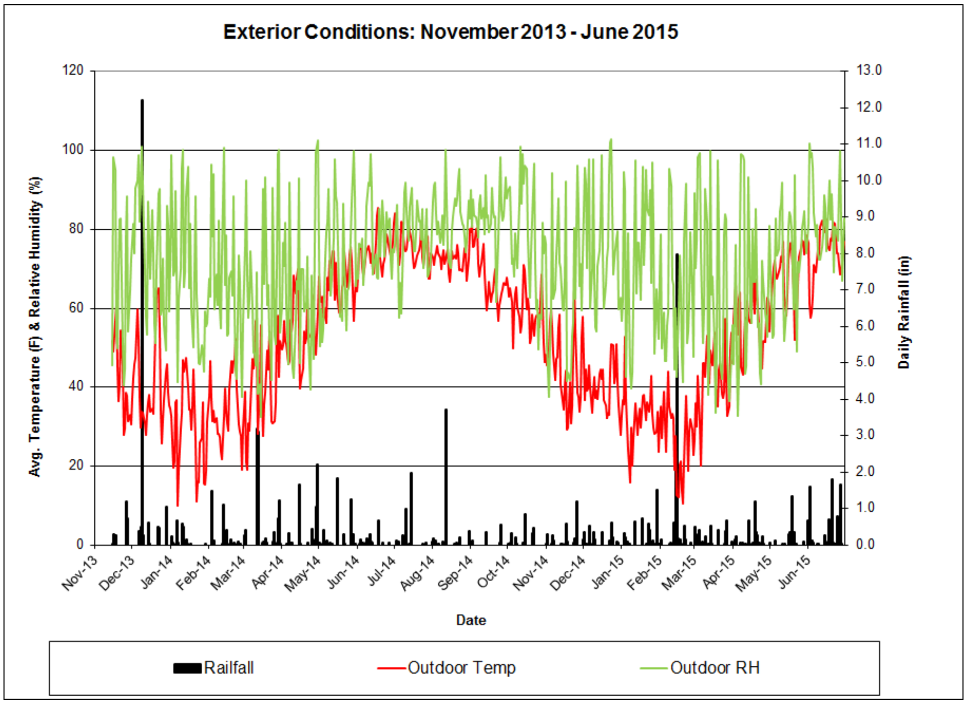

Figure 11. Measured Outdoor Conditions

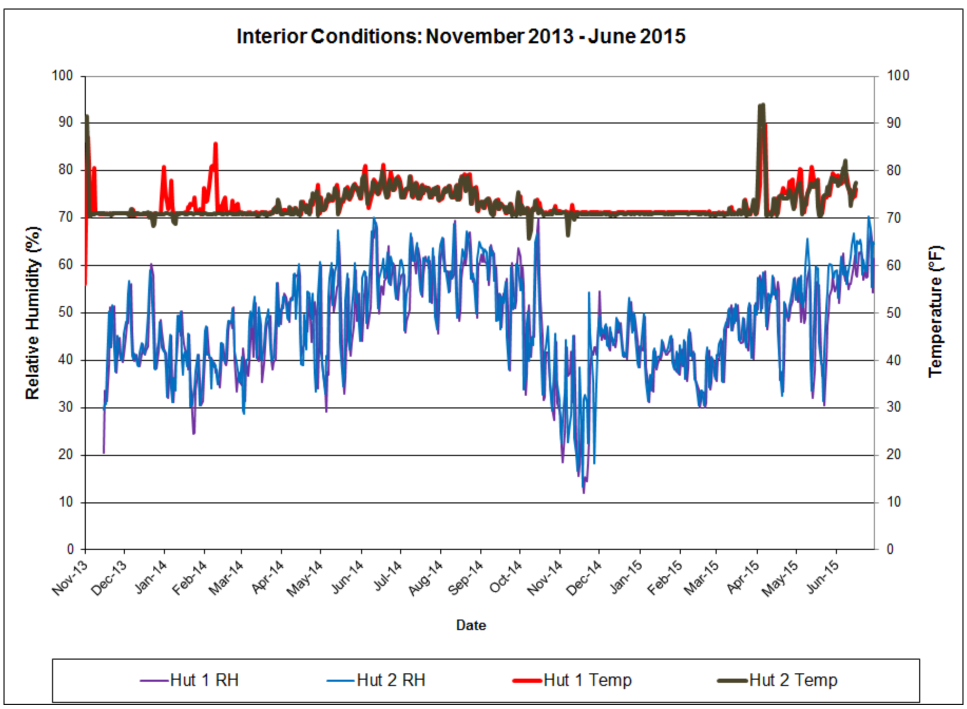

Figure 12. Measured Indoor Conditions

Incident Solar Radiation

Figure 13 depicts solar radiation data measured on a horizontal surface and in the plane of the north- and south-facing walls. The figure shows that the radiation on the south-facing surface was at a maximum in the summer. The figure also indicates the north-facing walls received only a fraction of the radiation received by the south-facing walls; the north-facing walls appeared to receive only diffuse radiation and little or no direct radiation. This information is useful when trying to understand the solar intensity on the north and south walls throughout the year. Figure 13 also shows similar solar exposure for both structures.

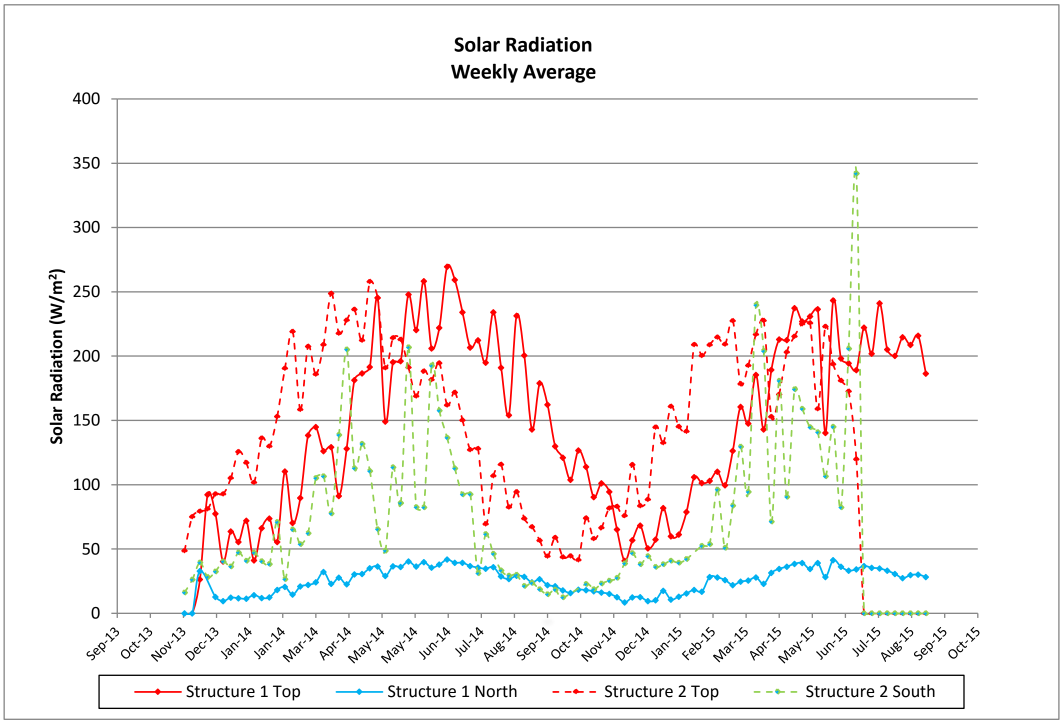

Figure 13. Measured Solar Radiation

Moisture Content of OSB Sheathing for All Walls

All Northern Exposure Walls

Throughout the 20-month test period, sheathing for all north-facing walls on both Hut 1 and Hut 2 remained below 25 percent MC, as shown in Figure 14. The following are general observations for all walls:

- A positive vapor pressure difference indicates that the net vapor pressure drive is from the inside of the building outward. The actual MC measurements followed the vapor drive reasonably closely with a time lag in year 2 (2014 – 2015) which also had higher drive than year 1.

- The sheathing of the following walls showed higher than 20 percent MC: stucco; manufactured stone; fiber cement; and brick, all with unfaced batts.

- The walls that had high MC between 18 and 25 percent in winter dried out quickly during summer to below 16 percent every year.

- Two walls showed increasing peak MC values in year 2, which are higher than 20 percent. These two walls are: 2x6 vinyl wall with 2 cfm air leakage (Hut 1 - wall 4B); and 2x4 vinyl wall with PIC exterior insulation.

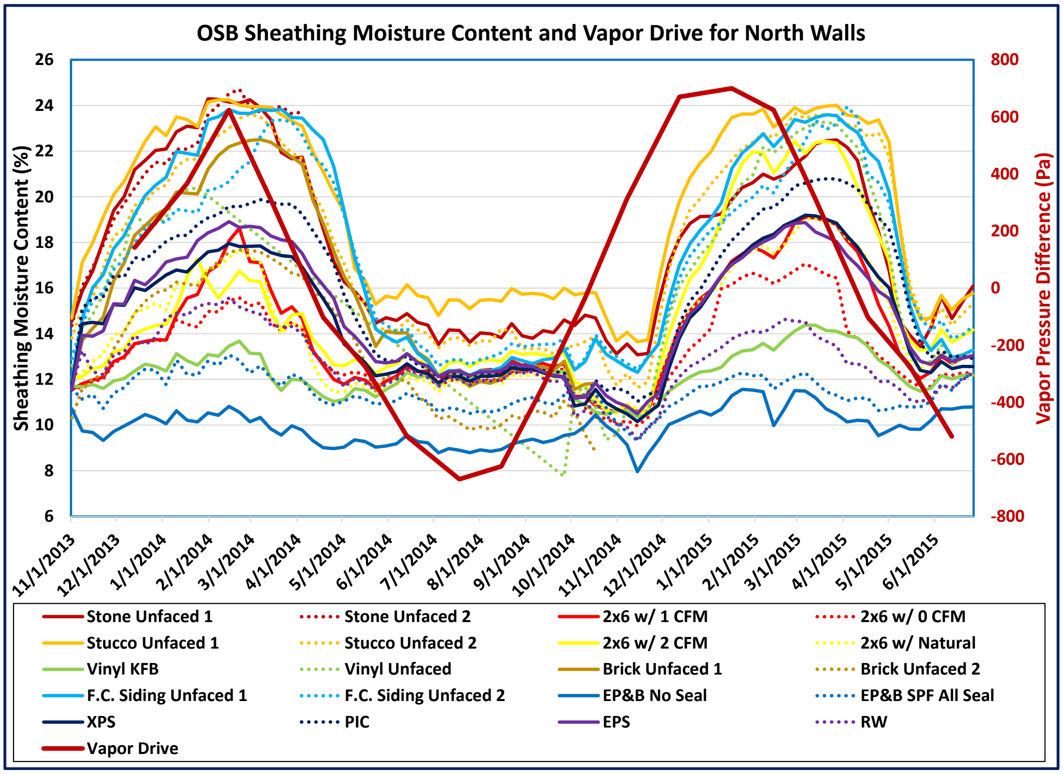

Figure 14. North Wall Sheathing Moisture Content and Vapor Drive

All Southern Exposure Walls

Throughout the same monitoring period, sheathing for all south-facing walls on both Hut 1 and Hut 2 remained below 24 percent MC, as shown in Figure 15. The following are general observations for all south walls:

- Same patterns of vapor drive, MC measurements, and the relationship between them as north-facing walls.

- Sheathing MC levels for the majority of walls are much lower than their north-facing counterparts. This is due to the higher level of solar vapor drive for the southern orientation compared to the northern orientation.

- The sheathing of two walls showed higher than 20 percent MC – the two stucco walls with unfaced batts (Hut 1 - walls 3A and 3B), one of which had a malfunctioning MC sensor in the second winter. These two walls dried out quickly during summer.

- Several walls showed increasing peak MC values in year 2, which were still lower than 20 percent. This might have been caused by the more severe winter between 2014-2015.

- The sheathing of the manufactured stone walls had a significant relative difference between the winter peak on the north and south walls. They peaked at 24 percent MC on the north walls, but 17 percent on the south walls. This is attributed to the darker wall color, which made the surface absorb more solar radiation and heat on the south wall surface than the north wall surface. This consequently increased driving out of the moisture in the wall.

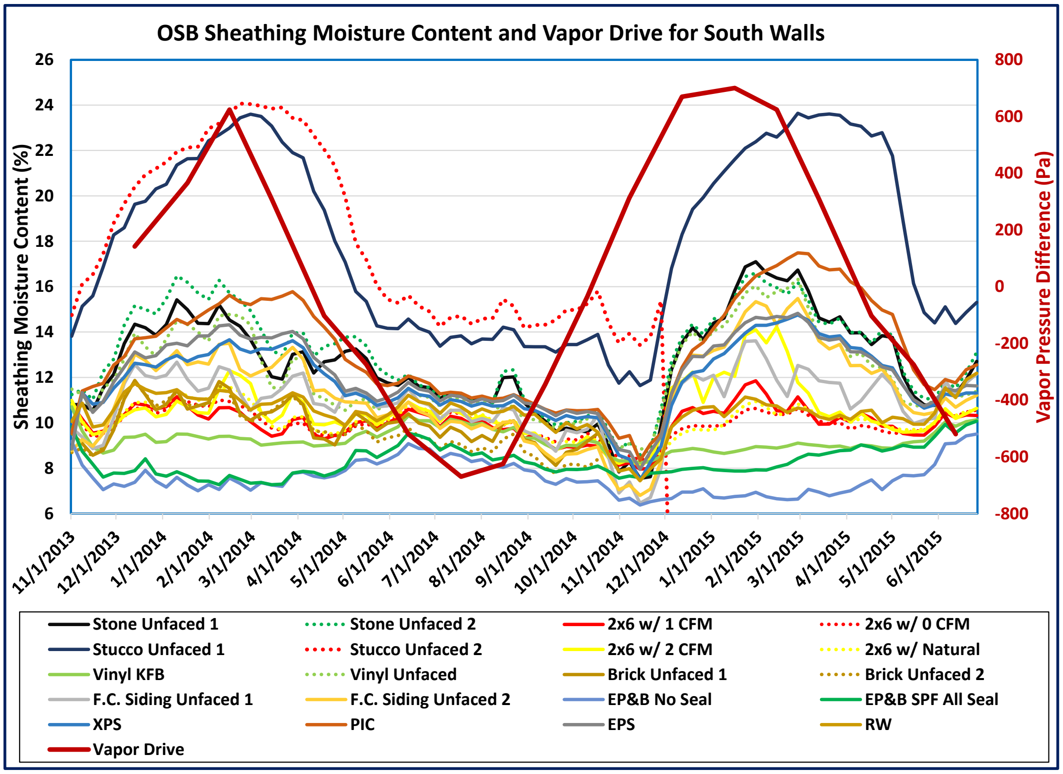

Figure 15. South Wall Sheathing Moisture Content and Vapor Drive

Comparison of Sheathing Moisture Content for Walls of Focused Study

Four specific focused studies were described in the “Research Focus” section of this report. The following provides a comparison of the walls under each focused study to investigate impacts of different systems and techniques on the wall moisture performance. Due to a loss of the majority of sensors in Hut 1 test wall panels 1A and 1B, the performance of fiber cement walls (Hut 2 – walls 4A and 4B) are used for baseline comparisons.

1. OSB Moisture Content for Extended Plate and Beam (EP&B) Walls

The advanced wall systems, EP&B with unfaced batts, had two variations tested – one with foam air sealing, the other without any air sealing. The air sealing was achieved by spray foam sealant between the 2x4 wood members and the exterior foam sheathing. Comparing with the baseline wall installed on the same hut (Hut 2), the north-facing EP&B walls showed superior moisture performance (as shown in Figure 16) including the following observations:

- The baseline fiber cement wall with unfaced batts showed winter peak MC of OSB sheathing close to 24 percent for two consecutive years. All the sheathing and stud MC measurements for both EP&B walls never exceeded 14 percent during the entire monitoring period.
- The difference of sheathing MC between the sealed and unsealed EP&B walls are approximately 2 to 3 percent indicating that the air sealing does not improve moisture performance of the EP&B walls. By design, these walls have excellent moisture performance due to the continuous foam board insulation on the interior side between the OSB and the studs.
- In the EP&B walls with unfaced batts, the studs performed well. The studs in the EP&B wall with air sealing had the best moisture performance as shown by the dark green line in Figure 16.

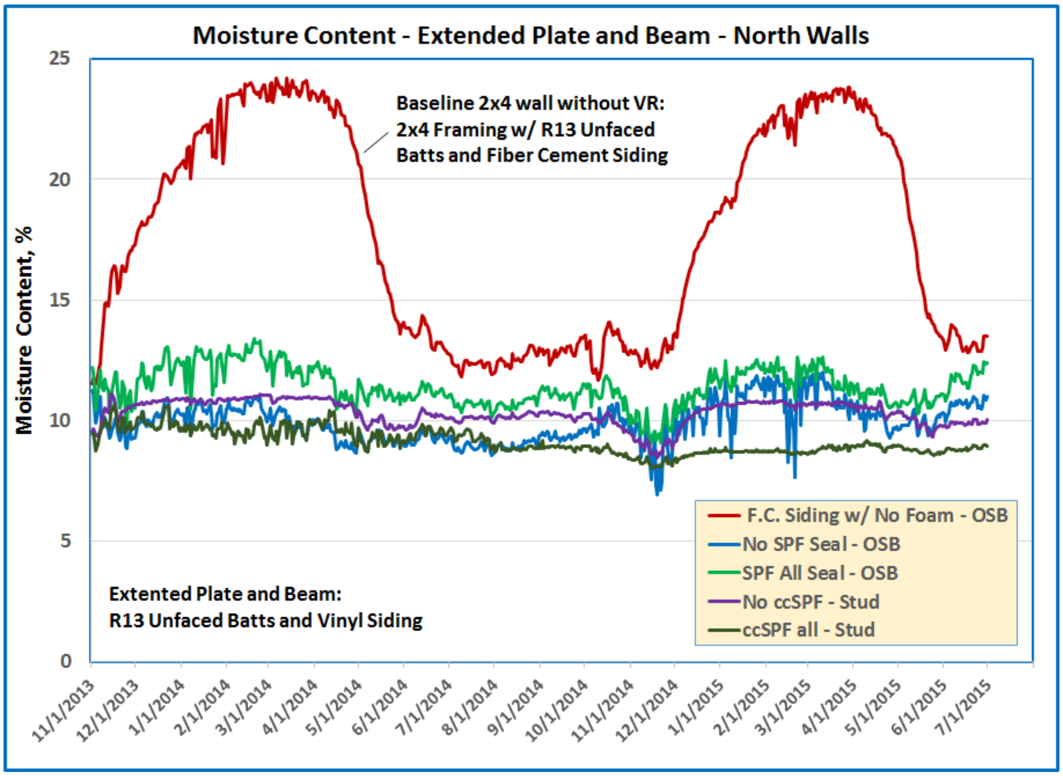

Figure 16. North Facing EP&B Wall Sheathing and Stud Moisture Content

2. OSB Moisture Content for Air Leakage Versus Vapor Diffusion Walls

There were four 2x6 walls installed in Hut 1 for different air sealing configurations – no air seal; fully air sealed; controlled air leakage of 1 cfm; and controlled air leakage of 2 cfm. The moisture performance for these walls showed significant insight to the importance of air sealing of wood-framed walls with vinyl siding, kraft-faced batt insulation, and drywall with one coat of primer and two coats of latex paint. The following are the observations from the field monitoring data shown in Figure 17 for the north-facing walls:

- The best performing wall was the 2x6 wall that was fully air sealed. Its peak sheathing MC measurements were 16 and 17 percent for year 1 and year 2, respectively. It dried out during the summer quickly to below 13 percent.

- The leakiest wall, the wall with 2 cfm controlled air leakage, demonstrated the highest winter peak MC in sheathing – 18 percent for year 1 and increased to 22 percent in year 2. The increasing winter peak sheathing MC for 2-3 months in year 2 is a performance concern even though it can dry out quickly during the summer.

- The 1 cfm and unsealed walls performed very closely to each other and between the fully sealed wall and the leakiest wall. The winter peak sheathing MC values were 19 percent.

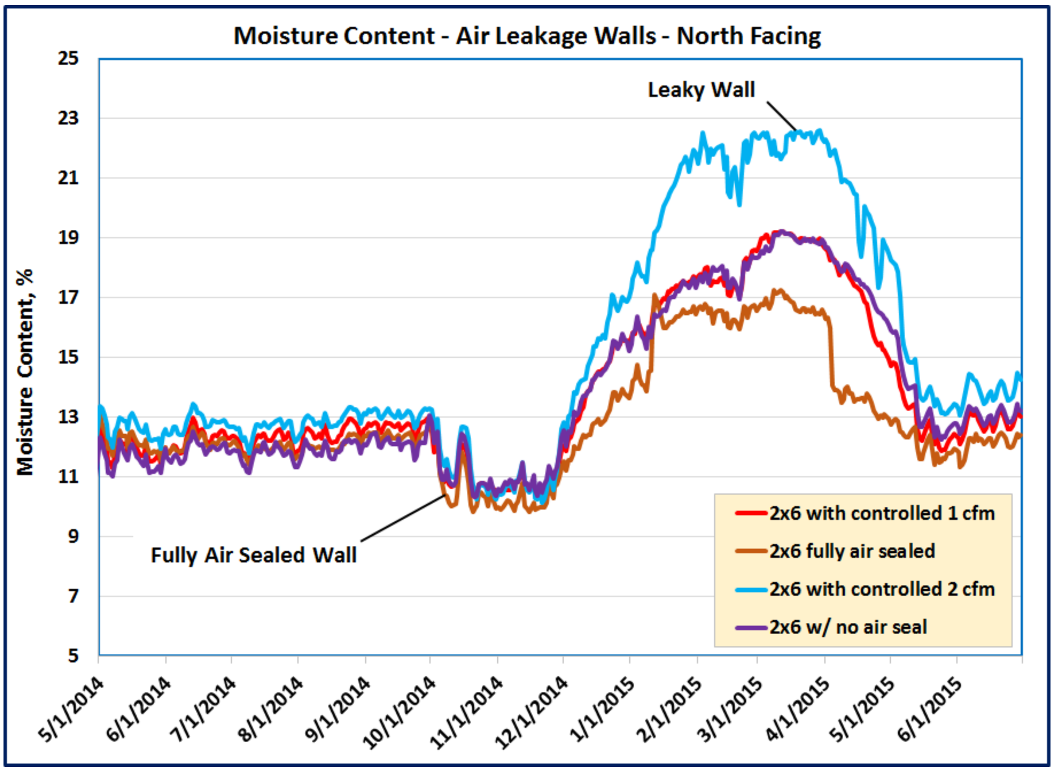

Figure 17. North-Facing Sheathing Moisture Content for Walls with and without Air Leakage

3. OSB Moisture Content for Walls with Exterior Insulation

Four 2x4 vinyl sided walls with unfaced R13 fiberglass batts were installed with different exterior continuous insulation materials: EPS (expanded polystyrene); mineral wool (rockwool); polyisocyanurate (PIC); and XPS (extruded polystyrene). These four walls were compared with a 2x4 fiber cement-sided wall with no unfaced R13 and exterior insulation and the results are shown in Figure 18. The following are observations for the moisture performance of the north-facing walls:

- All four walls with exterior insulation performed better than the wall with no exterior insulation, which had winter peak sheathing MC measurements close to 24 percent.

- Among the four walls with exterior insulation, the mineral wool wall performed the best. Its peak winter sheathing MC value was 16 percent for the year 1 and decreased to below 15 percent for the more severe winter in year 2.

- The wall with PIC insulation had the highest winter peak MC in sheathing – 20 percent in year 1 and increased to 21 percent in year 2. This was caused by the low vapor permeance (as shown in Table 3) of the PIC material, which reduced the drying capacity of the wall during winter when the indoor moisture was driven to and accumulated on the sheathing surface.

- The XPS and EPS walls performed very similarly. The peak winter sheathing values were between 18 and 19 percent.

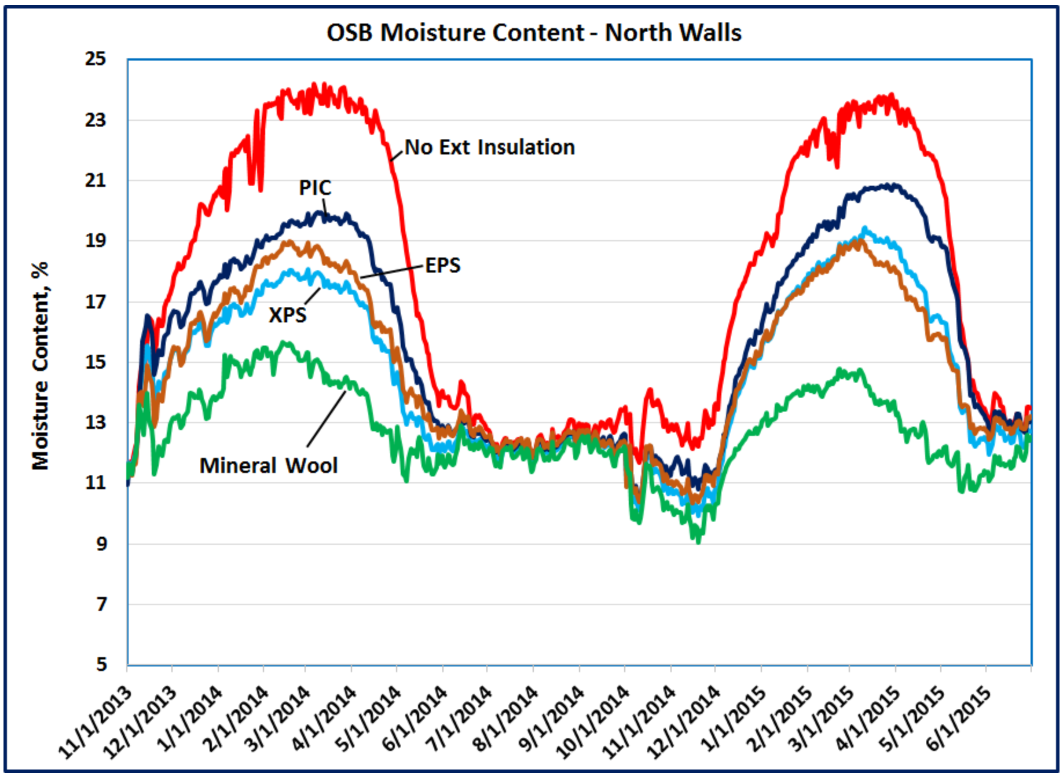

Figure 18. Sheathing Moisture Content for North-Facing Walls with Exterior Insulations

4. OSB Moisture Content for Walls with Kraft-Faced Batt Insulations with Lower Indoor Relative Humidity

The kraft facing on the insulation used in the wall cavity had significant impact on moisture performance as Figure 19 shows:

- The 2x4 vinyl wall with unfaced batt insulation performed the worst. Its peak winter sheathing MC went up to 24 percent approaching the wood fiber saturation limit of 25 percent.

- The 2x4 vinyl wall with kraft-faced batt insulation performed the best with sheathing MC never exceeding 15 percent, while the 2x6 vinyl wall with kraft-faced batts performed in between.

- All walls were able to dry out during the summer. The kraft facing on the batt insulation provided vapor resistance during the winter to prevent significant indoor moisture from transporting into the wall while allowing moisture flowing through during the summer into the conditioned space.

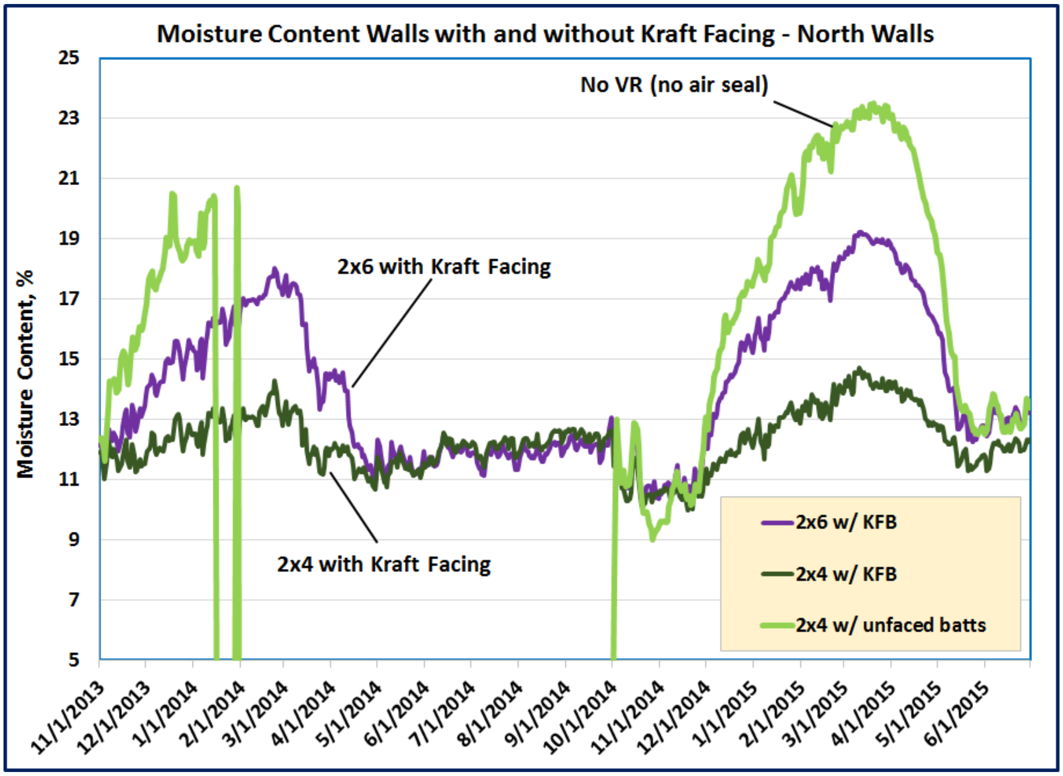

Figure 19. Sheathing Moisture Content for Walls with and without Kraft Facing with Lower Indoor Relative Humidity

Wall Cavity Temperature

The following observations were made based on the field temperature data for all walls:

- As expected, due to solar gains, wall cavity temperatures in south-facing walls were consistently warmer than in north-facing walls. The south-facing walls with stone and brick claddings had the highest year-round temperatures with the exception of the insulated siding in the winter months, as shown in Figure 20 and Figure 21.

- The 2x6 walls with kraft-faced batt insulation and air sealing had the highest cavity temperature in the summer and lowest in the winter, as shown in Figure 22 and Figure 23.

- In the cavity temperature charts for both northern and southern exposure walls, Figure 24 and Figure 25, the 2x4 walls with no exterior insulation showed lower winter values than those 2x4 walls with exterior insulation. The thermal resistance of the exterior insulation causes the wall cavity to remain warmer in the winter.

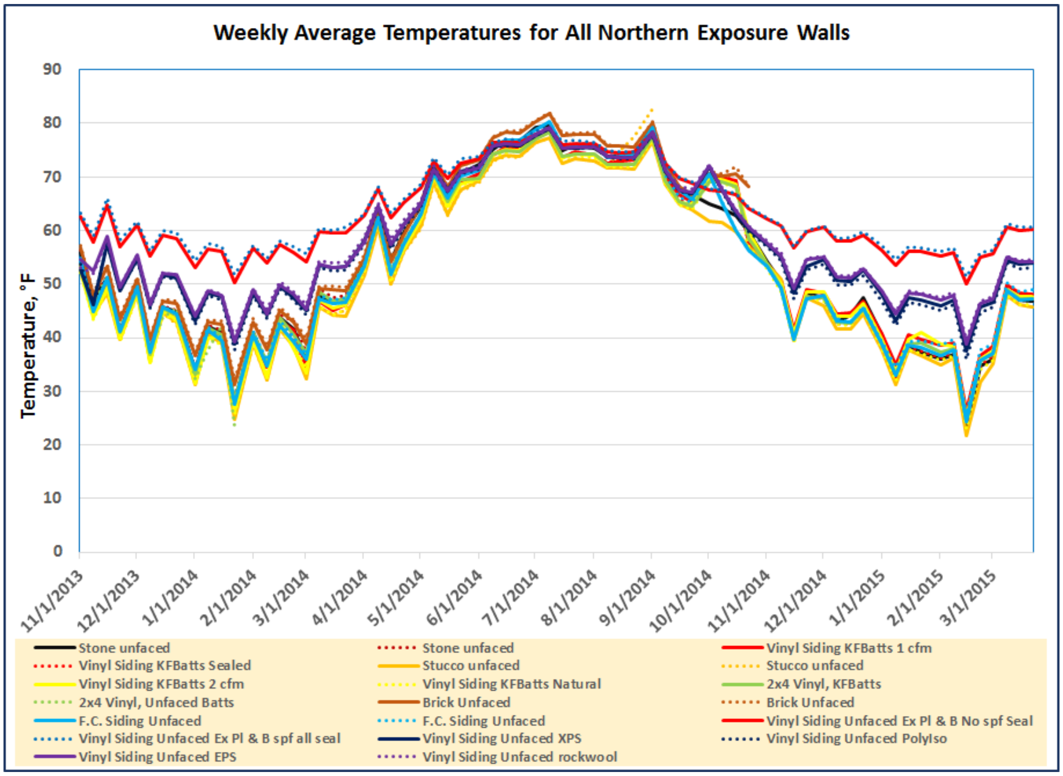

Figure 20. Weekly Average Temperature for All Northern Exposure Walls

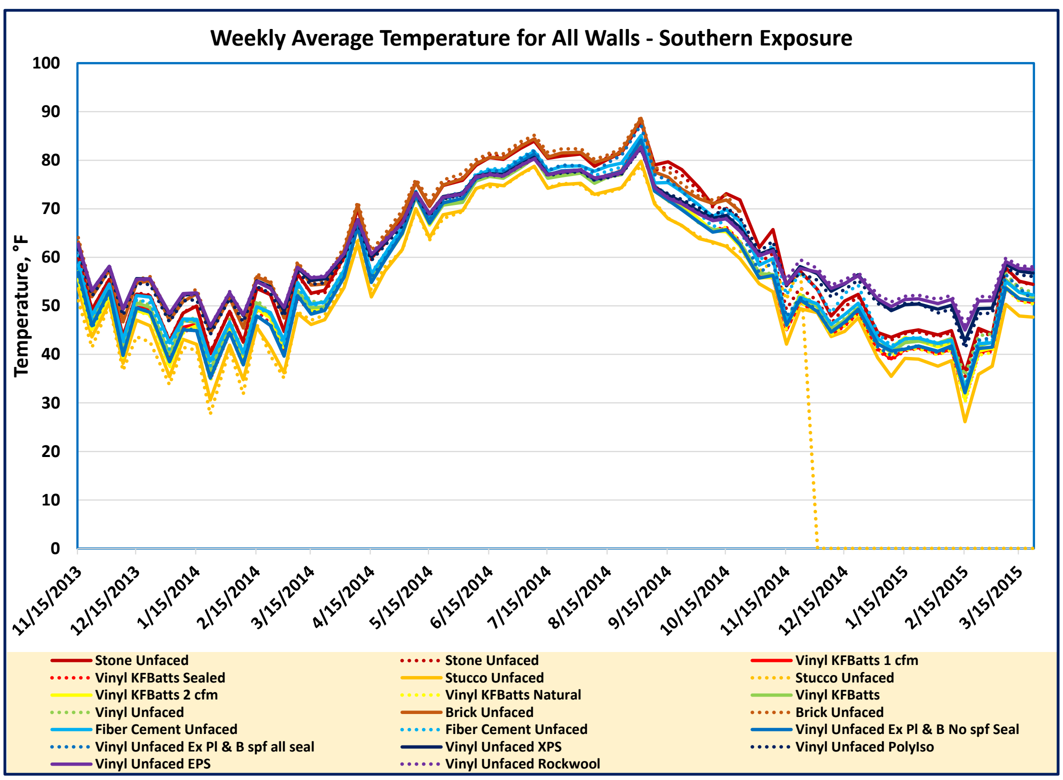

Figure 21. Weekly Average Temperature for All Southern Exposure Walls

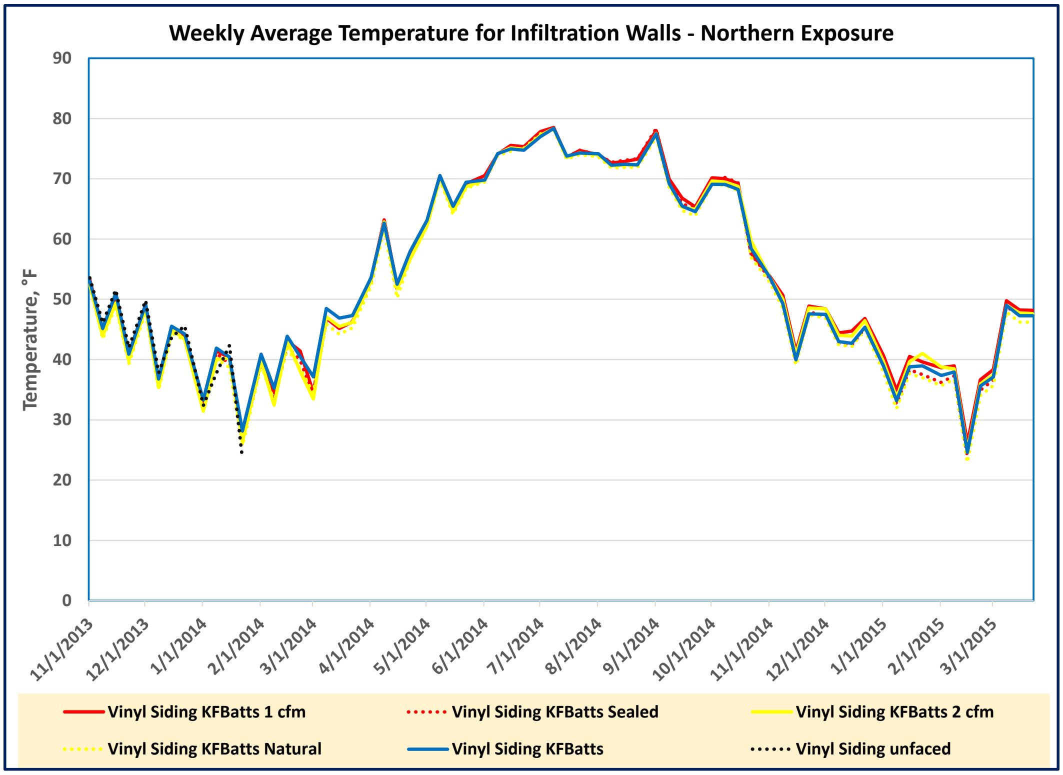

Figure 22. Weekly Average Temperature for Northern Exposure Walls with Air Leakage

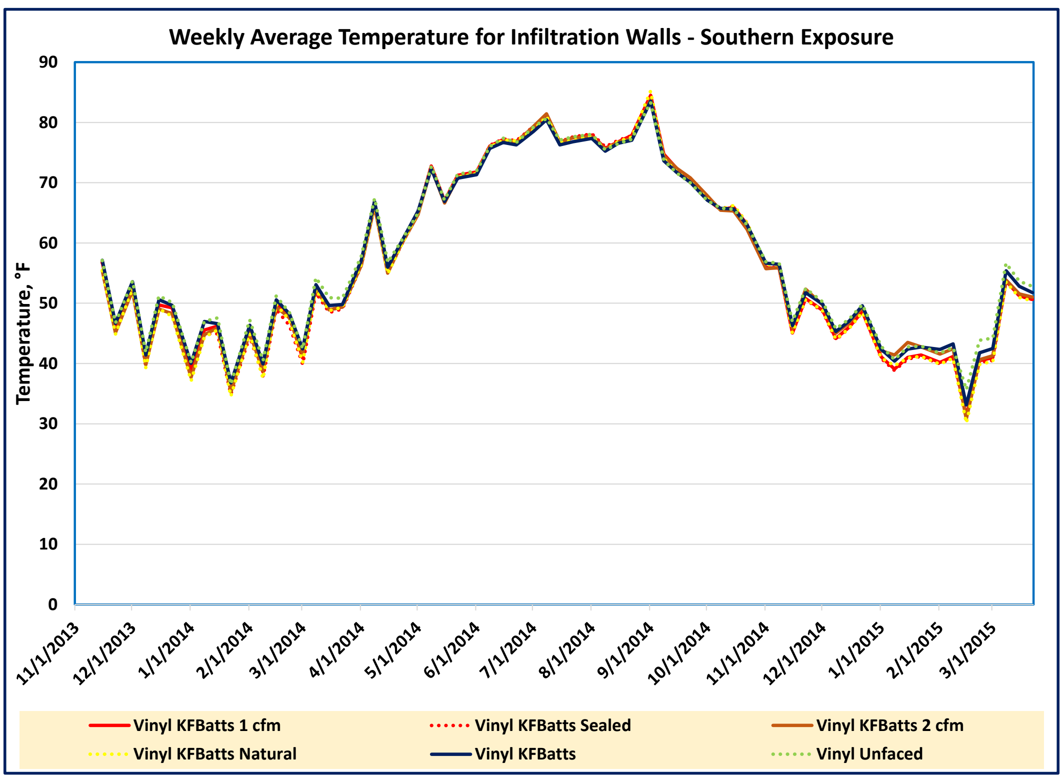

Figure 23. Weekly Average Temperature for Southern Exposure Walls with Air Leakage

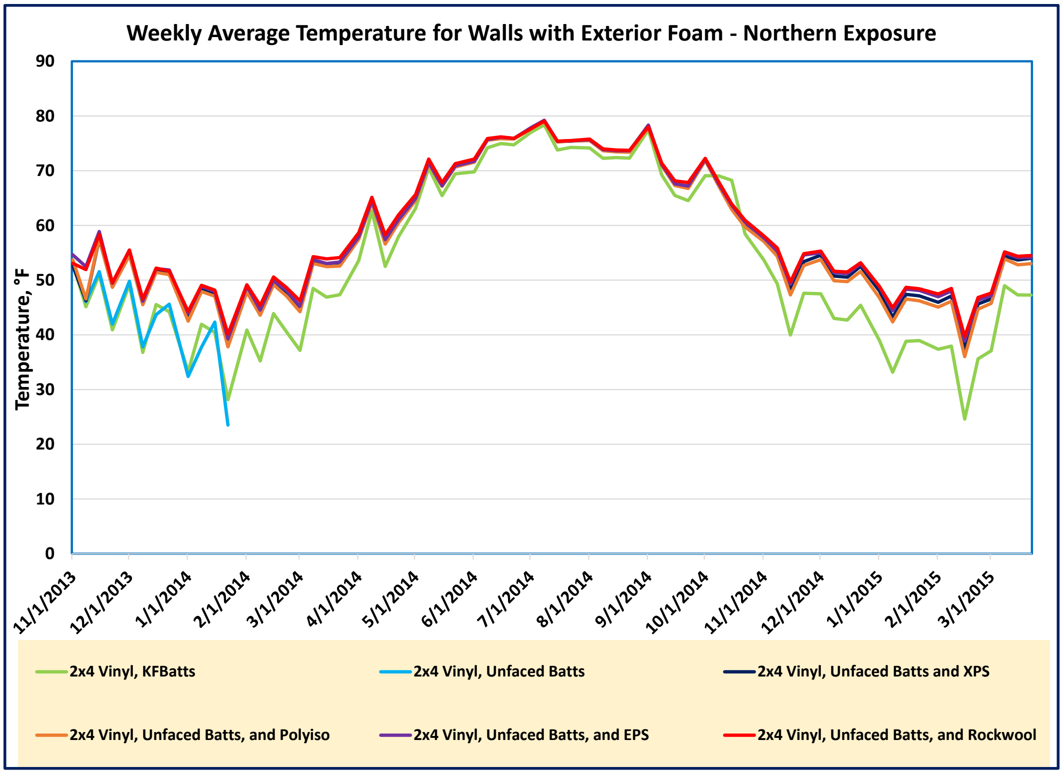

Figure 24. Weekly Average Temperature for Northern Exposure Walls with Exterior Insulations

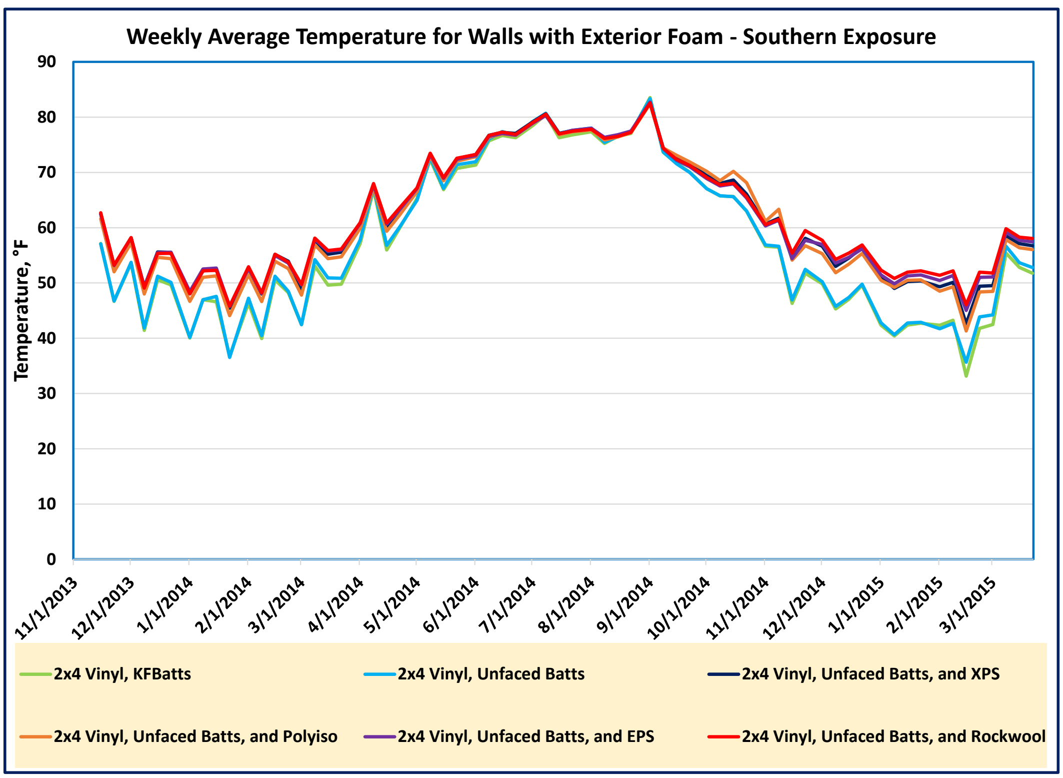

Figure 25. Weekly Average Temperature for Southern Exposure Walls with Exterior Insulations

Bulk Moisture Injections

Seasonal injections were performed in February, May, and August for six pairs of wall assemblies: 2x4 wall with vinyl siding and unfaced batts; 2x4 wall with vinyl siding and kraft-faced batts; and the four 2x4 vinyl siding walls insulated with cavity unfaced batts and exterior insulation. These four walls have EPS, XPS, PIC, and mineral wool (rockwool) exterior insulations. The water injection events raised the window sill MC instantly for all six walls, as shown in Figure 26 and Figure 27. There were periods of malfunctioning of a couple sill MC sensors for the north-facing 2x4 wall with vinyl siding and unfaced batts (yellow curve), and the north-facing 2x4 wall with rockwool exterior insulation (purple curve). Also during those periods not all sensors responded to water injections and some sensors showed no increase in MC, such as those in the south-facing XPS wall.

The following observations can be made for the window sill MC based on the field data shown in Figure 26 and Figure 27:

- For both north- and south-facing walls, the winter water injection events raised the window sill MC slightly over 30 percent. All south walls that experienced bulky water penetration in winter took less time (less than a month) than the north-facing walls to dry out below 20 percent.
- Among all north-facing walls with exterior insulation, the ones with PIC and XPS exterior insulations took the longest amount of time in the winter to dry out to below 15percent, as Figure 25 shows. This is caused by the low water vapor permeance value of the PIC material.
- At other times, the water injections raised window sill MC for all walls between 25 and 30 percent. Due to higher temperature and vapor drive, the walls were able to dry out to below 20 percent much more quickly compared to in the winter.

Figure 28 and Figure 29 show the differential MC for the OSB sheathing at injection locations and the average OSB sheathing MC for the whole wall. After each water injection, the MC for the OSB sheathing of the window sill area where the injection occurred increased substantially compared to the whole wall OSB average MC. The following observations are made based on the field data shown in Figure 28 and Figure 29:

- For north-facing walls, the winter injections can bring the MC of window sill OSB up to 13 percent higher than that of the average wall OSB. The injections at other times raised the MC of the window sill OSB by 6 to7 percent. For the south-facing walls, the increase was up to 19 percent in the winter, and 10-15 percent at other times.
- The OSB at the window sill area for the PIC wall took the longest time to dry out the additional moisture. Also note that the sensor for the PIC wall on the OSB near the window sill did not function well during the first winter of the test period. The OSB MC sensor at the window sill location for the 2x4 wall with vinyl siding and kraft-faced batts did not function correctly either.

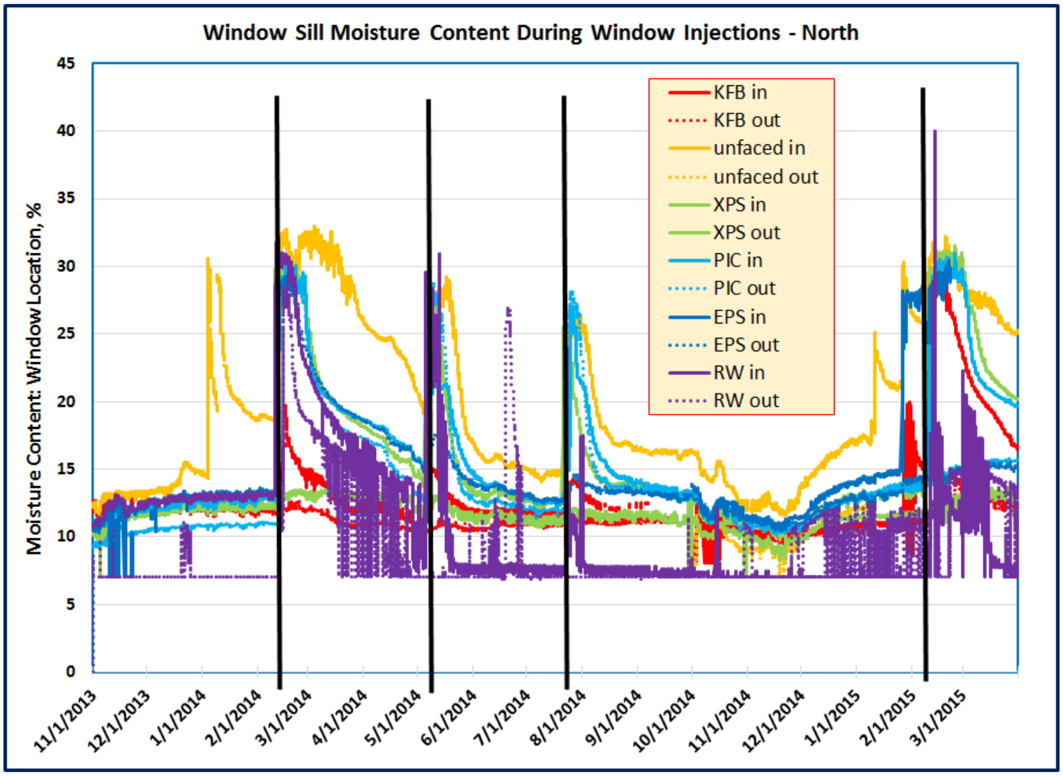

Figure 26. Daily Average Window Sill Moisture Content for Northern Exposure Walls with Water Injection

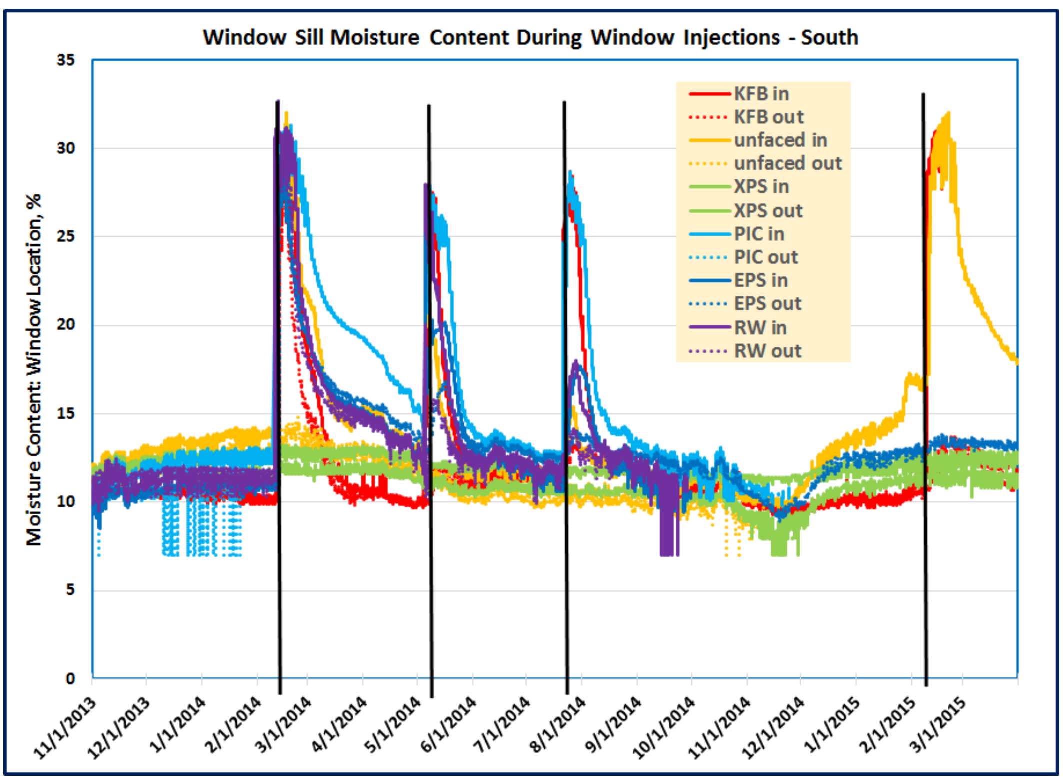

Figure 27. Daily Average Window Sill Moisture Content for Southern Exposure Walls with Water Injection

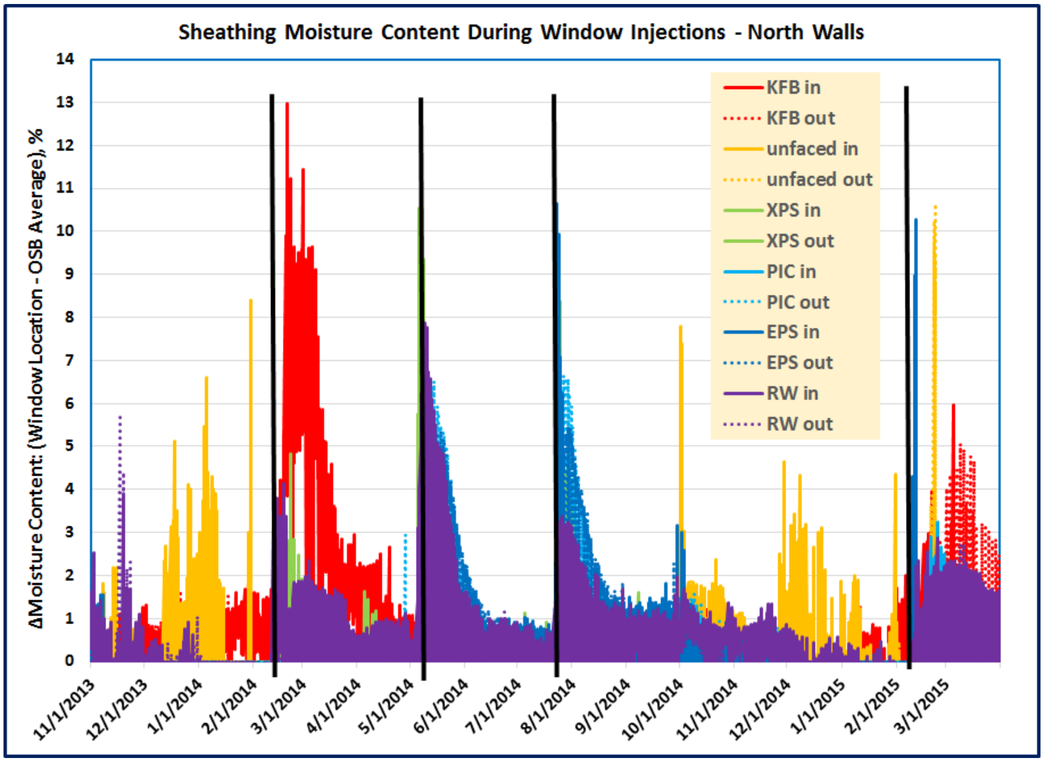

Figure 28. Daily Average Sheathing Moisture Content Differential for Northern Exposure Walls with Water Injection

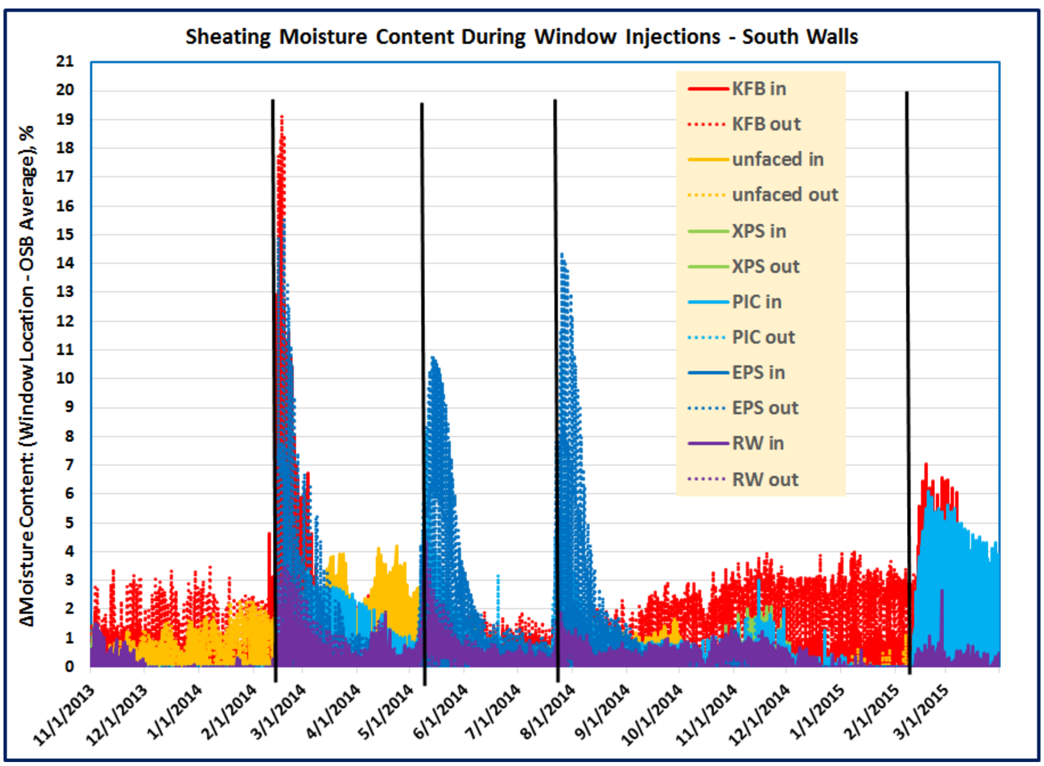

Figure 29. Daily Average Sheathing Moisture Content Differential for Southern Exposure Walls with Water Injection

CONCLUSIONS

Overall, during the 20-month monitoring period from November 2013 to June 2015, many test wall panels performed satisfactorily by maintaining wood sheathing MC levels below a generally acceptable level of 20 percent. However, the walls with stucco, brick, manufactured stone, and fiber cement siding showed MC increases in the sheathing to between 20 and 24 percent for at least one month in the winter. This might be caused by the lack of an interior vapor resistance layer when the unfaced batt insulation was used without extra vapor retarder. Further investigation is needed when the walls are torn down to check for mold growth.

Both EP&B walls with and without air sealing by spray foam sealant used between the 2x4 wood members and foam sheathing never exceeded 14 percent MC in the exterior sheathing and studs for the whole field monitoring period; however, 2x4 wood-framed wall with unfaced batt insulation and fiber cement cladding showed peak MC of 24 percent in the wood sheathing. This demonstrates that the EP&B walls have adequate moisture performance due to the continuous rigid foam board insulation installed on the interior side of the OSB and the exterior side of the 2x4 wood members.

The walls with intentional air leakage did show significant impact on the wall sheathing MC. The 2x6 vinyl-sided wall with kraft-faced batt insulations having 2 cfm controlled air leakage from the room to the cavity showed over 20 percent winter peak MC in sheathing for an extended period. Therefore, air sealing to minimize air leakage through the wall system is important to achieve satisfactory moisture performance.

The 2x4 vinyl-sided wall with unfaced batt and PIC exterior insulation also experienced high (over 20 percent) winter peak MC in OSB sheathing. This was caused by the low water vapor permeance of the PIC material. Thus, choosing the exterior insulation materials with medium to high vapor permeance can significantly improve the moisture performance, as was demonstrated in the similar walls with rockwool, EPS, and XPS tested in this study. Another option may be replacing the unfaced batt insulation with kraft-faced batts to provide winter moisture resistance to keep the sheathing at a satisfactory MC level.

Walls in this study, with unfaced batts, showed 24 percent MC in the sheathing at a lower indoor relative humidity level (30-60 percent) compared to the previous study (Home Innovation Research Labs 2013 and Glass, et al. 2015), which maintained indoor relative humidity between 40 and 70 percent following ASHRAE Standard 160 simplified method. This study concluded that the combination of high indoor RH levels and high vapor permeance of painted gypsum board led to significant moisture accumulation in OSB sheathing during the winter in walls without a vapor retarder.

Moisture injections on both exterior and interior surfaces of the sheathing showed that exterior insulation materials with medium to high water vapor permeance should be considered in order to allow for water that gets behind the cladding to readily dissipate, especially in the winter. Generally, the EPS, XPS, and mineral wool performed better than assemblies installed with PIC insulation, which has a substantially low vapor permeance.

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