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Extended Plate and Beam Wall System

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Extended Plate and Beam Wall System

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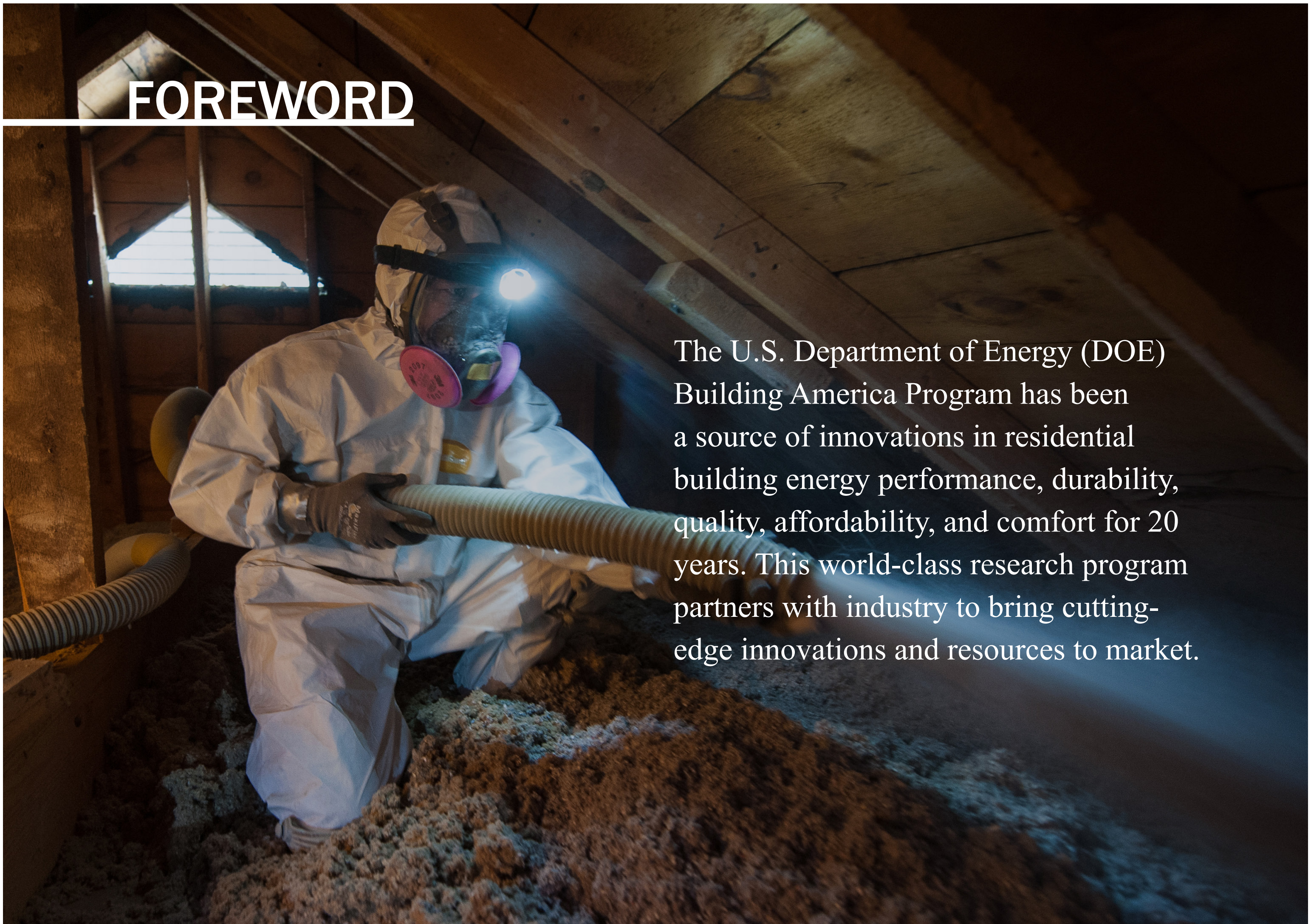
FOREWORD



The U.S. Department of Energy (DOE) Building America Program has been a source of innovations in residential building energy performance, durability, quality, affordability, and comfort for 20 years. This world-class research program partners with industry to bring cutting-edge innovations and resources to market.

The Building America Program supports the DOE Building Technologies Office Residential Building Integration Program goals to:

1. By 2020, develop and demonstrate cost-effective technologies and practices that can reduce the energy use intensity (EUI) of new single-family homes by 60% and existing single-family homes by 40%, relative to the 2010 average home EUI in each climate zone, with a focus on reducing heating, cooling, and water heating loads.
2. By 2025, reduce the energy used for space conditioning and water heating in single-family homes by 40% from 2010 levels.

In cooperation with the Building America Program, the Building America Partnership for Improved Residential Construction is one of many Building America teams working to drive innovations that address the challenges identified in the Program's Research-to-Market Plan.

This report, "Extended Plate and Beam Wall System," explores the extended plate and beam wall system to determine its structural performance, moisture durability, constructability, and cost-effectiveness for use as a high-R enclosure system for energy code minimum and above-code performance in climate zones 4–8.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.

PREFACE

This report was prepared by Home Innovation Research Labs for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Office, with industry cost-share support from the American Chemistry Council. The Forest Products Laboratory and the Dow Chemical Company also assisted in the development of this report.

The aim of the Building America Program is to develop market-ready solutions that improve energy efficiency, durability, quality, affordability, and comfort for new and existing houses. Specifically, this study is intended to address the objectives of the Building America Moisture Risk Management and High-Performance Envelope Systems Roadmap by validating and demonstrating durability, constructability, and cost-effectiveness aspects of the extended plate and beam (EP&B) wall system for new construction housing projects using both field-framing and factory panelization methods.

Since 2012, the International Energy Conservation Code has required an R-5 or R-10 layer of continuous insulation for all walls in climate zones 6, 7, and 8, and continuous insulation is one of two prescriptive solutions for climate zones 4 and 5. Although foam plastic insulating sheathing as continuous exterior insulation has been used by a small cohort of high-performance building builders for approximately two decades, by 2015 the practice had achieved only about 11% market penetration for all thicknesses of foam. Constructability challenges associated with exterior foam are presumed to be a barrier to adoption. Potentially, 60% to 80% of residential builders in the targeted climate zones are candidates for adopting the EP&B wall system as local jurisdictions begin to require the most recent codes.

ACKNOWLEDGMENTS

Home Innovation Research Labs acknowledges the U.S. Department of Energy Building America Program and the American Chemistry Council for their invaluable support of this research project.

Home Innovation also thanks the following builder partners for their participation in the field study:

- Arn McIntyre of McIntyre Builders
- Kevin Smith of Kevin L. Smith Construction.

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LIST OF ACRONYMS

c.i.	Continuous insulation—generally a rigid or semi-rigid board insulation material installed exterior to the wall cavity.
ccSPF	Closed-cell spray polyurethane foam
CZ	Climate Zone, as defined by the International Energy Conservation Code
DOE	United States Department of Energy, a federal agency that conducts and solicits research on energy efficiency topics, and includes the Building America program
EPS	Expanded polystyrene, a type of rigid foam sheathing suitable for use in the EP&B wall system with the addition of a film
EP&B	Extended Plate & Beam, a light frame wall system under development at Home Innovation Research Labs
FF	Framing Factor—the percentage of a wall's area that is made up of lumber that spans the full depth, and forms a thermal bridge from the interior to the exterior. Typical light-framed construction may be made up of as much as 28% lumber by area as viewed in elevation. Advanced framing techniques can reduce this to as little as 15%.
FPIS	Foam plastic insulating sheathing—a rigid foam board typically made from extruded polystyrene (XPS), expanded polystyrene (EPS) or Polyisocyanurate (PIC) and used to provide a layer of continuous insulation for house walls or other components. In this report, FPIS generally refers to rigid foam installed as continuous insulation exterior to the wood sheathing, or in place of the wood sheathing.
High-R	Building America program reference to wall systems with high thermal resistance, exceeding energy code minimum requirements
ICF	Insulated Concrete Forms
IECC	International Energy Conservation Code
IRC	International Residential Code
MC	Moisture content, generally reported on a percentage basis by weight (MC%)
o.c.	On center—the measurement for lumber with dimension, e.g., studs, whose 1-½-in. width means that 16-in. o.c. installation leaves a 14-½-in. stud bay.
OSB	Oriented Strand Board, a manufactured wood sheathing product
PIC	Polyisocyanurate, a type of rigid foam sheathing suitable for use in the EP&B wall system
R-value	Quantitative measure of resistance to conductive heat flow (hr·°F·ft2/Btu)
Rigid Foam	FPIS used primarily as an insulation material, rather than for the purpose of sheathing. In an EP&B wall, the rigid foam is installed between the framing and the OSB.
SIP	Structural Insulated Panel
TMY	Typical meteorological year
U-value	Quantitative measure of thermal conductance: Btu /(hr·°F·ft2) (the inverse of R-value)
WRB	Water Resistive Barrier—used to protect the building envelope from liquid water, while allowing the diffusion of water vapor back out
WSP	Wood Structural Panel—the layer of wood sheathing (plywood or OSB) that provides shear and racking strength when properly attached to wall framing
XPS	Extruded Polystyrene, a type of rigid foam sheathing suitable for use in the EP&B wall system

EXECUTIVE SUMMARY

Home Innovation Research Labs studied the extended plate and beam (EP&B) wall system during a two-year period from mid-2015 to mid-2017 to determine the wall's structural performance, moisture durability, constructability, and cost-effectiveness for use as a high-R enclosure system for energy code minimum and above-code performance in climate zones 4–8.

> Previous proof-of-concept research projects used comparative labor and material cost comparisons, ASHRAE parallel-path thermal transfer equations, thermal bridging calculations, moisture and heat-transfer computer simulations, laboratory structural testing, and construction demonstrations in test buildings to refine the initial design.

This research was intended to explore the structural, thermal, and moisture performance of a wall that can be readily adopted by the large cohort of traditional builders who have previously resisted the switch to a high-R wall. Despite many years of development, structural insulated panels, insulated concrete forms, and double wall construction command a small market share of residential wall systems, which is largely because of atypical materials, methods, and details that require retooling and retraining. Use of 2x6 framing provides deeper stud cavities for more insulation, but the maximum thermal performance of the wall is effectively limited to 2015 International Energy Conservation Code (IECC) targets for climate zones 3–5, and the temperature profile across the wall subjects the cavity to moisture condensation risk in colder climates.

Another leading approach to increasing the R-value of walls is to add rigid insulation outboard of the sheathing, a technology that was demonstrated more than 40 years ago but remains underused, with only about 11% nationwide market penetration in 2015 for all foam thicknesses. The specific transition barriers to the widespread adoption of this method include the lack of a nailing base to support the cladding, drainage plane, and window flashing and the concern with the possible creation of dual vapor barriers leading to moisture problems.

EP&B walls integrate rigid foam sheathing with standard framing practices into a cost-effective system that preserves many conventional construction features and minimizes builder risk. The rigid foam insulation board is installed between the 2x4 framing and the wood structural sheathing, with the top and bottom plates extending to the exterior plane of the rigid foam. This method keeps approximately 95% of the wall area free of thermal bridging while using common methods and materials for framing, air sealing, insulation, drainage plane, and siding attachment by retaining the wood structural panels (WSP) as an exposed nailing surface. The extended plates in conjunction with the WSP mounted at the exterior plane of the wall protect the foam during transit, making EP&B uniquely suited to factory wall panelization in addition to field-framing.

A continuous 2-in. layer of rigid foam insulation located between the wall cavity and the wood structural sheathing provides the thermal benefits of traditional exterior continuous insulation: higher winter temperatures inside the wall to reduce condensation risk and warmer wall surface temperatures in the room for better thermal comfort. The location of the rigid foam layer constitutes a centrally-located vapor control plane with effective drying to the direction from which the source moisture originated—exterior to the exterior and interior to the interior.

Laboratory tests based on AC269.1 confirmed the EP&B wall performance for the International Residential Code (IRC) intermittent and continuous braced wall equivalency. The calculated allowable design racking shear load value for EP&B walls is 256 plf (lbs/ft) for spruce-pine-fir framing. As a point of comparison, the minimum acceptable IRC WSP braced wall is listed at 184 plf (lbs/ft).

Monitoring in two demonstration houses as well as WUFI computer simulations confirmed the EP&B wall's long-term moisture performance—the average peak wood moisture content was less than 15%, significantly less than accepted levels of risk—with a variety of construction material choices and climate zones. Relative humidity readings in wall cavities were less than 80% for the full year of monitoring, and they averaged between 40% and 60%, close to interior ambient conditions. Finally, observation of the two field-test construction processes confirmed that the EP&B wall can be built by framing crews with typical experience in light-frame construction, can provide a tight envelope with low infiltration, and provides improved simplicity for several construction processes compared to traditional exterior continuous insulation over WSP while providing a 95% thermal break for the entire wall enclosure.

EP&B walls in the 2x4/2x6 configuration are cost-effective and can perform reliably as an alternative IRC structural braced wall with good moisture durability and thermal performance that meets 2015 IECC minimum insulation requirements throughout climate zones 6–8 and that exceeds minimum energy code prescriptive requirements in climate zones 3–5. Thicker EP&B walls can provide better-than-code thermal performance up to Climate Zone 8 with similar comparative cost savings.

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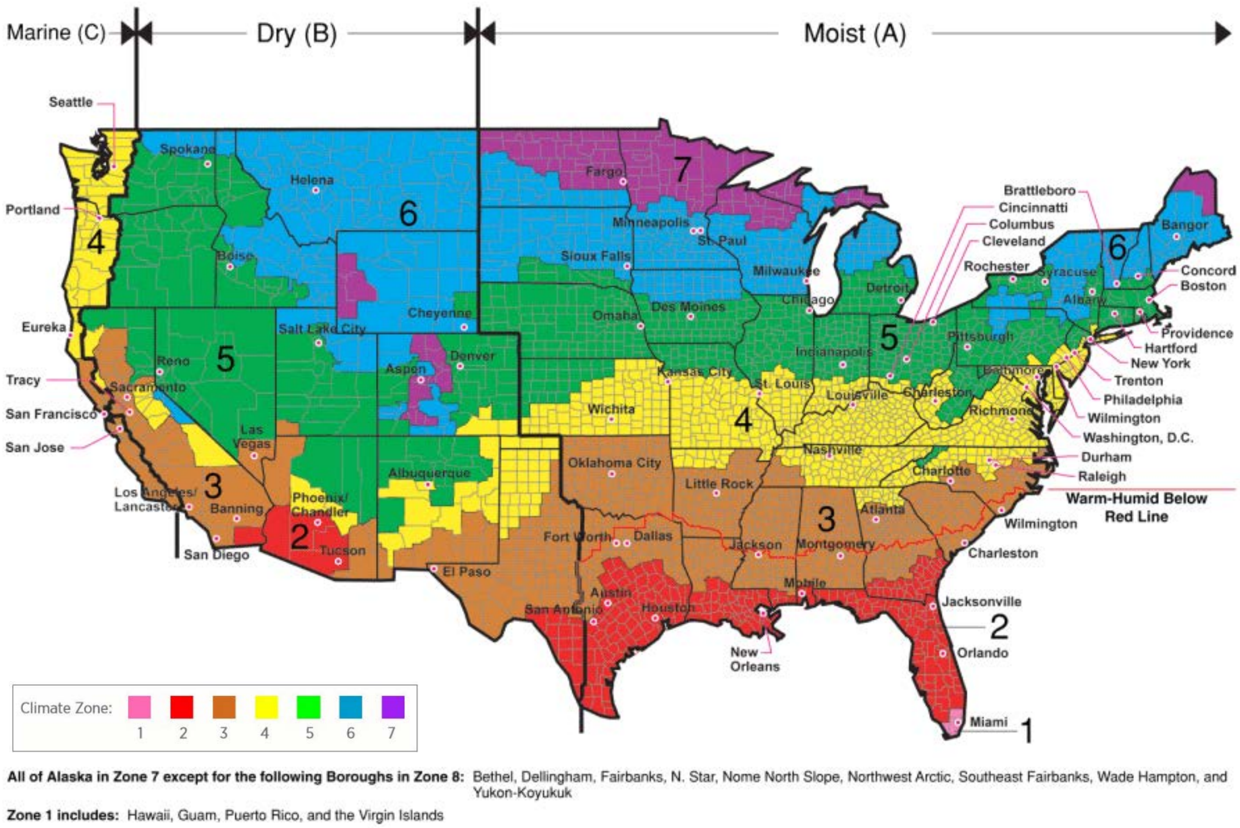
1 Introduction and Background

This document is the final report for Building America research conducted by Home Innovation Research Labs on the extended plate and beam (EP&B) wall system. Project activities included structural lab testing, construction observation of two demonstration houses built in Grand Rapids, Michigan, 12-month moisture monitoring of the OSB sheathing and wood framing within the walls of those field tests, and WUFI moisture and heat transfer simulations.

1.1 Background of High-R Wall Development

For several decades, the residential building industry has been seeking to expand the list of available options for increasing the thermal resistance of walls. Although multiple high-R wall construction methods have been developed during the last 25 years, the market penetration for high-R walls remains low. The EP&B wall system is a solution that can be appealing to a large swath of typical builders looking to improve their homes' thermal performance because the system incorporates a layer of nearly continuous rigid foam insulation while minimizing many of the common risks and concerns associated with high-R envelope systems.

The International Energy Conservation Code (IECC) Table R402.1.1 lists prescriptive thermal performance values for envelope components based on local climate conditions. Figure 1 illustrates the range of each climate zone.



Source: U.S. Department of Energy

Figure 1. Climate zones

Compared to IECC 2009, envelope requirements have increased for all major envelope components. An NAHB Research Center report (2012) determined that the savings resulting from the 2012 IECC energy components baseline compared to the 2006 baseline averaged more than 30% for homes across all eight climate zones.

Table 1 (derived from IECC for various cycles) shows the trend for several IECC prescriptive insulation and fenestration requirements during the last decade. Changes compared to previous years are highlighted in green. Note that the 2015 IECC envelope components are the same as those for 2012.

Table 1. Evolution of Prescriptive Wall Requirements from 2006 to 2015

	IECC Climate Zone	Wood Frame Wall R-Value[a]
2006	Climate zones 1, 2, 3, 4 except marine	13
	Climate zones marine 4, 5, 6	19 or 13+5
	Climate zones 7, 8	21
Improved 2009	Climate zones 1, 2, 3, 4 except marine	13
	Climate zones marine 4, 5, 6	20 or 13+5
	Climate zones 7, 8	21
2012	Climate zones 1, 2	13
	Climate zones 3, 4, 5	20 or 13+5
	Climate zones 6, 7, 8	20+5 or 13+10
2015	Climate zones 1, 2	13
	Climate zones 3, 4, 5	20 or 13+5
	Climate zones 6, 7, 8	20+5 or 13+10

[a] Nominal resistance to conductive heat flow: (hr·°F·ft2)/Btu

Beginning with IECC 2012, residential builders in Climate Zone 6 and above can meet prescriptive above-grade wall insulation requirements only by using a layer of continuous insulation, either R-5 or R-10.

The standard EP&B configuration (2x4 studs with 2x6 plates) meets or exceeds the prescriptive R-value requirements for all climate zones, and it provides an above-code solution up to Climate Zone 5. The configuration can be modified to better than nominal R-30 by using 2x6 studs and plates 2 in. wider, offering opportunities to pursue several voluntary green building certification programs and providing an alternative to exterior-applied continuous insulation up to Climate Zone 8.

Exterior continuous insulation is commonly seen as foam plastic insulating sheathing (FPIS) installed at the exterior plane of the wood structural panel (WSP); this technique was demonstrated more than 40 years ago, and it is now standardized as a prescriptive method in the IECC. Yet continuous insulation of any thickness still accounted for only 11% nationwide market penetration in 2015 (Home Innovation Research Labs, 2016). There are several perceived transition barriers to the widespread adoption of this method, such as:

- Concern about reducing the ability of the oriented strand board (OSB) to dry outward because of the low permeability of most foam plastic insulated sheathing, which is installed directly over the WSP
- Lack of a nailing base to support the cladding
- Difficulty identifying and detailing a drainage plane
- Unusual installation of windows and doors
- Atypical attachment of flashing to or through the FPIS.

With the steady increase of IECC energy requirements, adoption rates by builders of continuous insulation wall systems will undoubtedly grow. For builders who have not yet transitioned to using FPIS as an exterior option, EP&B offers an alternative location for a layer of continuous insulation.

1.1.1 System Description and Background

The EP&B wall assembly currently under study is intended to address many of the transition barriers for high-R walls. The method launches from a starting point comfortable for residential builders today: 2x4 light-frame wood construction. The key difference is that the bottom and top plates are one dimension wider than the stud lumber and attached flush to the interior stud plane, creating space on the exterior side of the stud framing that accommodates a 2-in. layer of rigid foam insulation. The single layer of OSB or plywood sheathing is attached directly to the extended plates at the top and bottom and to the studs through the rigid foam, effectively encasing the continuous insulation with WSP.

EP&B walls can be built in various configurations, including 2x4 studs with 2x6 plates (2-in. rigid foam), 2x6 studs with 2x8 plates (1¾-in. rigid foam) and 2x6 studs with 2x7.5*[1] plates (2-in. rigid foam.) This last configuration can be achieved by rip-cutting 2x10s to reduce their width. The configuration with 2x7.5* (2x10) plates tends to be less expensive than 2x8 plates (actual lumber dimensions 1½ x 7¼) because rigid foam is not available in 1¾-in. thickness and must be installed as two layers: 1 in. and ¾ in.

Typical materials and layering are shown in Figure 2.

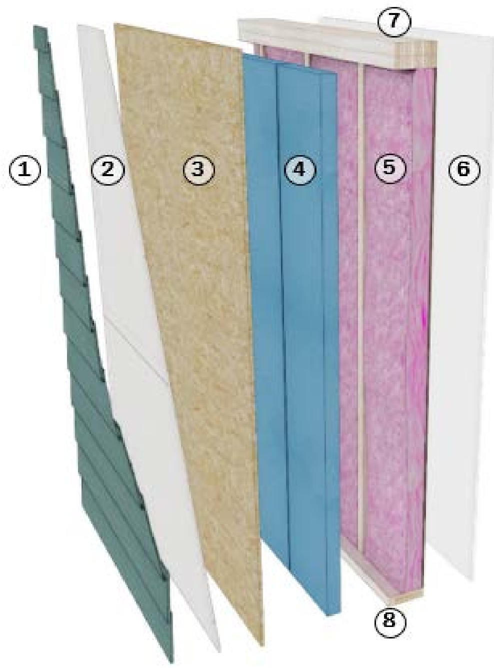


Figure 2. Materials layering for an EP&B wall

[1] The asterisk in 2x7.5* denotes an actual, rather than a nominal, width measurement

EP&B components are:

1. Exterior siding
2. Water Resistive Barrier (WRB)
3. Wood Structural Panel Sheathing (WSP)
4. FPIS
5. Framed 2x4 16 in. o.c. wood stud-wall with cavity insulation (and interior vapor retarder if specified)
6. Interior gypsum dry wall
7. Extended top plates
8. Extended bottom plate

EP&B design features include:

- More than 95% framing coverage with continuous insulation to reduce thermal shorts caused by framing members
- Exterior WSP sheathing for siding attachment
- WSP sheathing is nailed directly to the extended bottom and second top plates for shear load resistance
- Wood Structural Panel (WSP) provides a flashing surface for windows and doors, for efficient installation and good durability.
- The exterior location of the WSP sheathing allows it to dry to the outside; the FPIS layer behind it protects the WSP from interior moisture diffusion
- Warm stud cavity space to reduce the risk of condensation potential
- Flexibility in the selection of insulation materials
- Flexibility in the use of framing sizes for incremental improvement of wall thermal resistance
- Band beam design to eliminate headers in many wall sections

1.1.2 Energy Benefits

The rigid foam layer in the EP&B wall system provides two major thermal advantages: higher overall R-value and a nearly continuous insulation layer that spans more than 95% of the wall area.

The thermal bridge of the extended plates in the EP&B wall reduces the wall's thermal performance by slightly more than 4% compared to a similarly framed wall that has complete coverage with exterior continuous insulation, often referred to as "foam over-sheathing." See Table 2; calculated assembly values are shown in parentheses.

Table 2. Thermal Performance of EP&B Wall Configurations Compared to IECC Code Requirements

Climate Zone	2012/2015 IECC Prescriptive R-value[a] for Above-Grade Walls (Calculated Assembly Value[b])	Nominal R-value (Calculated Assembly Value[b])		
		EP&B 2x4/2x6 Std. 16-in. o.c.	EP&B 2x6/2x8 Adv. 24-in. o.c.	EP&B 2x6/2x7.5*[c] Adv. 24-in. o.c.
3, 4, 5	20 (16.8) or 13+5[d] (17.5)	13+10[d] (21.7) or 15+10[d] (22.8)	19+8.75[d] (26.6) or 21+8.75[d] (27.9)	19+10[d] (27.8) or 21+10[d] (29.1)
6, 7, 8	20 + 5[b] (22.5) or 13+10[d] (22.7)			

[a] R-value in h·°F·ft² /Btu. A 25% framing factor is assumed.

[b] The calculated assembly value assumes typical wall materials of gypsum drywall, spruce-pine-fur lumber, fiberglass batt insulation, XPS foam sheathing, OSB structural sheathing, WRB and vinyl siding. Framing of 16 in. o.c. assumes 75%/20.6%/4.4% thermal path ratios (cavity/framing/cantilevered plates); 24-in. o.c. framing assumes 85%/10.6%/4.4% ratios.

[c] Plates designated 2x7.5* indicate the actual 7½-in. width to allow 2 full in. of rigid foam insulation.

[d] The first value is cavity insulation, the second value is continuous insulation, so "13+5" means R-13 cavity insulation plus R-5 continuous insulation.

For houses with two stories, a double rim joist assembly can be used with EP&B walls to eliminate headers and provide space for additional insulation. This “rim beam” can perform the duties of a header in many cases, eliminating typical headers and freeing space for more insulation. The structural capacity of the EP&B wall system has been tested and confirmed for both conditions (Home Innovation Research Labs 2015a): (1) a double rim joist located at the exterior plane and (2) a single rim joist inset by 1 in. to accommodate a layer of rigid foam insulation.

1.1.3 Other Benefits

Because the WSP is exterior to the rigid foam layer, the EP&B wall offers trades a familiar approach to installing windows, the WRB, and cladding. The EP&B method is compared to the continuous insulation method for various components or construction processes as follows:

Siding: Siding attachment is straightforward using the alternate attachment schedule from the International Residential Code (IRC), R703.3.2 (Table 3), for fastening siding to wood sheathing instead of framing. With EP&B, the nail length for siding installation simply needs to capture the depth of the siding, plus the OSB, plus the required ¼-in. extension—approximately a ¾-in. ring shank nail.

In contrast, a typical prescriptive wall with 2 in. of continuous insulation requires fasteners to be nearly 3 in. long to attach the siding to the wood sheathing through the foam and nails in excess of 4 in. to attach to framing (Applied Building Technology Group 2015). More commonly, furring would be installed outboard of the foam (or let in to the foam layer) to provide a nailing substrate for shorter siding fasteners; however, the furring must still be attached directly to the framing with long nails or screws, and it requires extra labor and materials.

Table 3. IRC Table R703.3.2 Optional Siding Attachment Schedule for Fasteners Where No Stud Penetration Necessary

APPLICATION	NUMBER AND TYPE OF FASTENER	SPACING OF FASTENERS[b]
Exterior wall covering (weighing 3 psf or less) attachment to WSP sheathing, either direct or over foam sheathing a maximum of 2 in. thick.[a] Note: Does not apply to vertical siding.	Ring shank roofing nail (0.148-in. minimum diameter)	12 in. o.c.
	Ring shank nail (0.148-in. minimum diameter)	15 in. o.c.
	#6 screw (0.138-in. minimum diameter)	12 in. o.c.
	#8 screw (0.164-in. minimum diameter)	16 in. o.c.

[a] Fastener length shall be sufficient to penetrate the back side of the WSP sheathing by at least ¼ in. The WSP sheathing shall be not less than 7/16 in. in thickness.

[b] Spacing of fasteners is per 12 in. of siding width. For other siding widths, multiply “Spacing of Fasteners” above by a factor of 12 s, where “s” is the siding width in inches. Fastener spacing shall never be greater that the manufacturer’s minimum recommendations.

WRB: An EP&B wall has OSB as the exterior layer, so traditional sheet-goods WRB can be installed in the usual fashion with staples or cap nails.

On a foam over-sheathed wall, WRB can also be installed over FPIS, or the foam sheathing might be detailed to act as the WRB (Holladay 2010). The joints between the sheets are then taped, and all edges must be detailed for resistance to bulk water intrusion. Although this approach is common among the cohort of builders already using exterior foam sheathing, it can be complex and requires advance planning and manufacturer-approved joint tape. Not all rigid foam sheathing is approved for such use; check the manufacturer’s requirements.

Window installation: In an EP&B wall, windows can be framed with 2x4s, preserving the continuous insulation layer of rigid foam behind the wood sheathing. The window’s frame can bear on both the rigid foam and the edge of the OSB, or the window can be shimmed. OSB has enough rigidity to bear the wind load, and nailing the window flange to the OSB sheathing is generally sufficient. Longer nails can be used to attach the window directly to framing if additional support is desired; check the manufacturer's requirements.

But for windows in a wall with an exterior continuous insulation, all fasteners must penetrate through the foam to connect with framing. The window frame must be supported to avoid bearing on the foam with additional framing or with additional fasteners.

Window flashing: Because of the exterior layer of WSP, attaching and shingling the window flashing in an EP&B wall is almost identical to that for a typical wall.

A potential complication with traditional continuous insulation is that it is often recommended to create a reglet in the face of the foam above the window head to accept a drip cap, and seams in the FPIS over the header of the window should be avoided (Building Science Corporation 2005).

Panelization: Unlike a wall with exterior continuous insulation, the EP&B wall is an excellent candidate for factory panelization. The extended plates at the top and bottom of the wall sections and the OSB sheathing effectively protect the foam in transit. The rigid foam can be cut with the same saws used for lumber, and excess material can be used in header and cripple stud locations, minimizing waste.

Continuous insulation: Like exterior continuous insulation, EP&B walls provide thermal performance benefits with respect to materials durability. A 2-in. layer of insulating foam exterior to the framing maintains a much warmer temperature in the wall cavity during winter (Table 4). Should water vapor make its way to the interior plane of the rigid foam, the warmer temperatures make it much less likely to condense; liquid water in building materials is often a precursor to mold and mildew.

Table 4 shows that the resistance-weighted temperatures calculated for a typical light-wood frame wall are 28°F outdoors and 68°F indoors. The temperature in the wall cavity at the interior plane of the WSP is at or below freezing for both 2x4 and 2x6 framing. In a wall with a layer of R-10 continuous insulation, the temperature in the cavity remains above 45°F, the dew point of 70°F/40% relative humidity (RH) indoor air.

Table 4. EP&B Provides a Warm Cavity to Protect Against Condensation

Interface/Wall Assembly	EP&B, R13/10	2x4, R13	2x6, R20
	Temperature (°F)		
Indoor temperature	68	68	68
Cavity interior face	66.28	65.2	66
Cavity exterior face	**46.5**	32.8	31.3
OSB interior plane	31.3		
OSB exterior plane	30.4	28.4	28.3
Outdoor temperature	28	28	28

Thermal comfort: The surface of a poorly insulated wall can be cold compared to the rest of the space, which can cause occupant discomfort even when the building's heating system is capable of maintaining the room's set-point air temperature (Fanger et al. 1985). Both continuous insulation and EP&B provide continuous insulation exterior to the framing and wall cavity, which can help maintain more uniform surface temperatures in a space, improving occupant comfort.

Drying capability: In the EP&B configuration, the foam sheathing installed on the interior side of the OSB provides a distinct, centrally located vapor control plane with effective drying to the direction from which the source moisture originated—exterior to the exterior and interior to the interior. In an EP&B wall, outward drying of the WSP is facilitated by the use of a high-perm WRB.

When the OSB is located behind the foam, as with an exterior continuous insulation configuration, the drying of the wood sheathing primarily occurs to the inside. Inward drying is effective when vapor drive is low, or during nonwinter seasons when the direction of the vapor drive is also to the inside, but inward drying does not occur in the winter when there is a strong vapor drive in the opposite direction. EP&B potentially outperforms continuous insulation in this situation.

An appropriate interior vapor retarder helps prevent the accumulation of moisture in the wall cavity caused by humid conditions inside the building. The IRC allows a Class III vapor retarder to be used in certain wall configurations that include a rigid foam layer, specifically because of the foam insulation's ability to keep the cavity warmer and reduce the potential for condensation. Outward vapor drive (from inside to outside) is high where outside conditions are cold and dry. A Class II interior vapor retarder is recommended for EP&B walls in Climate Zone 5 and above using a "smart" vapor retarder or Kraft paper to protect the wall assembly against high winter interior vapor and to allow inward drying of the cavity as humidity reduces seasonally, allowing a balanced condition. Proprietary "smart" vapor retarder products have perm ratings that rise with increasing RH from 1 perm or less at normal conditions (Class II) up to 35+ perms (vapor permeable) in high humidity, and they represent a "belt and suspenders" approach, excellent for use with EP&B. EP&B walls monitored for a two-year period in controlled test buildings in Climate Zone 4 (Home Innovation Research Labs 2015b) showed that in this configuration the OSB performs well with respect to moisture (Figure 3). OSB sheathing on EP&B walls with vinyl siding and unfaced fiberglass batts remained below ~13% moisture content (MC) throughout the test period.

Increased air sealing improves thermal performance but potentially reduces drying capability. The Climate Zone 4 data indicate that the EP&B wall with air sealing in Figure 3 was more resilient to this effect than the Kraft-faced batt wall with air sealing. This is likely due to the location of the rigid foam layer which provides a centrally located vapor plane, allowing the OSB to dry directly to the outside and protecting it from interior vapor drive.

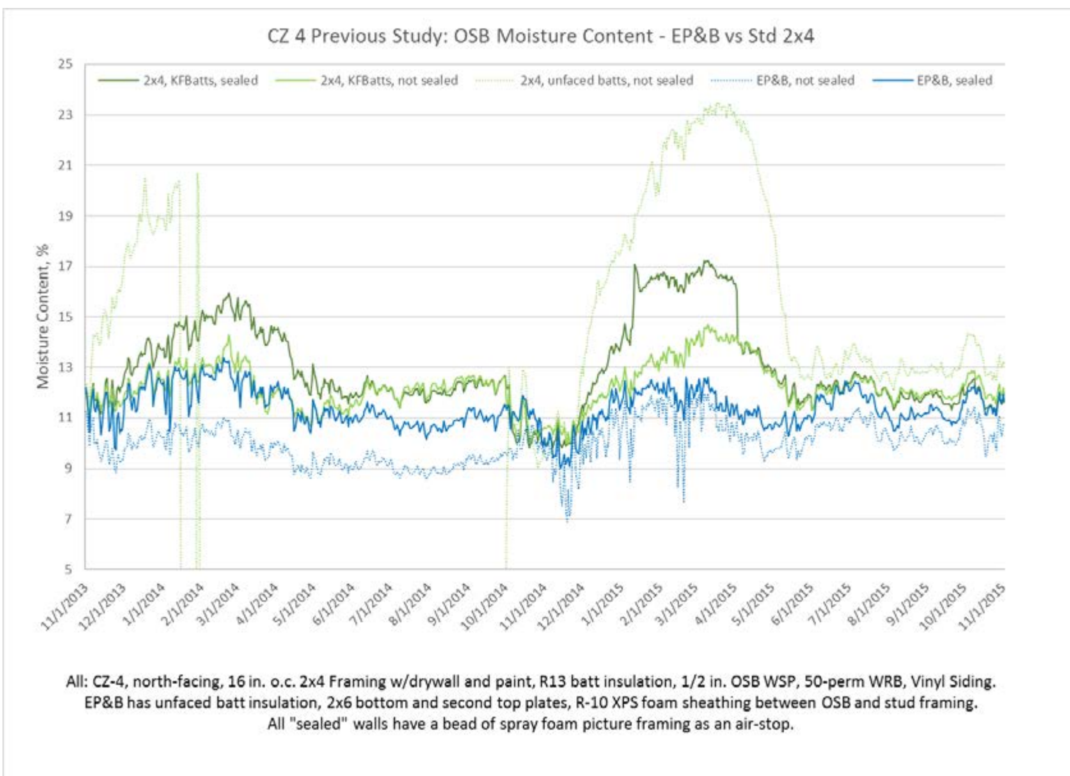


Figure 3. Proof-of-concept EP&B walls in Climate Zone 4 maintained moisture levels below ~13% (blue)

2 Implementation

The purpose of this project is to use the EP&B innovation to demonstrate a path for framers using traditional techniques to incorporate the energy-efficient component of rigid insulation and participate in the high-performance construction market with low risk, good marketability, and low—or no—additional cost. It is also anticipated that some builders may choose to transition from traditional continuous insulation techniques to EP&B for scheduling, cost, or simplicity reasons, or to realize the process savings of factory panelization.

2.1 Project Team

Table 5. EP&B Test Home Project Team

Organization	Role
Home Innovation Research Labs	Research and evaluation
Dow Chemical Company	Materials, technical support, quality control
U.S. Department of Agriculture Forest Products Laboratory	Technical support
American Chemistry Council	Materials, technical support, quality control
McIntyre Builders, Inc.	Builder
Kevin L. Smith Construction	EP&B Framing, WRB, air sealing, window installation, roof trusses, and decking

2.2 Research Objective

This project's main objective is to identify, implement, verify, and publish specific performance aspects, construction details, and integration strategies that can be used to support builder transition to the EP&B system. Key research goals are to:

- Perform laboratory testing to demonstrate IRC braced wall equivalency and to provide data to support a code proposal and Evaluation Service reports.
- Develop WUFI heat and moisture simulations to establish likely EP&B assembly choices for all appropriate climate zones.
- Construct demonstration houses to evaluate the implementation of an EP&B wall system from plan layout through final testing, including moisture and temperature meters in various locations within the walls to track performance.
- Use moisture and temperature data from the demonstration homes to validate materials choices and to fine-tune the WUFI models for broader application.

2.3 Structural Testing

2.3.1 Equipment and Methodology

EP&B wall testing began in the fall of 2015 and proceeded under the version of AC269.1 that had been approved as of February of 2013. Analysis was also done against the updated criteria of AC269.1 2017. Home Innovation Research Labs regularly performs construction testing using International Code Council published Acceptance Criteria (AC). Home Innovation's equipment is calibrated and audited in accordance with the International Organization for Standardization 17025:2005.

See Appendix B for specific details on the EP&B braced wall testing.

2.3.2 Test Methods and Materials

Tests were executed in general conformance with the provisions of International Code Council-Evaluation Service AC269.1: Acceptance Criteria for Proprietary Sheathing Attached to Wood Light-Frame Wall Construction Used as Braced Wall Panels Under the IRC (IRC evaluation—prescriptive bracing tables) as applicable to the specific objectives of this study. AC269.2: Acceptance Criteria for Proprietary Sheathing Jobsite-Attached to Wood Light-Frame Wall Construction Used as Shear Walls (International Building Code evaluation—engineered design values) procedures were used to develop the allowable design racking shear load values.

Racking shear performance testing of the EP&B wall system was conducted in two phases. Phase I of the test plan applies American Society for Testing and Materials (ASTM) E72 Section 14 procedures per AC269.1 Section 4.1 to qualify the wall system for intermittent bracing. Phase II of the test plan applies ASTM E564 procedures per AC269.1 Section 4.2 to qualify the wall system for continuous bracing. See Figure 4 for an example of a wall specimen installed in the testing apparatus.

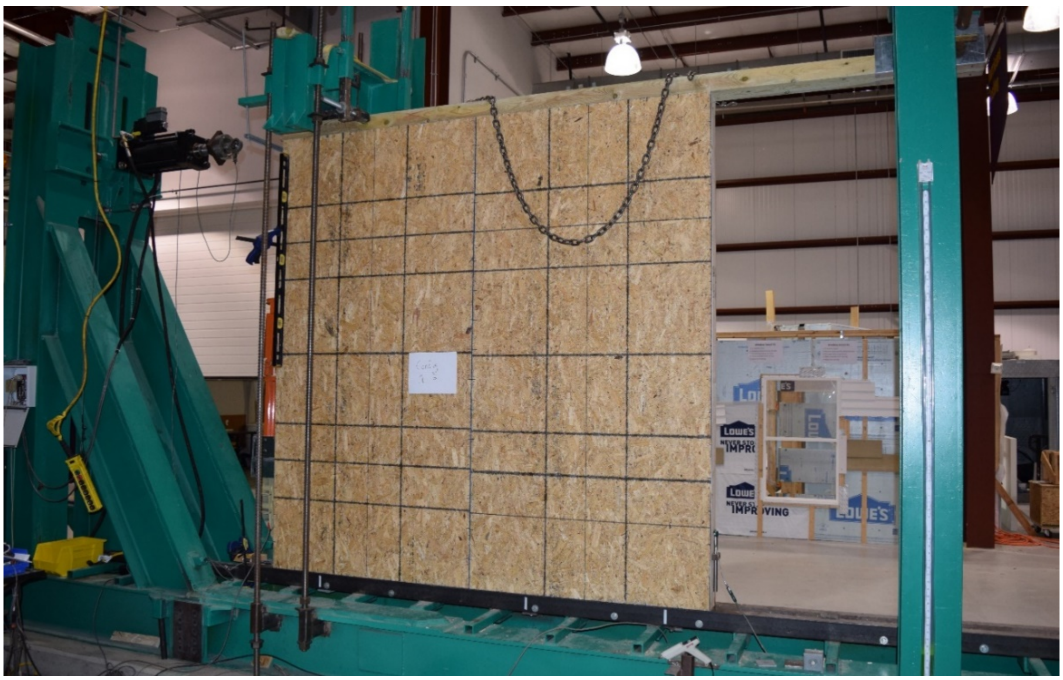


Figure 4. A 2x6 standard reference wall in testing apparatus prepared for an ASTM 72 test

Note that AC269.1 criteria were developed for the evaluation of proprietary sheathing materials; OSB-braced walls were used as the basis for developing most of the evaluation criteria for AC269.1. The EP&B wall system as tested used OSB as exterior structural sheathing. The purpose of this evaluation was not to verify the performance of the OSB sheathing. The purpose was to verify that the EP&B assembly with a modified nailing schedule continues to meet the established strength and stiffness performance criteria for a minimum code shear wall. Three dry specimens were tested for Section 4.1 conformance; wet tests were not necessary because the sheathing as a material was not the focus of the evaluation.

Per AC269.1, “Framing members receiving sheathing fasteners shall have a measured average specific gravity (oven-dry basis) not exceeding the nationally specified value plus 0.03 for the species of framing member in accordance with NDS Table 11.3.2A.” All lumber was prequalified by estimating the specific gravity based on the weight of each board, and its MC was measured with a handheld moisture meter with appropriate species adjustment. Following destructive testing, multiple lumber samples from each specimen were weighed and dried in the oven to confirm average specific gravity. All lumber was within the specified range.

2.3.3 Intermittent Braced Wall: Test Protocol and Results

Testing for intermittent braced walls follows Section 4.1 of AC269.1 in accordance with ASTM E72 regarding specimen construction and loading protocol using the testing apparatus described above and in Appendix B.

Shear test results are summarized in Table 6 for the three E72 EP&B specimens. All tested EP&B walls exceed AC269.1; each criterion's minimum and maximum is shown in italics below each column's header. The EP&B walls also meet the deflection requirements at 200 plf and 400 plf—a prerequisite for evaluation as an alternative to the continuously sheathed wood structural panel bracing method (CS-WSP) per ASTM E564.

Table 6. AC269.1 Section 4.1 (ASTM E72) EP&B Baseline Wall Specimens (Douglas Fir-Larch): Intermittent Bracing

Wall Type	Max Shear Load (lb) (Peak)	Net Deflection at Peak Load (in.)	Unit Shear (lbs/ft) (plf)	Deflection at 23% Load	Deflection at 46% Load	Deflection at 200 plf	Deflection at 400 plf
AC269.1 Criteria 4.1:	*>4,480*	*>0.75*	*>560*	*<0.2*	*<0.6*	*<0.2*	*<0.6*
EP&B 1	7,060	3.35	882	0.134	0.353	0.127	0.348
EP&B 2	6,673	3.77	834	0.134	0.386	0.139	0.409
EP&B 3	6,851	3.73	856	0.135	0.336	0.135	0.352
Average	***6,861***	***3.62***	***858***	***0.134***	***0.359***	***0.127***	***0.348***

Figure 5 shows the deflection curves for the three EP&B baseline walls.

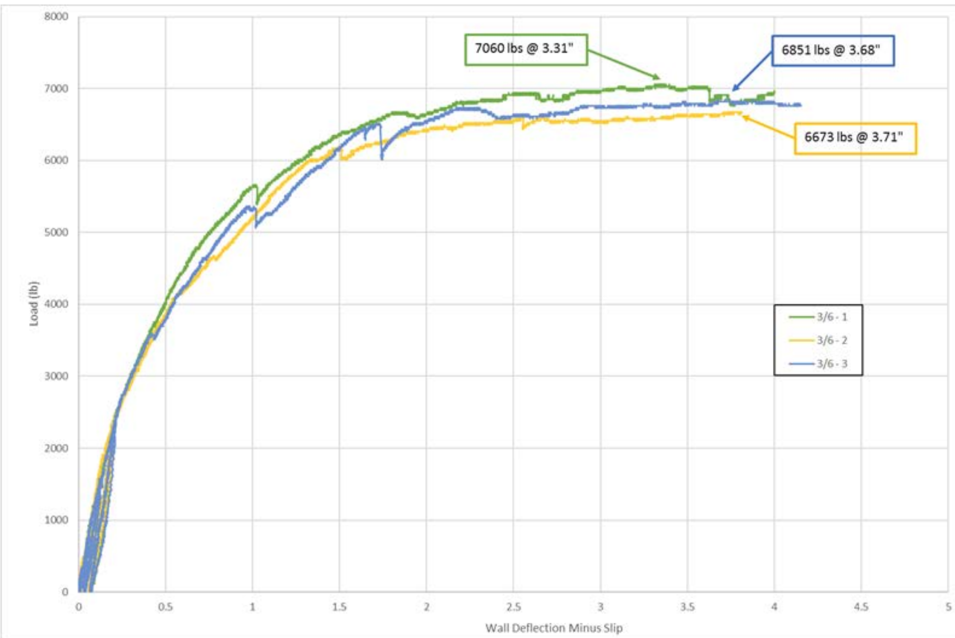


Figure 5. Maximum loads: E72 test—EP&B baseline walls (Douglas fir-larch)

2.3.4 Continuous Braced Wall: Test Protocol and Results

Testing for continuously sheathed braced walls follows Section 4.2 of AC269.1 regarding specimen construction, wall type test matrix, and loading protocol. The racking shear tests were conducted in accordance with ASTM E564. Loading was applied in a single, continuous phase using the test apparatus described above and in Appendix B.

Following the E72 qualification, the E564 tests were performed on EP&B wall samples for wall type 1 (baseline), wall type 2 (12-ft. wall section with corner returns), and wall types 3–7 (perforated walls having various combinations and sizes of window and door openings).

Table 7 summarizes the E564 test results for the EP&B wall type 1 (the baseline) including maximum recorded (peak) shear load, net deflection at peak shear load, maximum unit shear, and the maximum net deflections at two target loads: 200 plf and 400 plf. The column headers for the last three parameters show the thresholds required by the acceptance criteria. When two tests are performed, each specimen must pass all criteria.

Table 7. AC269.1 Section 4.2 (ASTM E564) for EP&B Baseline Wall Specimens (Spruce-Pine-Fir): Continuous Bracing

E564 Wall Type 1	Max Shear Load (lb) (Peak Horizontal Racking Shear Load)	Net Deflection at Peak Load (in.)	Max Unit Shear (lbs/ft)	Net Deflection at 200 plf	Net Deflection at 400 plf
AC269.1 Criteria 4.2	n/a	n/a	≥ 560 plf	≤ 0.2 in.	≤ 0.6 in.
EP&B Baseline 1-1	6,181	2.62	773	0.148	0.506
EP&B Baseline 1-2	5,274	2.68	659	0.136	0.569
Average	*5,728*	*2.65*	*716*	*0.142*	*0.528*

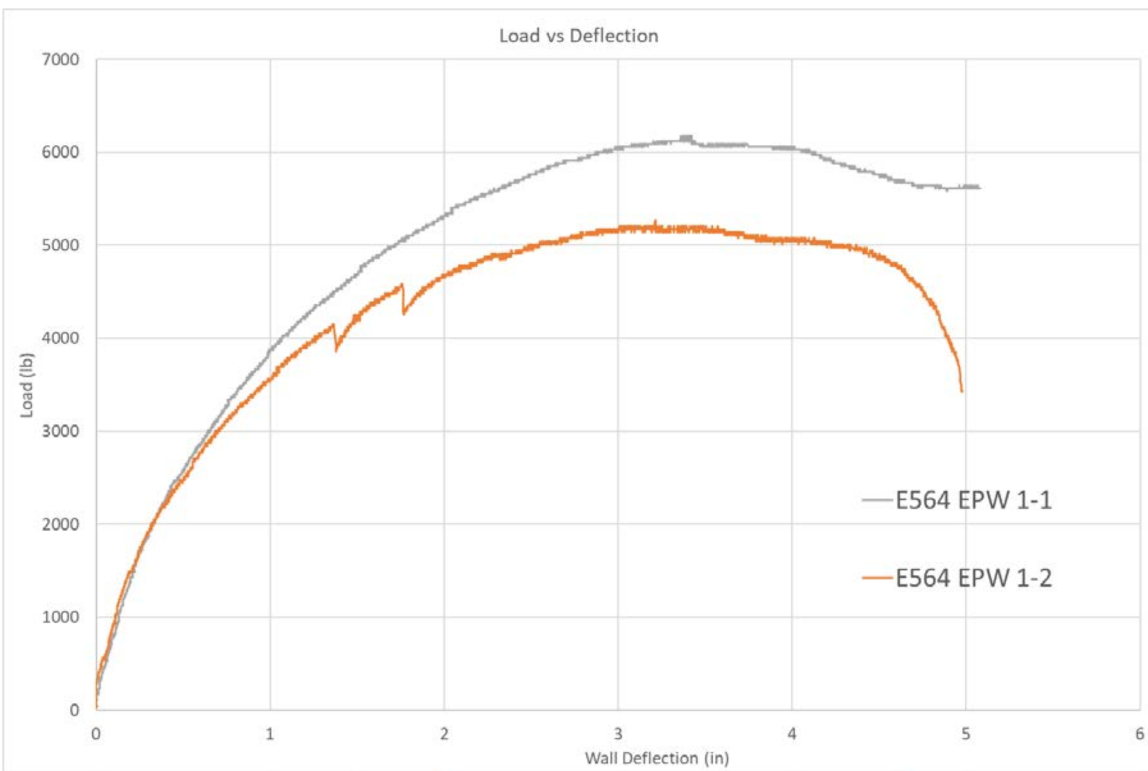


Figure 6. Shear load deflection curves: E564 test—baseline EP&B walls (spruce-pine-fir)

The AC269.1 Section 4.2 ASTM E564 criteria are self-referencing, i.e., the average maximum shear for wall type 1 specimens is used to develop the wall type 2–7 reference values for racking shear strength per the Acceptance Criteria protocol. All EP&B walls were constructed with spruce-pine-fur lumber per 4.2.1, so no species adjustment is required for comparison to target performance values.

Figure 7 graphs the load deflection curves for the EP&B wall specimens of the ASTM E564 tests for IRC continuous braced wall equivalency. Tested values for wall types 2–7 meet all target performance values for both strength and stiffness (drift at reference shear load) per AC269.1. See Table 8.

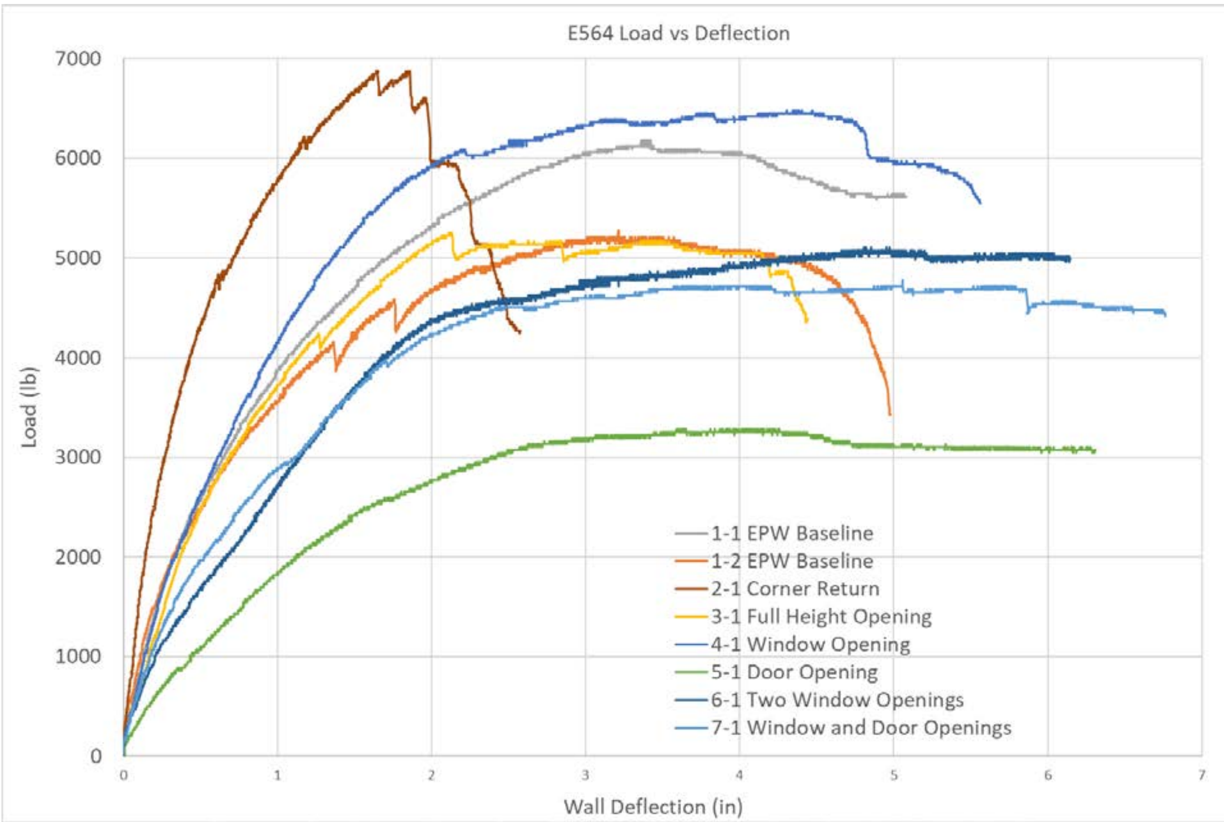


Figure 7. Load deflection curves: E564 test—EP&B walls (spruce-pine-fir)

Table 8. AC269.1 Section 4.2 (ASTM E564) for EP&B Wall Specimens: Wall Types 2–7

Description	Max Shear Load (lb) (Peak Horizontal Racking Shear)	Net Deflection at Peak Load (in.)	Max Unit Shear (lbs/ft)	Reduction Factor	Drift at Ref. Shear Load ≤ 0.6 in.	Drift (Stiffness) Pass/Fail	Predicted Peak Racking Unit Shear Strength (lbs/ft)	Shear Strength Pass/Fail (Max Shear Load > Pred. Peak)
Baseline average	5,728	n/a	716	n/a	n/a	n/a	n/a	n/a
Corner return	6,874	1.46	573	0.79	0.2224	Pass	566	Pass
Full-height	5,255	1.74	438	0.43	0.2571	Pass	308	Pass
Window	6,480	3.65	540	0.65	0.3793	Pass	465	Pass
Door	3,281	3.18	246	0.29	0.4982	Pass	208	Pass
Two windows	5,105	4.49	365	0.41	0.4527	Pass	294	Pass
Wind and door	4,776	4.36	311	0.38	0.3590	Pass	272	Pass

Both E564 baseline walls exceeded the 560 lbs/ft minimum shear strength requirement of Section 4.1 by 18% to 38%, respectively; the average shear strength for the specimen set was 28% above code minimum. This resulted in predicted ultimate racking shear capacity values for wall types 2–7 that are much higher than required for a minimally compliant wall to meet IRC braced wall equivalency.

When the racking shear load performance of EP&B wall types 2–7 is judged in relation to an IRC code-minimum wall with nominal unit shear of 560 plf, wall types 2–7 exceeded the shear strength targets by a range of 30% to 82%. See Table 9.

Table 9. AC269.1 Section 4.2 (ASTM E564) for EPW Wall Specimens with 560 plf (Code Minimum) as Baseline

Description	Max Shear Load (lb) (Peak Horiz Racking Shear Load)	Max Unit Shear (lbs/ft)	Reduction Factor	Predicted Peak Racking Shear Strength at IRC minimum 560 plf	Shear Strength Pass/Fail (Max Shear Load Must Exceed Predicted Peak)	Compare Net Shear Strength to IRC minimum 560 plf
Code minimum	4,480	560	n/a	n/a	n/a	n/a
Corner return	6,874	573	0.79	*442*	*Pass*	*129.5%*
Full-height	5,255	438	0.43	*241*	*Pass*	*181.8%*
Window	6,480	540	0.65	*364*	*Pass*	*148.4%*
Door	3,281	246	0.29	*162*	*Pass*	*151.5%*
Two windows	5,105	365	0.41	*230*	*Pass*	*158.8%*
Window and door	4,776	311	0.38	*213*	*Pass*	*146.4%*

In addition to the EP&B test specimens, standard 2x6 (spruce-pine-fur) IRC CS-WSP reference walls were constructed in conformance with ASTM E72 and tested for comparison only; these reference values are not required for AC269 equivalency. The 2x6 configuration was selected to match the framing material and finished wall thickness of the EP&B walls to allow for direct comparison. Sheathing for the 2x6 standard reference wall was attached using collated 2-3/8-in. 0.131-diameter clipped head nails with 6/12-in. o.c. nail spacing. IRC reference walls were constructed with spruce-pine-fir lumber.

The calculated allowable design racking shear load value for the EP&B wall system is 256 lbs/ft., the lesser of the loads determined based on the ultimate load limit and the drift limit, in accordance with sections 4.2.3.1 and 4.2.3.2. See Table 10.

The averaged result of two 2x6 IRC reference walls having the same width as the tested EP&B specimens is included for comparison only (it is not an Acceptance Criteria requirement).

Table 10. Results of AC269.1 and ASTM E72 Shear Tests: EP&B and IRC 2x6 Walls

E72 Shear Capacity Comparison	Target	2x6 IRC Comparison Wall (Spruce-Pine-Fur)	EP&B (Douglas Fir-Larch)
Unit shear (lbs/ft) min (set)	560	618/652	834/856/882
Unit shear (lbs/ft) (average of set)		635	858
Unit shear average (lbs/ft) (EP&B normalized to spruce-pine-fur)		635	767
Ultimate load (safety factor=3)		206	256
Drift limit		284	268
Allowable design racking shear load value, psf (lesser value: ultimate load vs. drift limit)		206	256

All tested EP&B walls exceed the required shear strength criteria. The average maximum unit shear load in lbs/ft for the 3/6 EP&B walls, adjusted for the wood species, exceeds the 560 lbs/ft unit shear requirement by 207 lbs. (37%).

2.4 Field Test

The EP&B system was evaluated in two demonstration houses in Grand Rapids, Michigan, Climate Zone 5. The 2x4/2x6 EP&B design of the Building America demonstration houses used 2-in. extruded polystyrene (XPS) rigid foam continuous insulation, OSB exterior structural sheathing, high-perm WRB, and a flash coat of closed-cell spray polyurethane foam (ccSPF) approximately 1-in. thick with blown fiberglass cavity fill insulation. In each of the two test houses, two comparison bays were constructed with R-15, 3½-in. thick, Kraft-faced fiberglass batts for comparison to more traditional insulation methods. There appears to be almost no difference in performance between the two methods, as described in the Moisture Evaluation section and detailed in Appendix D.

The EP&B field tests led to several system improvements, which are detailed in the companion *EP&B Construction Guide* (Home Innovation Research Labs, 2018); however, the photographs and site observations necessarily show the original, field-tested configuration. The first design for the EP&B wall extended only two of the three wall plates—the bottom and the second top plate—and used 4-in. nails with a slightly different fastening schedule. Although this configuration was strong and minimized thermal bridging due to framing, improvements to reduce complexity and cost were found. The appendix contains additional background information, including interviews with project contractors. Both the contractor and the framer considered the cost, performance, and simplicity of EP&B to present a compelling choice for the large cohort of builders who have not yet transitioned to high-R wall systems. They both noted that the steepest learning curve for EP&B is the nailing angle at studs where wood sheathing panels meet. This can be overcome with proactive training and practice. Figure 8 and Figure 9 show the very traditional appearance of the completed homes.

Figure 8. House 1 front (left) and back (right)

Figure 9. House 2 front (left) and back (right)

2.4.1 Demonstration Houses

2.4.1.1 General Contractor

The partner builder for the two Grand Rapids test houses, Arn McIntyre, typically constructs high-performance homes with better than code thermal performance and much lower than average envelope air leakage (< 2 ACH).

For builders—such as McIntyre—who use FPIS as the building's only sheathing (also called "open framing"), the EP&B wall is a net materials cost increase (the addition of OSB or plywood sheathing). Because of this added net cost, McIntyre reports he is unlikely to replace his own current practice with EP&B; however, he considers EP&B a strong choice for builders who have not yet made the transition to a high-R wall and who are looking for a safe, constructible, reliable, high-performing solution. He pointed out that EP&B is likely to be less expensive than proprietary panels with rigid foam laminated to the WSP, and it provides more flexibility in the choice of rigid foam. He considers EP&B to be very cost-competitive against traditional foam over-sheathing as well as more moisture resilient and potentially less complex with regard to detailing and window installation.

McIntyre's siding subs have been executing his standard foam sheathing-only design for nearly 15 years and have a high degree of comfort and accuracy attaching cladding by nailing through foam with long fasteners to engage the framing. One of the strengths of EP&B is the ability to use shorter but more frequent nails attached to the WSP per IRC Table 703.3.2 (in lieu of framing engagement). This allows the use of a nail gun and provides much more flexibility in nail placement. McIntyre believes that it would be a net savings for siding crews who do not have the same level of experience as his own crews do.

McIntyre noted that the EP&B has the immediate advantage of locating the OSB outside of the wall cavity, to address moisture and condensation, and it also incorporates a full 2 in. of rigid foam to maintain cavity temperatures in a safer range than that provided by a 2x6 wall in Climate Zone 5 and up.

2.4.1.2 Framer

The partner framer for the two Grand Rapids test houses, Kevin L. Smith, has framed McIntyre Builders houses with 1½-in. FPIS (only) and let-in bracing for many years. He is very comfortable with the necessary adjustments to window installation and detailing to specifically address the FPIS/lumber framing interface.

Smith and his crew also work for other builders in the area, so they were able to knowledgeably compare the EP&B process to both traditional framing methods and FPIS continuous insulation installed exterior to standard WSP.

As a result of the field tests, the nailing schedule for the EP&B wall has been modified for practicality. The new configuration extends all three plates and uses 3½-in. nails, which are readily available, reasonably priced, and fit into almost any nail gun that is currently in a framer’s tool trailer. The WSP attachment follows a perimeter/field schedule that will be familiar to most framers (as opposed to the original plate/stud pattern).

Smith and the framing crew were able to identify time-saving methods and suggest several tools for simplification, such as:

1. An 8-in. reciprocating saw blade (6 in. is too short)
2. A 3-in. hand blade available for manual foam cuts
3. Cutting a 2-in. jig from scrap wood to ensure the correct offset for the rigid foam layer when end-nailing studs to plates.

Smith estimated that it took approximately 30% additional time to frame the EP&B walls compared to the typical McIntyre Builders wall (foam sheathing only). He estimated the EP&B wall would take the same or less time than a wall with continuous insulation over WSP (both have two layers of sheathing). He also predicted that EP&B framing time would be reduced for subsequent builds because of a relatively short learning curve.

When bidding the two EP&B projects, Smith added a $500 labor and materials premium because of the double sheathing effort and the additional materials: OSB and Tyvek. The rigid foam for the two projects was donated by industry partners.

One surprising advantage noted by the framing crew was that they appreciated the limited need for cap nails, which they described as irritating to work with—the nails are thin, bend easily, leave a mess around the work site, and are not handy in their nail pouch.

Other opportunities for savings were related to framing. For houses with FPIS as the only sheathing, doubled trusses are typically used at each gable end to ensure bearing over the wall framing, or other means are necessary at that interface to achieve a flush gable-end profile. This added cost and complexity exists for walls with exterior continuous insulation over WSP (foam over-sheathing), as well. The roof truss at the gable end of an EP&B wall can bear on the extended 2x6 plates with the 2x4 vertical framing member below. Also, with the FPIS-only sheathing and exterior continuous insulation methods, the crew generally adds a 1x6 sill at the bottom of each window opening to support window weight. This is not necessary with EP&B. In a traditional WSP-braced wall with exterior continuous insulation, the window and door bucks must often use 2x6 framing to extend to the exterior plane of the foam sheathing, which is also not necessary for EP&B walls.

As with all wall construction, joining wall sections require standard attention to sealing details.

2.4.2 Panelization Opportunities

2.4.2.1 Zeeland Truss and Components

Zeeland Lumber & Supply is a Midwest company that serves Michigan, northern Indiana, and northwest Ohio. Their manufacturing shop in Wyoming, Michigan, produces trusses and other light-frame building components for local markets.

According to plant manager Dean DeHoog, Zeeland has been supplying wall panels for local projects since about 1995, but the demand picked up drastically in 2014, warranting a plant expansion. The yard now has two identical covered and conditioned wall panel facilities, each with a heavy-duty adjustable bridge nailer as well as planning, measuring, cutting, and bundling stations. Zeeland designs, constructs, bundles, and stores wall panel and truss packages in the yard using the just-in-time approach to minimize project expenses. Zeeland has found it relatively easy to meet the delivery and construction schedules of several local architects and builders, and it has a reliable and loyal customer base. Their typical project for wall panels is a two- to five-story multifamily building in an urban setting. DeHoog noted that panelized construction is especially cost-effective in busy city conditions where staging area is limited. In some cases, Zeeland can deliver a panelized project from curbside with a crane or loader that can place each bundle in the required deck location. Each of the local construction companies with long-standing experience with Zeeland’s wall panels have now developed crews that can very quickly and efficiently erect the walls and close in the building.

Supplying both prefabricated trusses and wall panels allows for budget balancing; the trusses tend to save money upfront, and the wall panels cost a bit more so that for the same immediate cash outflow (as field-framing) the customer can realize savings later in the project because of quicker build times. DeHoog also said that there are time savings associated with the precision of prefabricated components, especially regarding straightness.

DeHoog speculated that the EP&B wall system may represent savings to certain prefabricators who can benefit from nonproprietary materials and the potential for a prescriptive braced wall solution (rather than an engineered design) as well as for clients who may want to choose particular materials (e.g., plywood versus OSB or XPS versus polyisocyanurate [PIC]).

At the time of the interview, the Zeeland panel plant was booked nine months in advance, indicating good local interest in wall panelization.

2.4.2.2 StarkTruss Panel Factory: NYSERDA Panelized EP&B Test House

In 2015–2016, the New York State Energy Research & Development Authority (NYSERDA) sponsored a high-impact research project on a demonstration house built with EP&B wall panels produced at a building components plant in Whitesboro, New York. The design used 2x4 lumber for the studs and first top plate and 2x6 lumber for the bottom and second top plates, with 2-in. XPS R-10 rigid foam, 7/16-in. OSB exterior structural sheathing, and 3.5 in. of R-15 unfaced fiberglass batts in the wall cavity.

The purpose of this project was to use the EP&B innovation to demonstrate a path for panelizers to add the energy-efficiency component of continuous insulation to the traditionally structure-only product and to participate in the high-performance construction market.

<u>Summary: Panel Production in the Factory.</u> The plant manager reported no difficulties in drafting the EP&B wall system. The addition of the rigid foam board accounted for the largest change to the team’s typical process. Cutting the foam proved to be the most time-consuming aspect of the EP&B wall construction.

After cutting some wall openings by hand, the production team was eventually able to locate a router bit long enough to span the combined depth of the 2-in. foam and 7/16-in. OSB. This allowed the crew to cut window and door openings at the typical location in the production line, after the foam had been installed over the studs and the OSB had been placed and fastened.

The 4-in. nails and framing gun required for fastening the OSB to the studs through the foam proved to be a challenge. Neither are typical and had to be special ordered (the nail length has since been modified). The plant manager and research project field representative both reported that the learning curve appeared to be short.

The plant manager estimated that for future projects he would plan to budget approximately another $500 to cover the necessary training and tooling changes to successfully bid and build EP&B wall panels. He predicted that with two or potentially three EP&B projects in close succession, any wall panel plant could optimize their processes so that little additional fee would be required, other than passing on the cost of the rigid foam.

Summary: Panel Erection On-Site. The wall panels arrived on-site and were moved as required with no apparent damage. The framing supervisor reported only two potential quality issues with this EP&B project: detailing the air gap between neighboring panels (true for any panelized wall system) and nails at studs that missed framing (this appeared to be more problematic with EP&B than with other panelized wall systems). He noted that a bridge nailer at the panel plant would likely solve this problem.

The framing supervisor noted there is some advantage to siding and window installation with EP&B compared to rigid foam over OSB because shorter nails can be used and less framing is required. He said that for a framing-only contract (no window installation or water or air sealing), he would bid and staff the project similarly to any other panelized wall system.

For any panelized project, whether standard or EP&B, he recommended care with air sealing, especially where wall panels meet. The framing supervisor has used a flash coat of ccSPF on other projects, and he suggested that it would also be a good solution for air sealing the EP&B wall system.

2.5 Moisture Evaluation

2.5.1 Moisture Monitoring: Instrumentation and Methodology

Monitoring of the walls in the Grand Rapids test houses is accomplished using commercially available sensors and data loggers from Omnisense. The sensor integrates a wireless transceiver, temperature sensor, humidity sensor, and pin type (resistance) moisture meter and has a battery life that can last up to 15 years. The sensors are permanently embedded in the EP&B wall structures for long-term building envelope performance monitoring. A wireless data logger with built-in cellular capabilities (Gateway, also from Omnisense, installed in the garage) collects and transmits that data to the manufacturer’s website for storage and periodic downloading for analysis.

Figure 10 and Figure 11 itemize the equipment used in both Grand Rapids demonstration house to monitor wood moisture, temperature, and RH.

Figure 10. Omnisense Gateway data acquisition unit

Figure 11. Omnisense T/RH%/MC% sensor

2.5.2 Moisture Monitoring: Data Type and Interpretation

The data collected from the sensors includes the local temperature and RH as well as the MC of the wood to which it is attached. See Appendix C for specific details.

The data logger is set to collect data at approximately 15-minute intervals. Data are uploaded continuously to a website for data storage; battery backup allows temporary local storage in the event of a power interruption. The Omnisense acquisition protocol processes this raw data to calculate the dew point and grains of moisture based on the temperature and RH. The MC data were calibrated to a standard wood MC% based on the temperature at the wood surface.

The data set stored on the website was downloaded on a monthly basis and averaged on several different time intervals (hourly to daily) for further analysis and charting. Twelve-hour averages are used in the graphs in this report.

The EP&B wall system is evaluated based on MC, temperature, and RH. The data from walls with north exposures is especially pertinent because this orientation represents a worst-case scenario, having less opportunity to dry out because of reduced solar exposure.

A key moisture performance characteristic is the fiber saturation point—the MC (percentage) at which only the cell walls are completely saturated (all bound water), but no water exists in cell lumen. Thirty-percent MC is considered the maximum fiber saturation point for solid wood. For OSB, the fiber saturation point is three to five percentage points below that of solid wood products, approximately 26%. As a design principle, wood and wood-based materials in buildings should be maintained at MC levels below the fiber saturation point, preferably with a margin of several percentage points. Above 20% MC, there may be a risk for moisture performance problems—actual limits are not well defined.

The MC of the lumber and WSP in the demonstration house was documented over time using the Omnisense monitors to determine MC trends in relation to seasonal temperature and RH (indoor and outdoor). Interior and exterior ambient conditions were also monitored and recorded with Omnisense equipment.

2.5.3 Moisture Monitoring: Sensor Placement in Building and Walls

Previous simulation and field-testing has indicated that most walls have ample opportunity to dry out diurnally and seasonally if they face south or west. Walls with east and especially north exposures encounter the most challenging moisture conditions, in large part because they get little or no direct sunlight. In these two field tests, the north and east walls were defined as primary walls for monitoring; House 1's east wall connects directly to the attached garage, so no sensors were placed in that wall.

For each house, a centrally located sensor in a public area reports temperature and RH inside the building, and an exterior sensor was installed below the back deck with protection from sun and wind to monitor outdoor ambient conditions. Bathrooms with sensors installed in the walls also have ambient sensors to record local temperature and humidity, which are expected to be different than in public areas because of bathing activities.

In each house, at least one stud bay with a north exposure was air sealed with acrylic caulk and had Kraft-faced batts installed. Otherwise, both houses received the builder partner's typical insulation: a flash coat of ccSPF for air sealing, approximately 1-in. deep, followed by blown-in fiberglass.

House 1 had 36 total sensors, and House 2 had 33. See Figure 12 and Figure 13 for the sensor layouts of the two houses. See Table 19 and Table 20 in Appendix D for a summary of the purpose and coverage of each sensor.

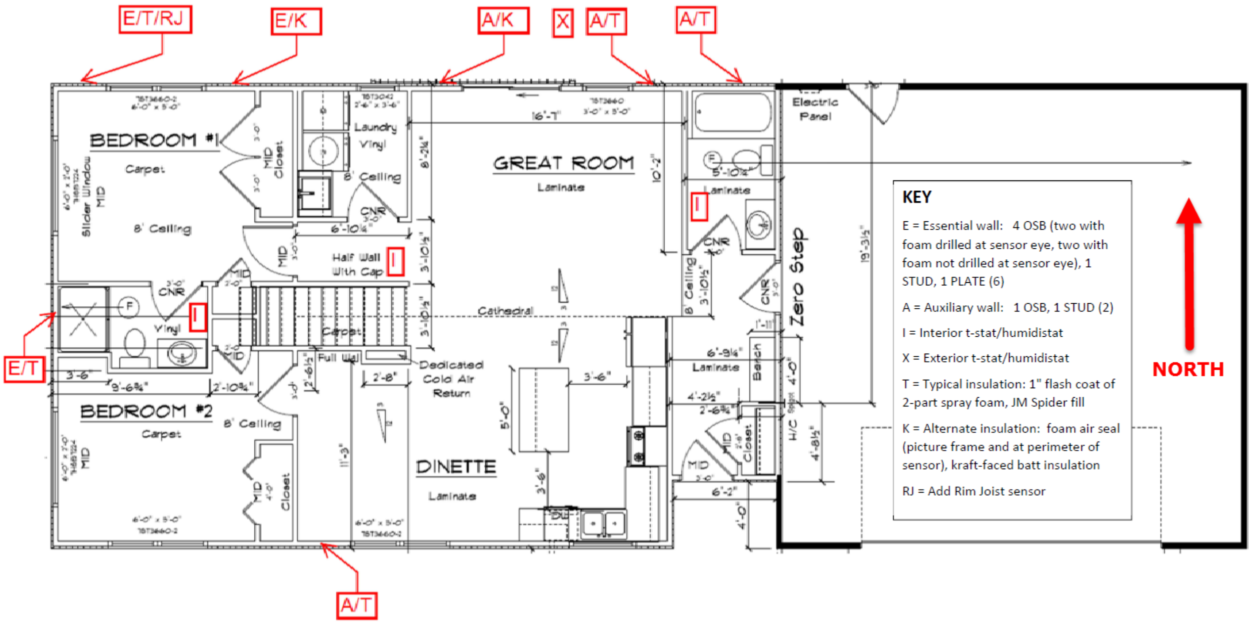


Figure 12. Sensor layout, House 1

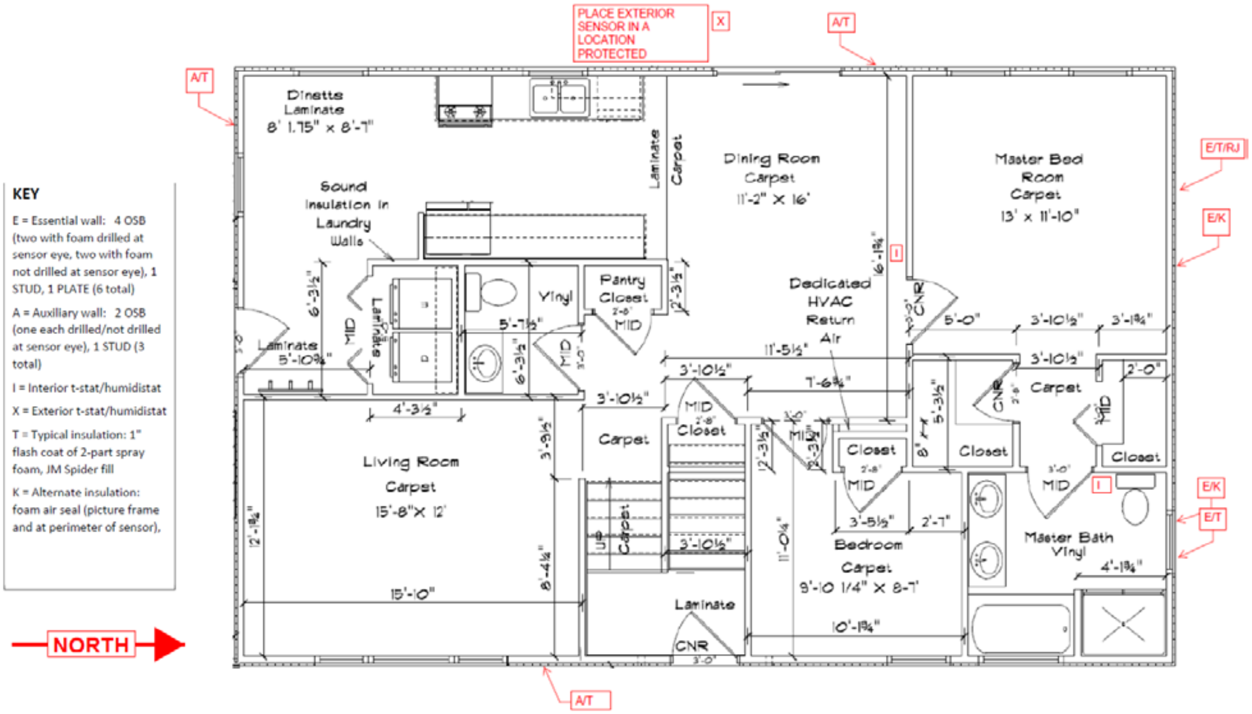


Figure 13. Sensor layout, House 2

2.5.4 Moisture Monitoring: Results

2.5.4.1 Data Characteristics

Data acquisition began in August of 2016, soon after occupancy. Interior and exterior ambient temperatures and RH readings are within expected ranges. See Figure 14 through Figure 17 for recorded interior and exterior ambient conditions. One full year of data has been gathered for both houses, and the sensors will remain in place for a second full year of monitoring to determine performance without the potentially confounding issue of construction moisture drying and to capture more typical winter conditions.

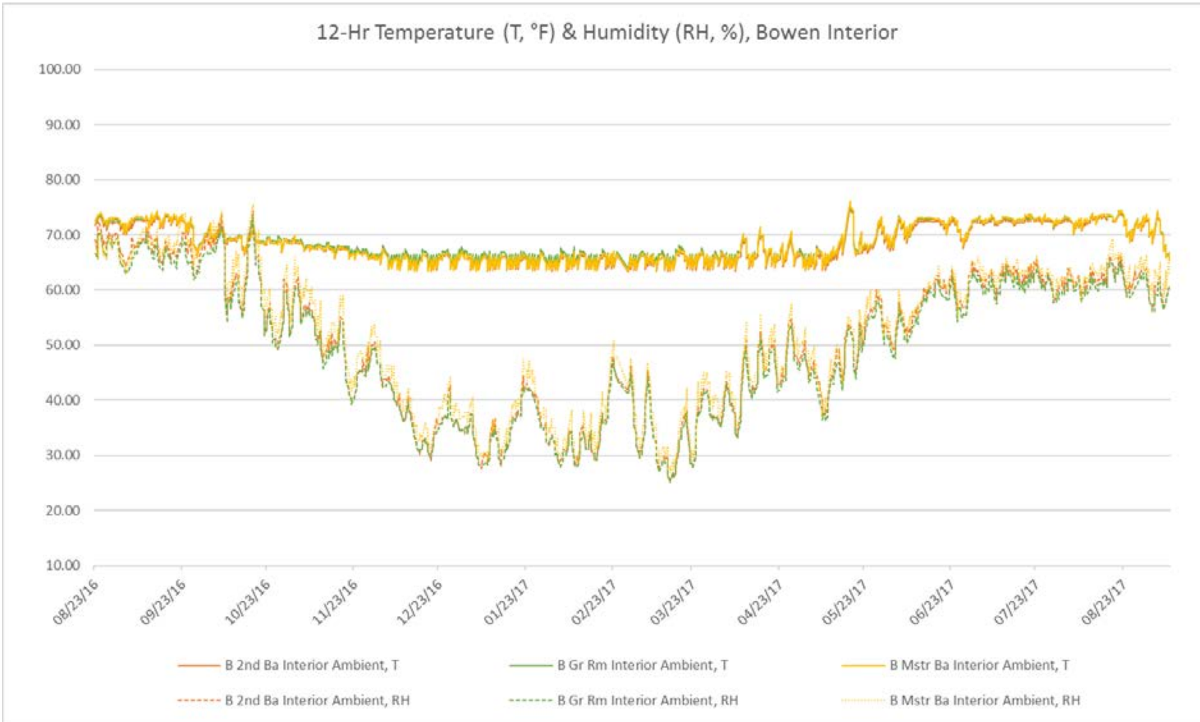


Figure 14. Interior ambient temperature and RH, House 1

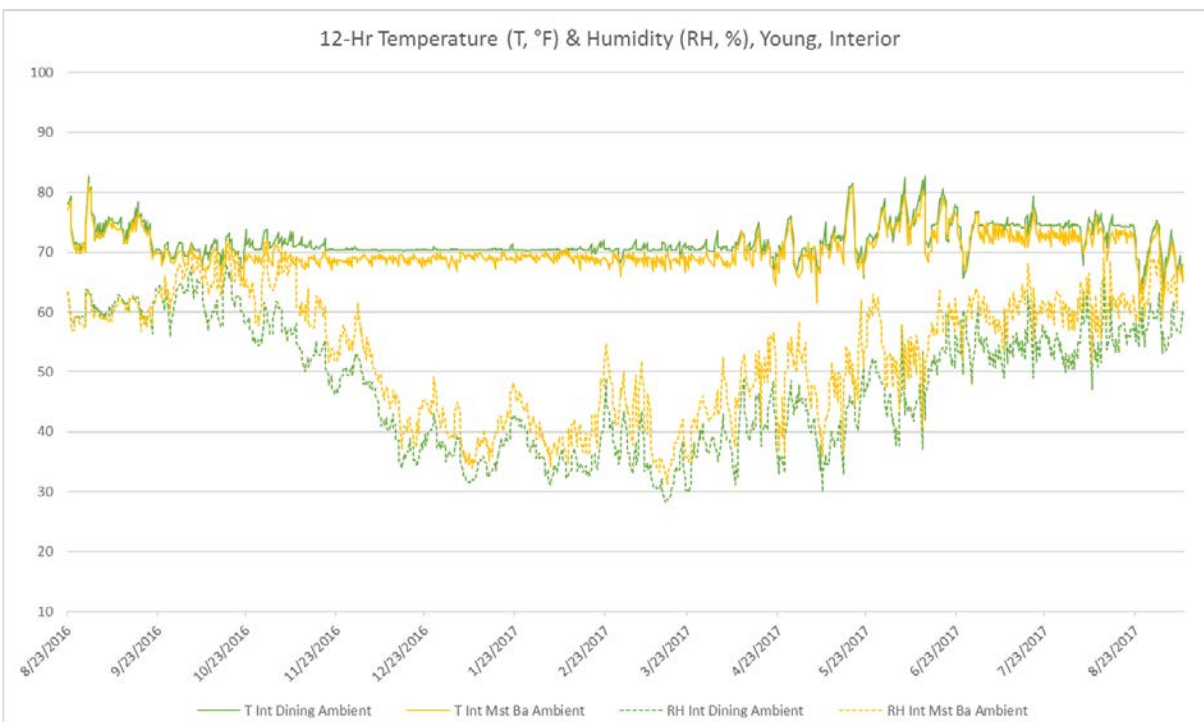


Figure 15. Interior ambient temperature and RH, House 2

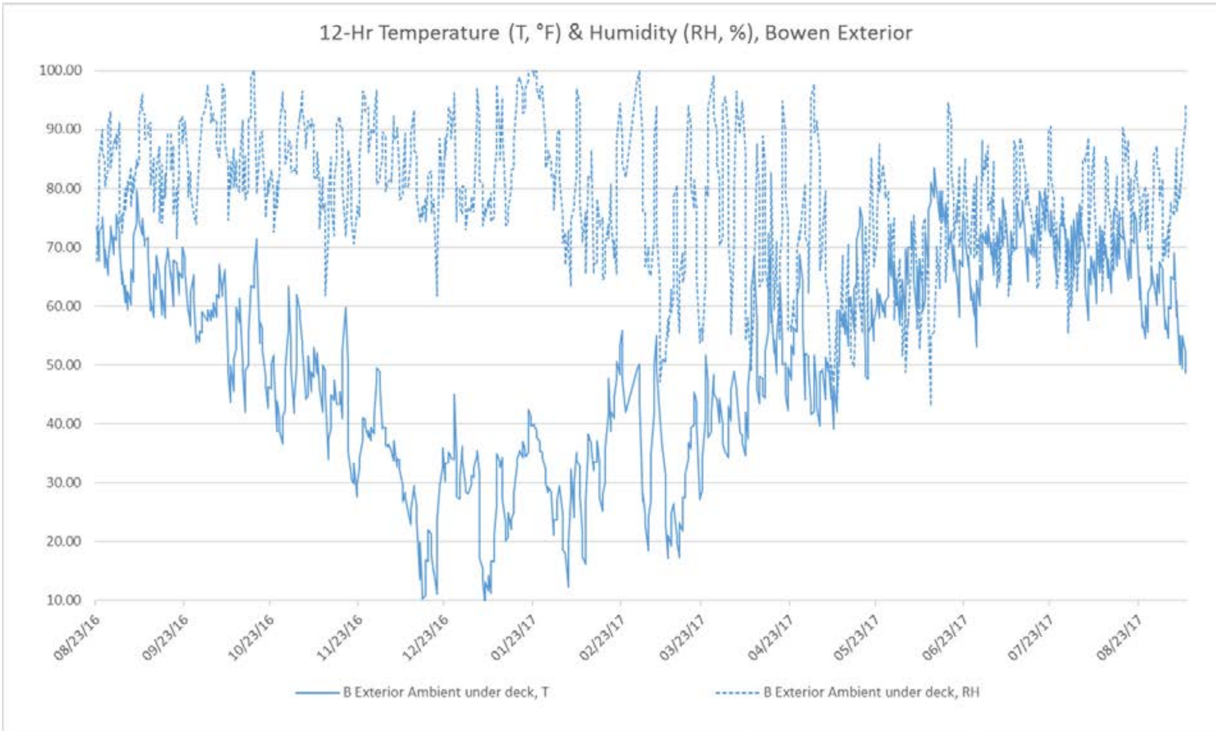


Figure 16. Exterior ambient temperatures, House 1

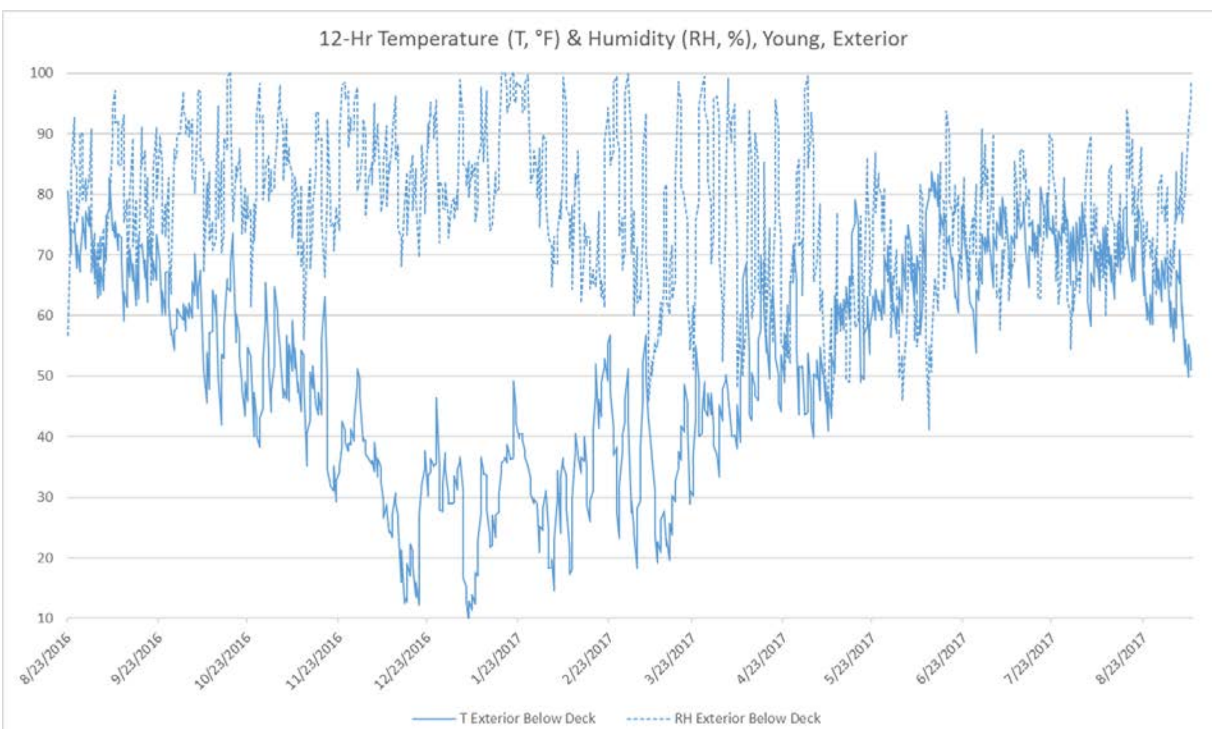


Figure 17. Exterior ambient temperatures, House 2

2.5.4.2 Wall Cavity Moisture

The sensors measuring the MC of studs and plates also record the RH within the wall cavities and provide local dry bulb temperatures and dew points. Beyond the advantage of overall thermal resistance, the location of the rigid foam continuous insulation layer in an EP&B wall is intended to protect the wall cavity from liquid water by maintaining the temperature above dew point. Condensation—100% RH—can result when surface temperatures drop below dew point. Although temporary conditions conducive to condensation can be tolerated, long-term wetness within a wall cavity indicates high risk; liquid water could wet the construction materials and allow the growth of mold, rust, and odors, and it could also eventually weaken structural materials. In both houses, the RH within the wall cavities remained less than 80% except for a single sensor in House 1, which peaked briefly at 82% in November. Wall cavities in both houses averaged between 40% and 60%, close to the coincident interior conditions.

The purpose of an interior vapor retarder is to protect the wall cavity when outward vapor drive is high, such as when warm, moist indoor conditions are coupled with cold, dry outdoor conditions. Both insulation/vapor retarder schemes (ccSPF with blown fiberglass and Kraft-faced fiberglass batts) used in the two test houses performed well. The dashed lines in Figure 18 and Figure 19 show the 12-hour average wall cavity dew point temperatures, and the solid lines show the wall cavity dry bulb temperatures for the full year of monitoring. Except for very brief periods, the local dry bulb temperature (expected to be similar to the material [stud] temperature as recorded) within all wall cavities in both houses remained safely above the local dew point temperature.

Theoretically, if the interior vapor retarder were to be breached, moisture-laden air from the interior might enter the wall cavity. The following pair of graphs (Figure 20 and Figure 21) shows that even intrusion by the worst-case interior air (bathroom areas—solid black line) is not likely to produce condensation. Again, except for very brief periods, the local temperature for all wall cavities in both houses remained safely above the coincident interior ambient dew point of air from within the house, indicating that the EP&B provides good moisture protection. The solid lines in Figure 20 and Figure 21 show the wall cavity dry bulb temperatures for each house; the solid black line shows the dew point temperature of the air inside the building for the two most challenging months: October and November.

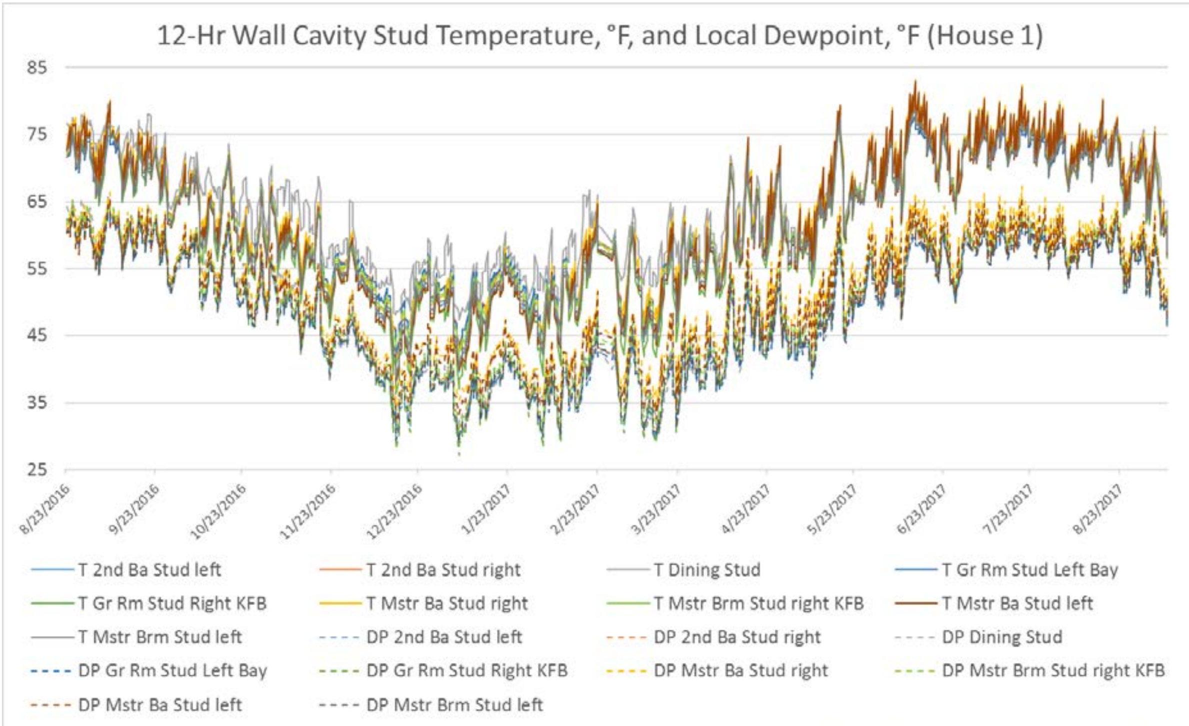


Figure 18. Wall cavity temperatures and dew points, House 1

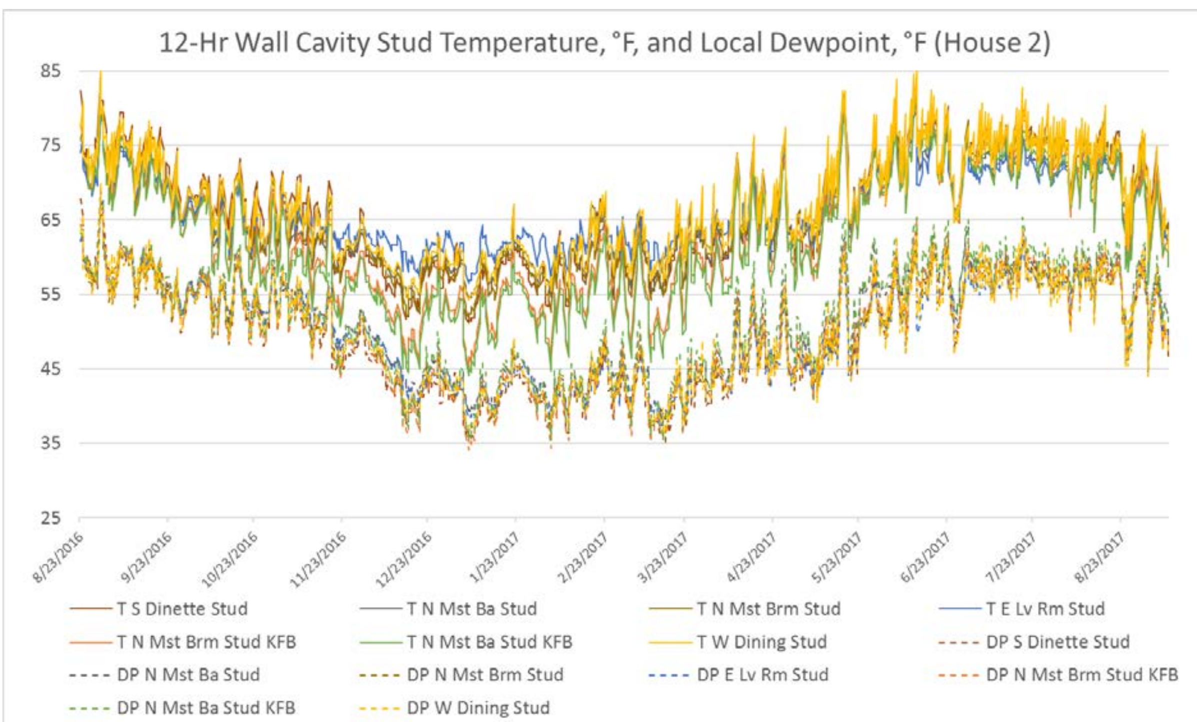


Figure 19. Wall cavity temperatures and dew points, House 2

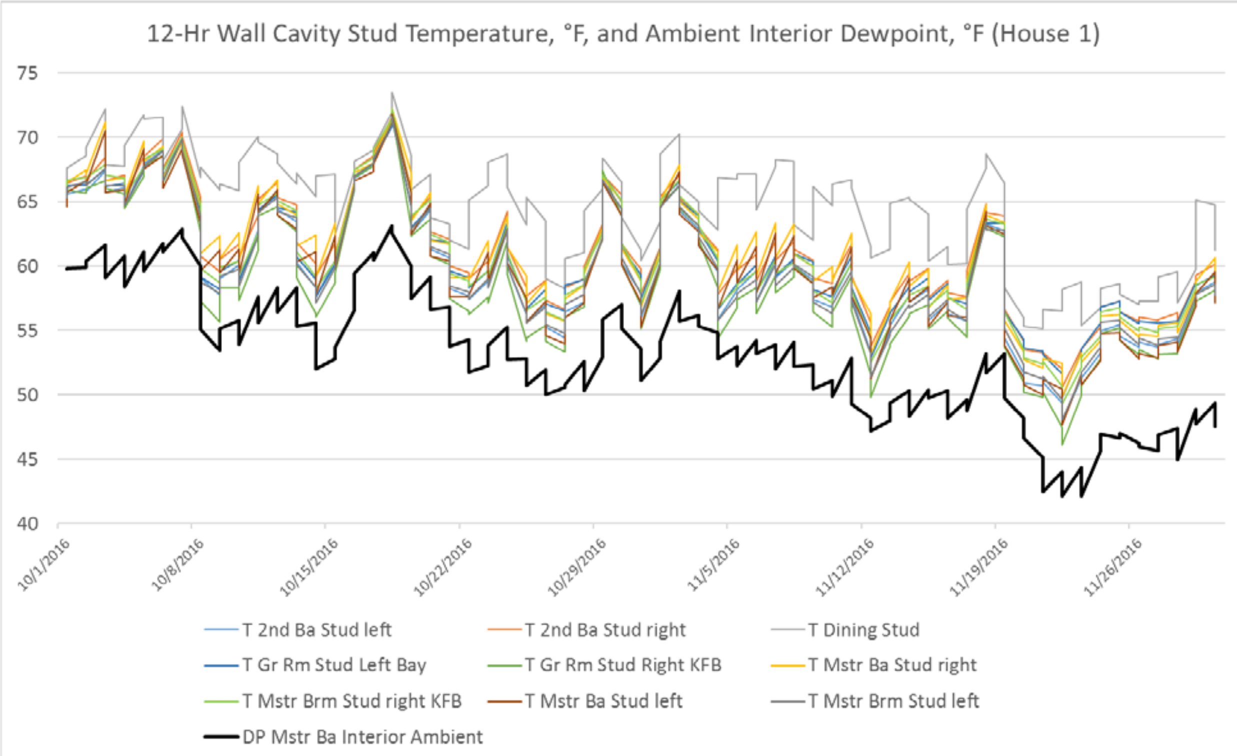


Figure 20. Wall cavity temperatures and house interior ambient dew point, House 1

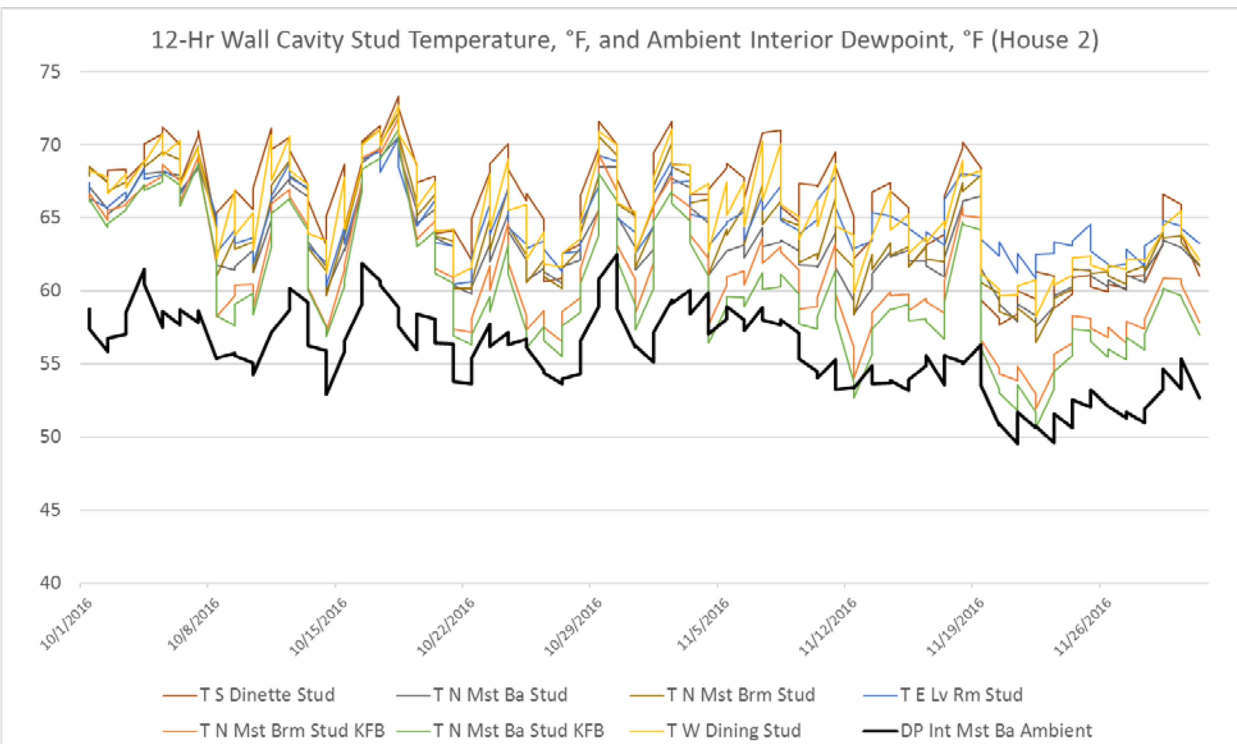


Figure 21. Wall cavity temperatures and house interior ambient dew point, House 2

2.5.4.3 Wood Moisture Content

Because MC of wood is a value calculated internally by the sensor based on the measured resistance across the pins (screws embedded in the wood) and adjusted according to local temperature, the calculated adjusted temperatures (T_{adj}) were used to correct the MC readings to actual. The methodologies for both adjustments (temperature and MC) are detailed in Appendix C.

Based on appropriately adjusted temperature and MC data, including calibration for wood species and type as previously described, EP&B walls in both houses exhibited good moisture performance.

2.5.4.4 House 1 OSB Moisture Results

Per the instrumentation and methodology discussion, for OSB the fiber saturation point is assumed to be approximately 26%. For the purposes of this study, MC above 20% indicates potential risk for moisture performance problems.

The following summary describes the 12-hour averaged MC for OSB in the House 1 walls for the full 12-month monitoring period of the field test:

- All walls: 10.6% MC average, 14.1% average peak and 28.3% maximum peak
- North-facing walls: 10.7% MC average, 14.3% average peak and 28.3% maximum peak
- South- and west-facing walls: 10.2% MC average, 13.6% average peak and 15.3% maximum peak
- Peak OSB MC for 19 out of 20 EP&B walls never rose above 17.6%
- All walls ultimately dried to below 11% during summer, 2017.
- On the north side, a single sensor recorded a maximum peak of 28.3% MC and a one-year average of 15.4%. This sensor is considered an outlier because three other OSB sensors in the same stud bay and within a distance of 18 in. had a combined average of 11.3% MC and respective maximums of 13.8%, 16.3%, and 17.6% MC. A discussion of this outlier is included in Appendix D under “Moisture Data Results and Analysis: Outlier Sensor.” This value has been removed from the data presented here to avoid skewing the averages.

As previously described, north-facing walls are expected to exhibit the highest MC readings because of the lack of direct sun to dry materials and the generally lower temperatures at north-facing walls.

Figure 64 graphs the 12-hour averaged MC readings for all sensors monitoring OSB in House 1 for a 12-month period starting in August, 2016 (outlier removed).

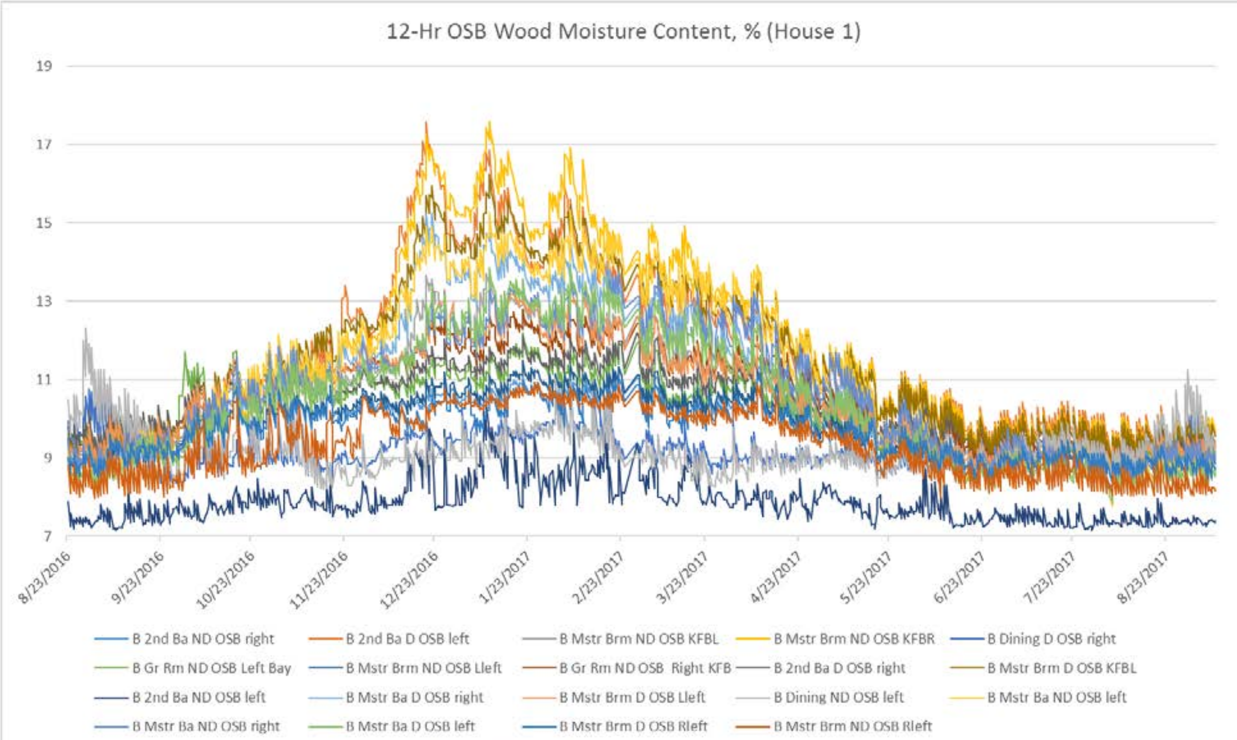


Figure 22. Moisture content for OSB in all EP&B walls, House 1

The following pairs of graphs illustrate various comparisons of OSB moisture readings in House 1.

Figure 23 and Figure 24 Comparing SPF/Fiberglass to Caulk/Kraft-Faced Batt Insulation. Both methods provide good moisture performance, but the ccSPF/blown fiberglass approach may potentially provide benefit by reducing moisture migration through the wall compared to the caulk-sealing/Kraft-faced batt insulation approach.

Figure 25 and Figure 26 Comparing Orientations. When controlled for construction configuration (ccSPF/fiberglass insulation only), EP&B walls with north orientations exhibit higher MC peaks and averages, and somewhat less stable behavior over time, than EP&B walls with south, east, and west orientations.

Figure 27 and Figure 28 Bathroom Wall Moisture Content. House 1 has two bathrooms: a master bath with a west orientation and a guest bath with a north orientation. The owner of House 1 is a single adult male; the guest bathroom is very seldom used for bathing. The moisture performance of the four OSB sensors in the guest bathroom appears to vary gradually with seasonal changes. The master bathroom appears to be more varied and responsive to daily and weekly changes, presumably because of more frequent bathing activities.

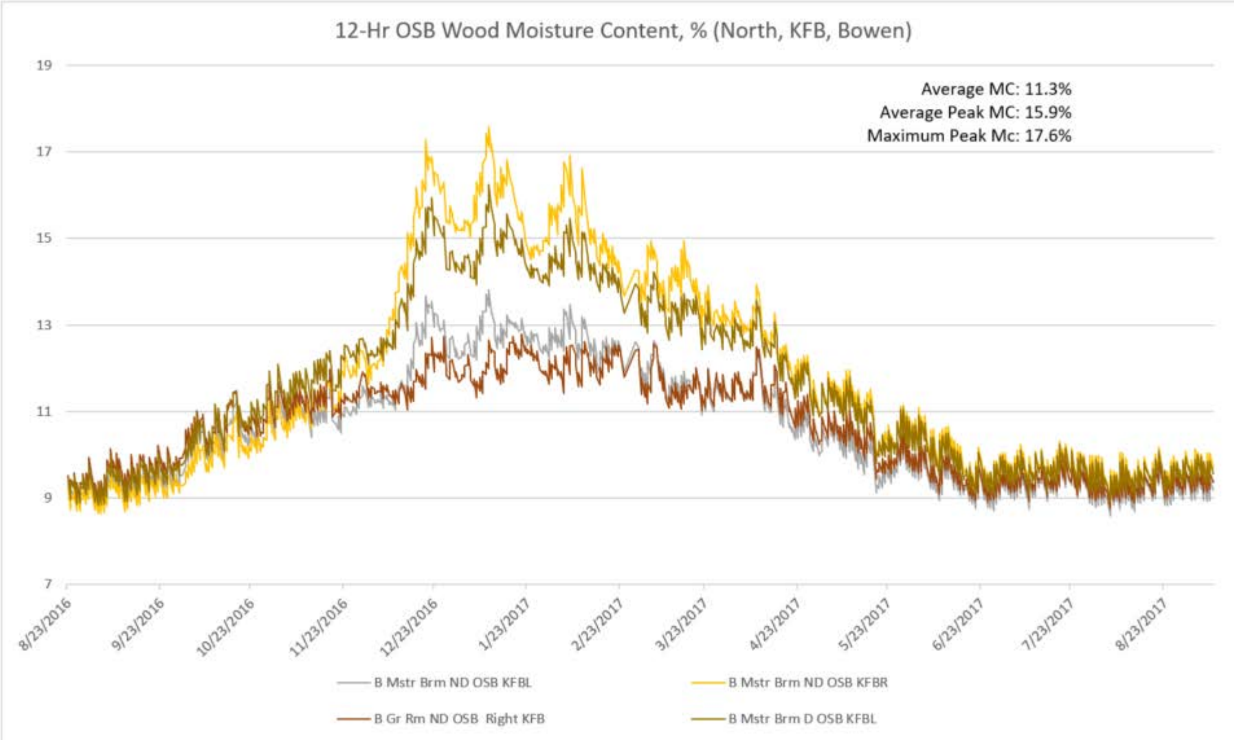


Figure 23. Moisture content for OSB in EP&B walls with acrylic caulk air sealing and Kraft-faced batt insulation, House 1

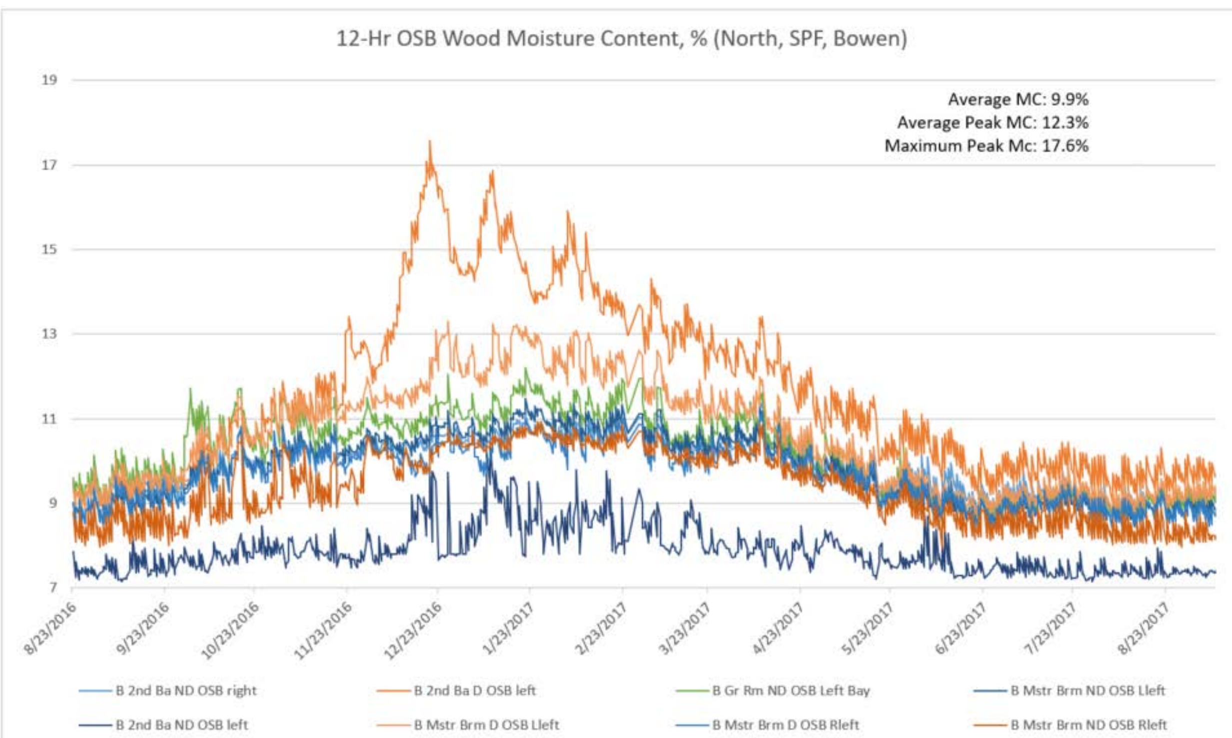


Figure 24. Moisture content for OSB in EP&B walls with ccSPF air sealing and blown-in fiberglass insulation, House 1

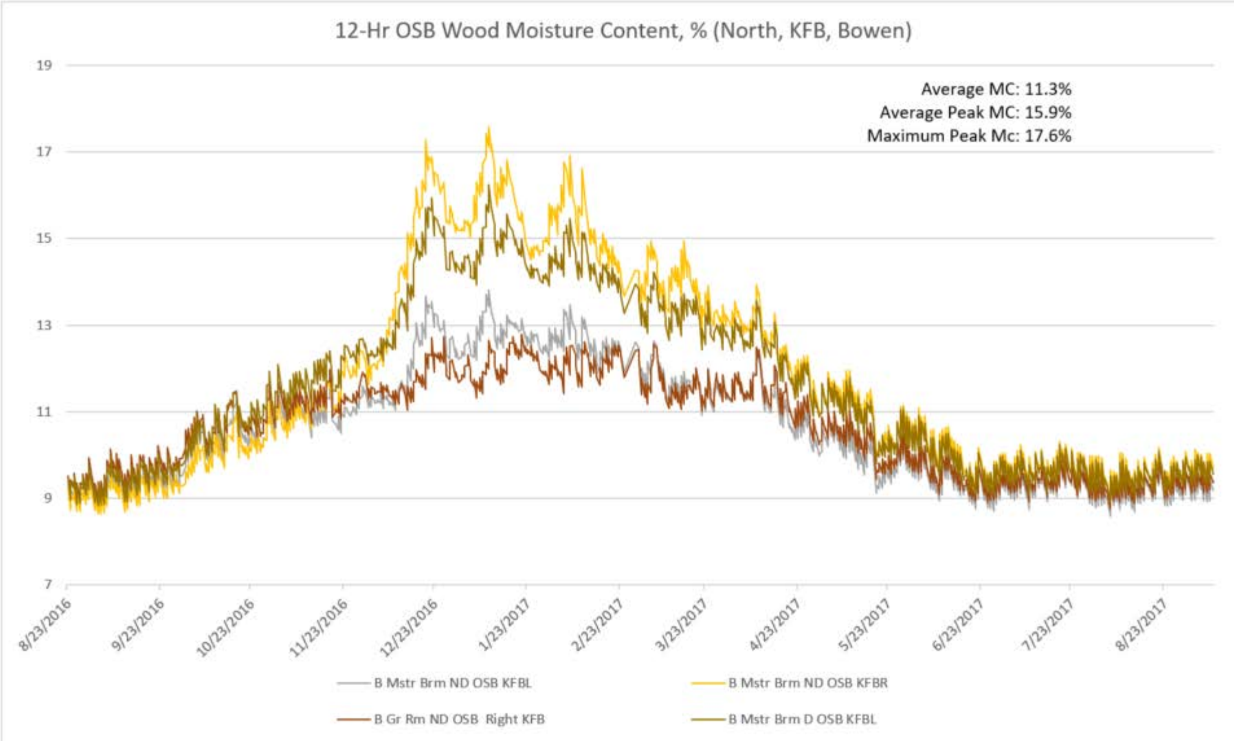


Figure 25. Moisture content for OSB in EP&B walls with ccSPF, north orientations, House 1

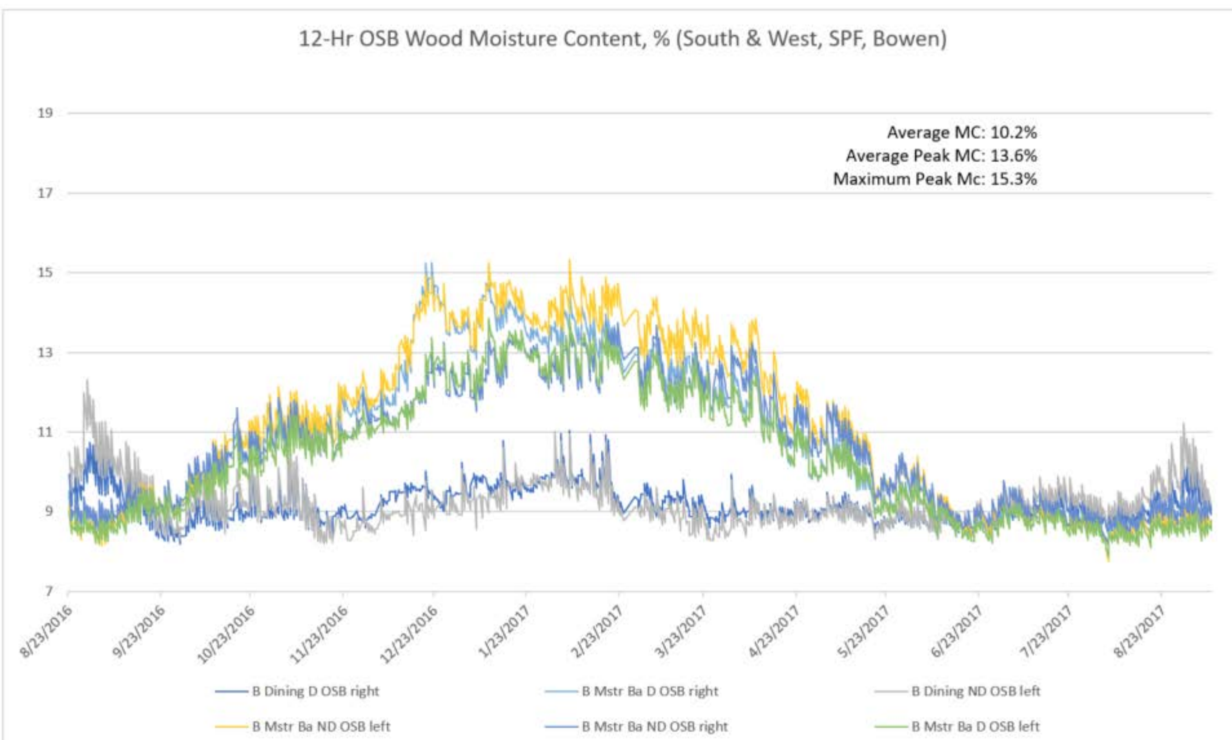


Figure 26. Moisture content for OSB in EP&B walls with ccSPF, non-north orientations, House 1

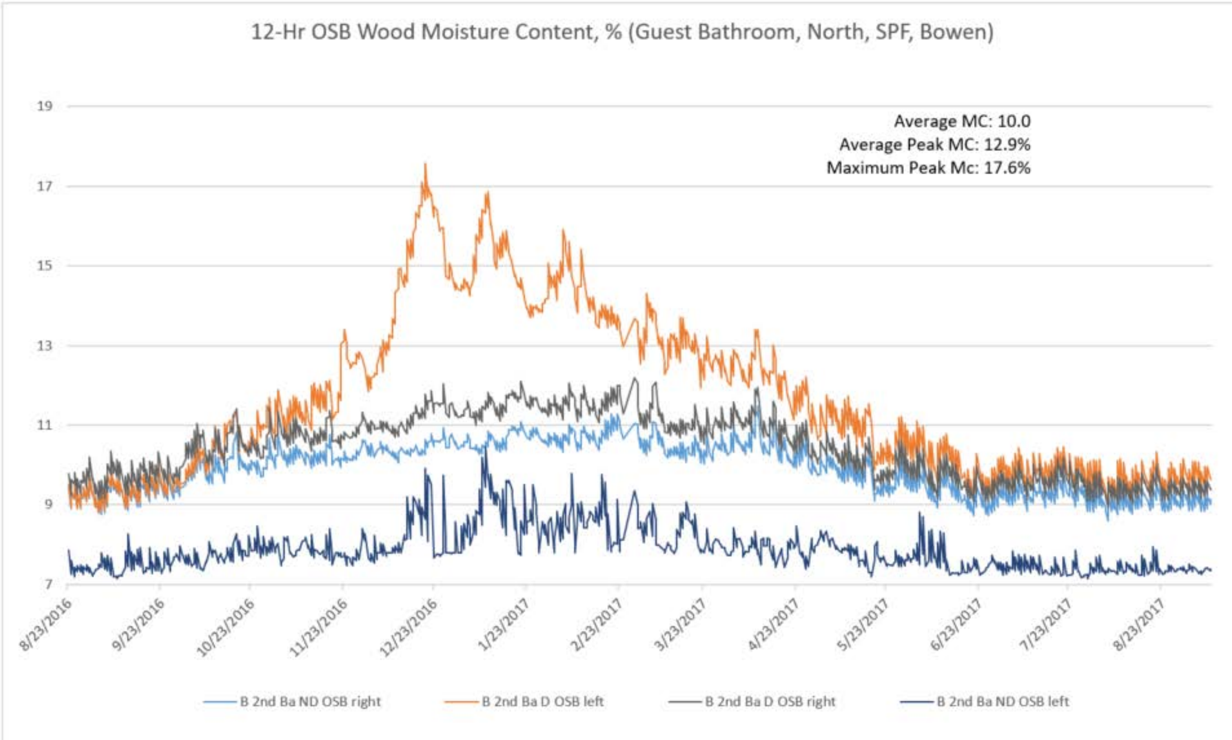


Figure 27. Moisture content for OSB in north-facing guest bathroom, ccSPF, House 1

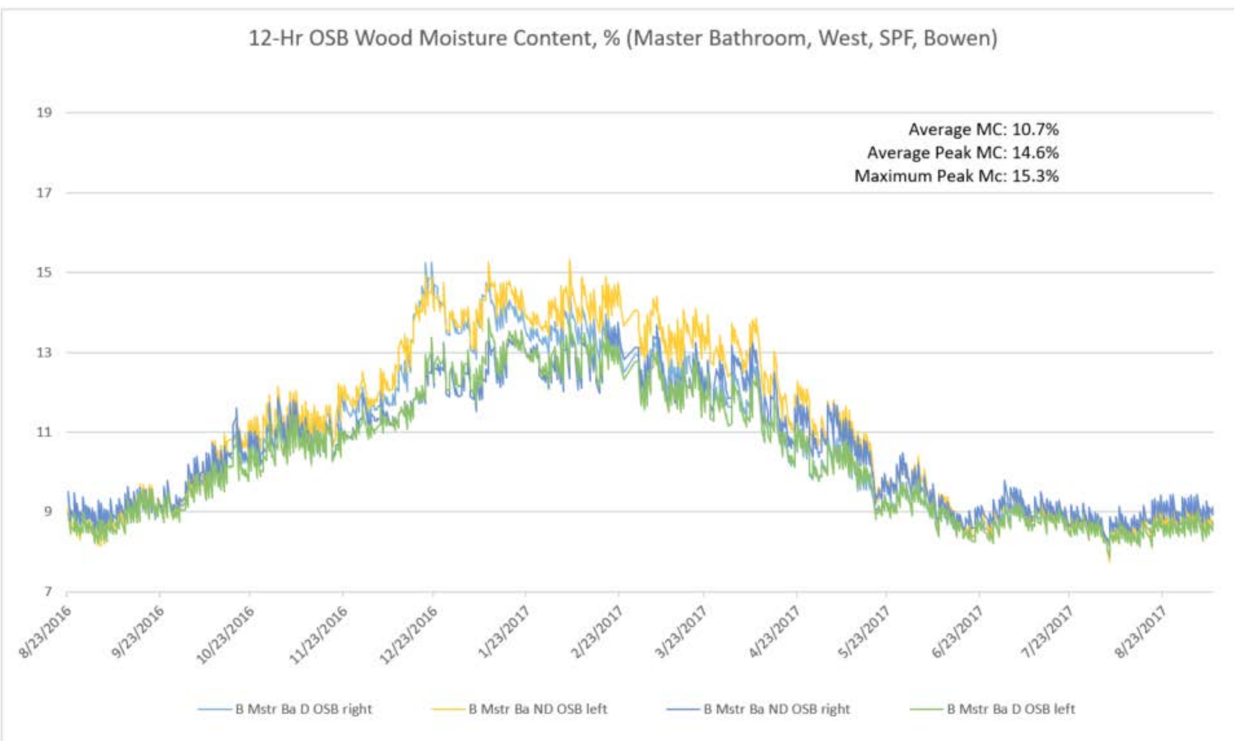


Figure 28. Moisture content for OSB in west-facing master bathroom, ccSPF, House 1

House 1 Lumber Moisture Results

All sensors monitoring studs, plates, and rim in House 1 exhibited excellent moisture performance with a maximum of 15.9%, well below the level generally considered to indicate moisture durability risk. Per the instrumentation and methodology discussion, for lumber the fiber saturation point is assumed to be approximately 30%. For the purposes of this study, MC above approximately 20% indicates potential risk for moisture performance problems. All sensors indicate good moisture performance for framing lumber in EP&B walls in House 1, with very little variation because of orientation, air-sealing methods, insulation materials, or seasonal psychrometric variations. See Figure 29.

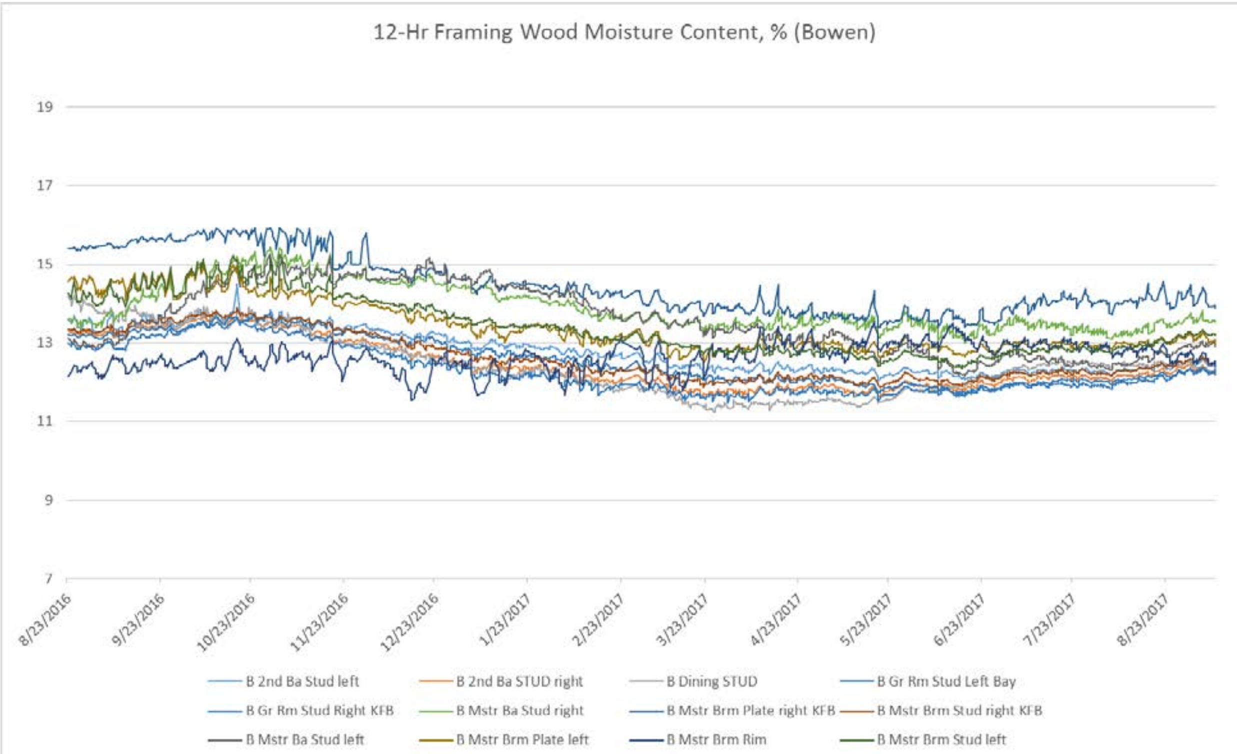


Figure 29. Stable moisture content for framing lumber in all EP&B walls, House 1

Compared to OSB, the studs, plates, and rims in the EP&B walls exhibited lower peak MC, a narrower range of MC, and less variation in MC in nearly all cases, though they experienced a slightly higher average MC than OSB.

Also, unlike with OSB, the cardinal orientation of the walls did not appear to significantly affect the MC of the framing lumber in EP&B walls. This more stable result is expected with greater wood density and volume, which allow the material to behave as a moisture sink to buffer short-term changes.

Although framing lumber in walls with ccSPF air sealing and blown-fiberglass exhibited somewhat lower overall MC readings compared to framing lumber in walls with acrylic caulk air sealing and Kraft-faced batts, this effect was much less pronounced for framing members than for OSB sheathing.

The following summary describes the MC for framing lumber in the House 1 walls for the full 12-month monitoring period of the field test:

- Sensors embedded in framing lumber recorded 13% average MC, 14.5% average peak MC, and 15.9% maximum peak MC for all walls. Subsets of predominantly north-facing walls and predominantly non-north-facing walls did not vary significantly in their MC behavior from the overall average.

- Sensors monitoring bays with ccSPF and blown-fiberglass insulation exhibited 13% MC average, 14.5% average peak, and 14.5% maximum peak for north-facing walls, only slightly lower (better) than the Kraft-faced batt insulation bays
- All lumber exhibited the expected seasonal trends: higher MC during winter, lower during summer.

2.5.4.5 House 2 OSB MC% Results

The following summary describes the 12-hour averaged MC for OSB in the House 2 walls for the full 12-month monitoring period of the field test:

- All walls: 10.7% MC average, 13.6% average peak and 19.5% maximum peak
- North-facing walls: 11.4% MC average, 14.6% average peak and 19.5 % maximum peak
- Non-north-facing walls: 9.1% MC average, 11.5% average peak and 13.0% maximum peak
- Peak OSB MC for 17 out of 18 EP&B walls never rose above 16.9%

Even including the single sensor identified as a potential outlier (see Appendix D for further discussion), EP&B walls in House 2 provide good moisture performance with both insulation/air-sealing methods and in all orientations. As previously described, north-facing walls are expected to exhibit higher MC% readings than those facing south, east, or west because of the lack of direct sun to dry materials and the generally lower temperatures at north-facing walls.

Figure 30 shows 12-hour averaged MC readings for all sensors (outlier removed) monitoring OSB in House 2 for a 12-month period starting in August, 2016.

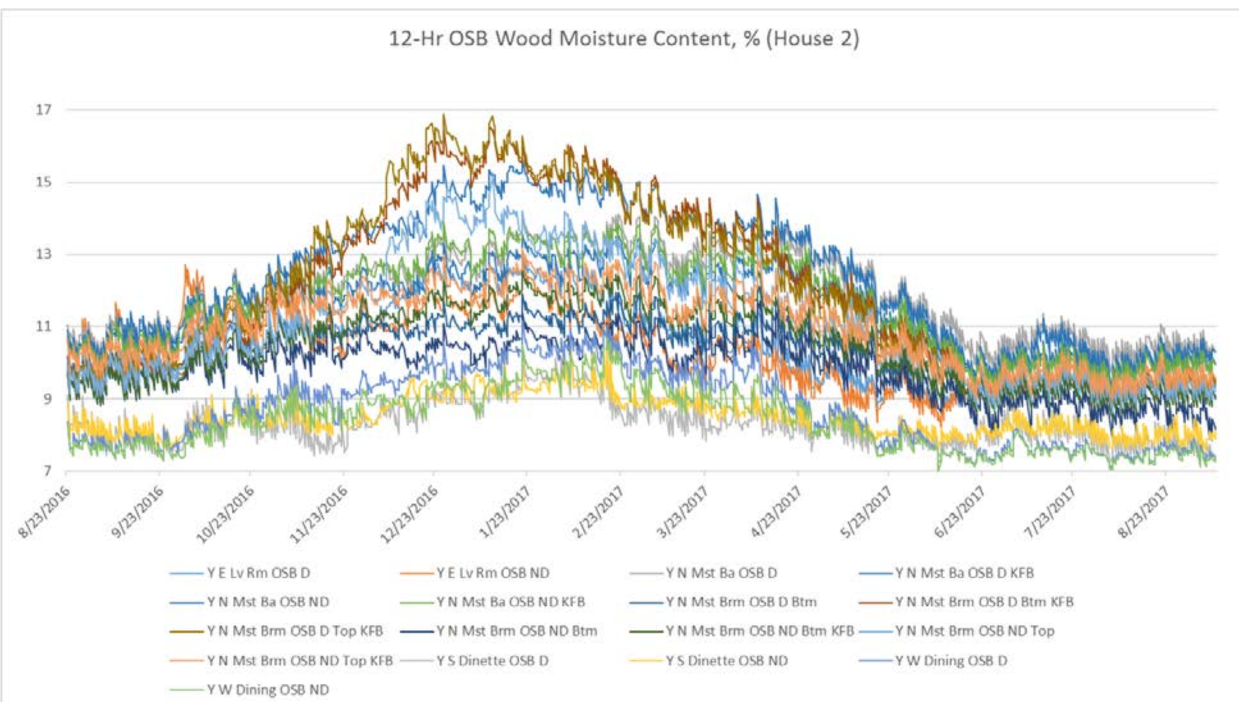


Figure 30. Moisture content for OSB in all EP&B walls, House 2

The following pairs of graphs illustrate various comparisons of OSB MC in House 2.

Figure 31 and Figure 32 Comparing SPF/Fiberglass to Caulk/Kraft-Faced Batt Insulation. Both types of walls perform well. When controlled for orientation (north-facing walls only) and removing the outlier (Y N Mst Brm OSB D Top) from consideration, EP&B walls with insulation consisting of ccSPF air sealing combined with blown-in fiberglass insulation seem to provide some benefit in reducing moisture migration through the wall compared to the caulk-sealing/Kraft-faced batt insulation approach. By the end of the first year (end of summer 2017), both installation methods settled into narrow bands of approximately 9% to 10.5% MC.

Figure 33 and Figure 34 Comparing Orientations. When controlled for construction configuration (SPF/fiberglass insulation only) and removing the outlier (Y N Mst Brm OSB D Top) from consideration, EP&B walls with north orientations exhibit higher MC peaks and averages and somewhat less stable behavior over time than EP&B walls with south, east, and west orientations.

Figure 35 and Figure 36 Comparing Bathrooms to Bedrooms. When controlled for room type, north-facing EP&B walls in the master bathroom exhibit very similar MC averages to north-facing EP&B walls in the master bedroom. The bathroom OSB exhibits a lower subset maximum peak than the bedroom OSB as well as somewhat more stable behavior over time.

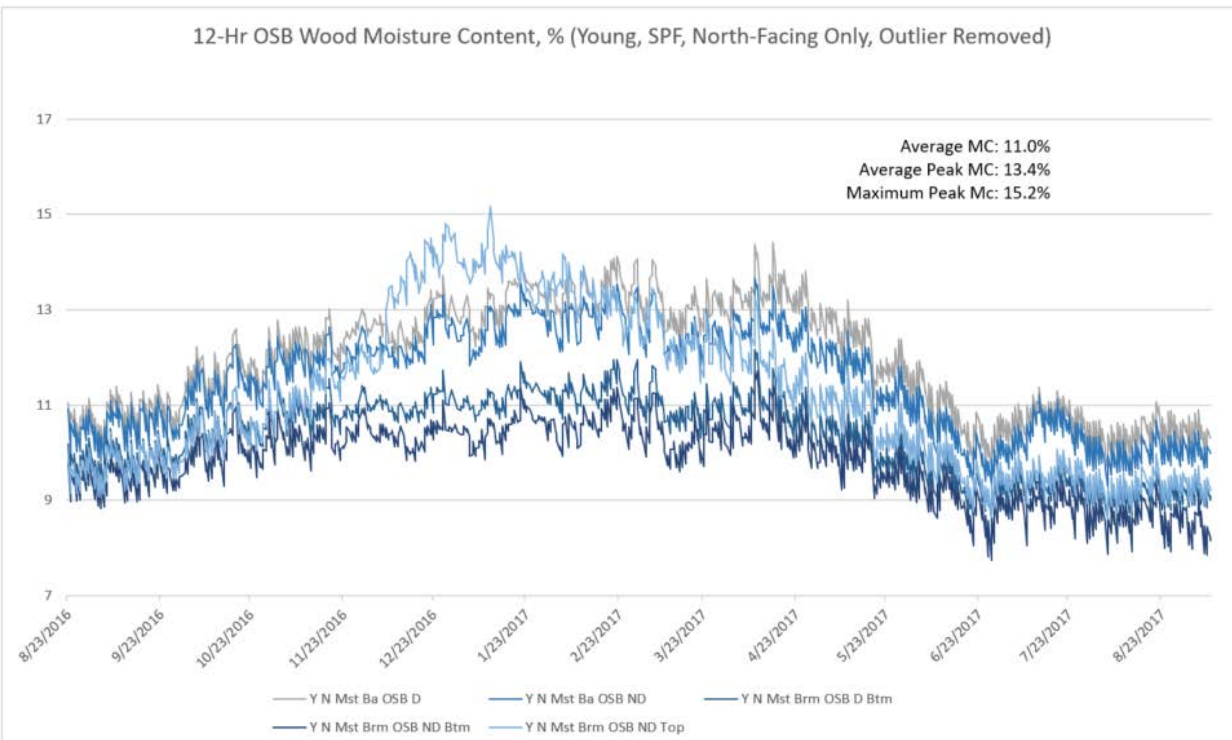


Figure 31. Moisture content for OSB in EP&B walls with ccSPF air sealing and blown-in fiberglass insulation, House 2

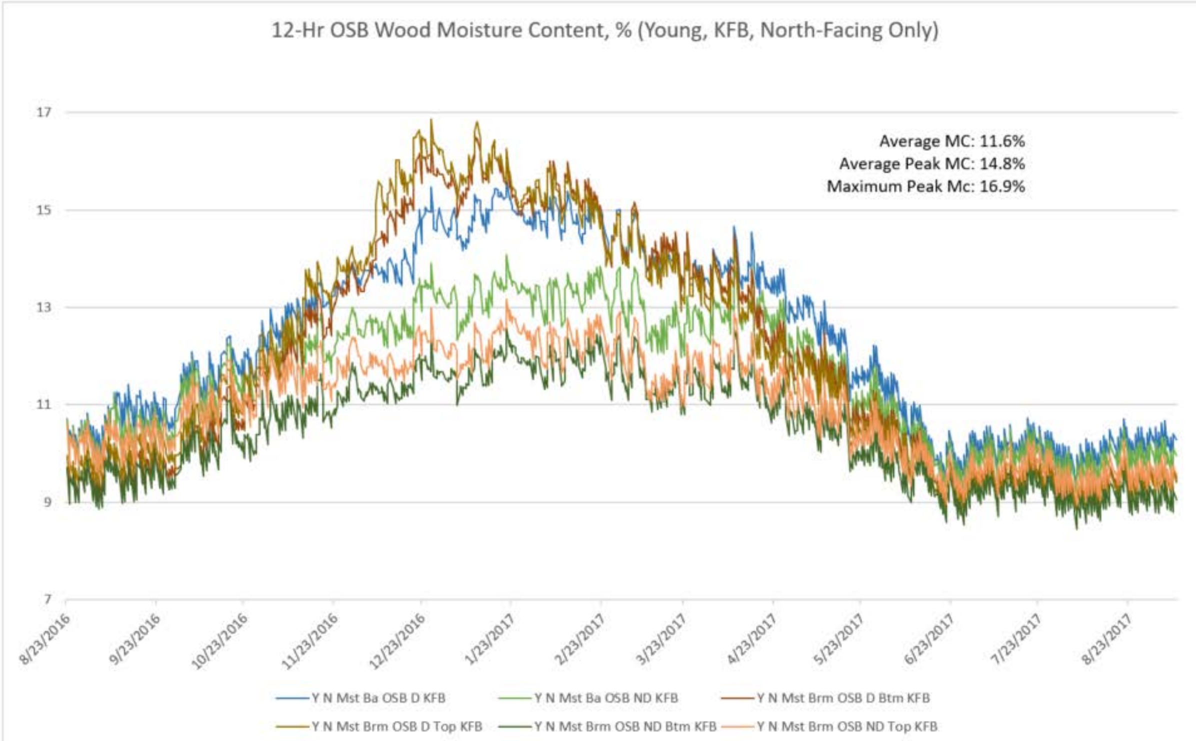


Figure 32. Moisture content for OSB in EP&B walls with acrylic caulk air sealing and Kraft-faced batt insulation, House 2

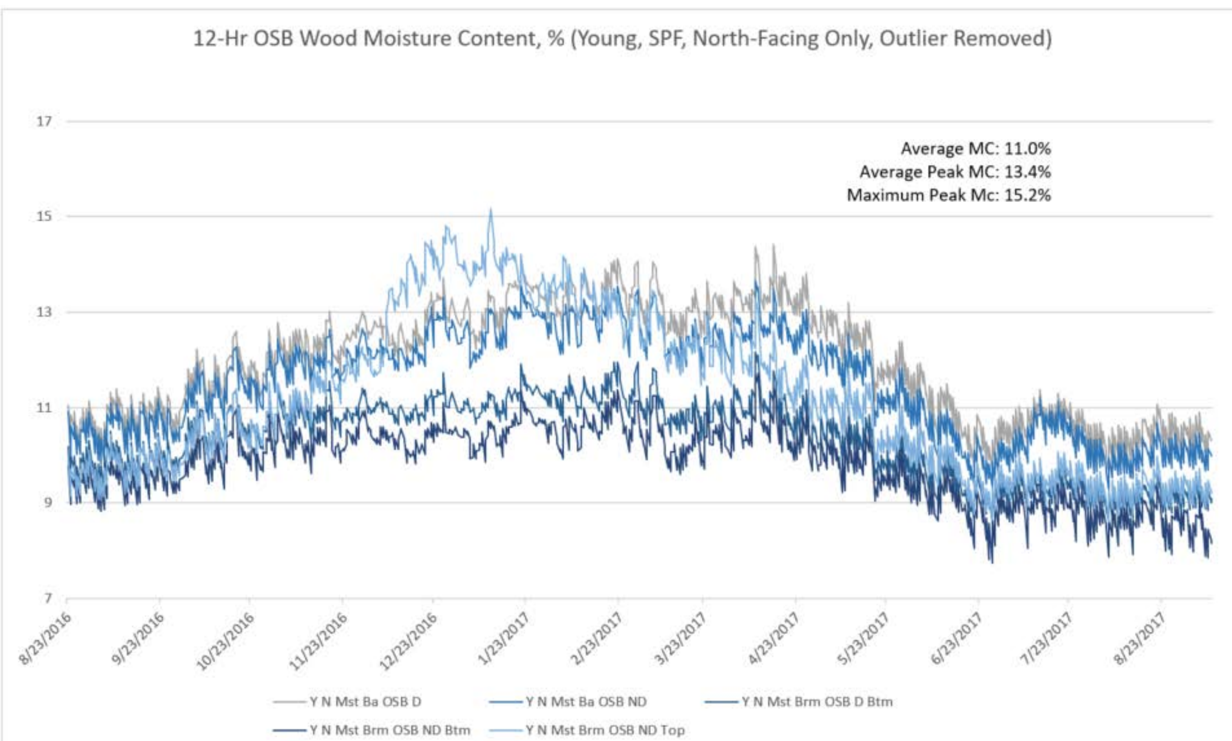


Figure 33. Moisture content for OSB in EP&B walls with ccSPF/blown fiberglass, North only, House 2

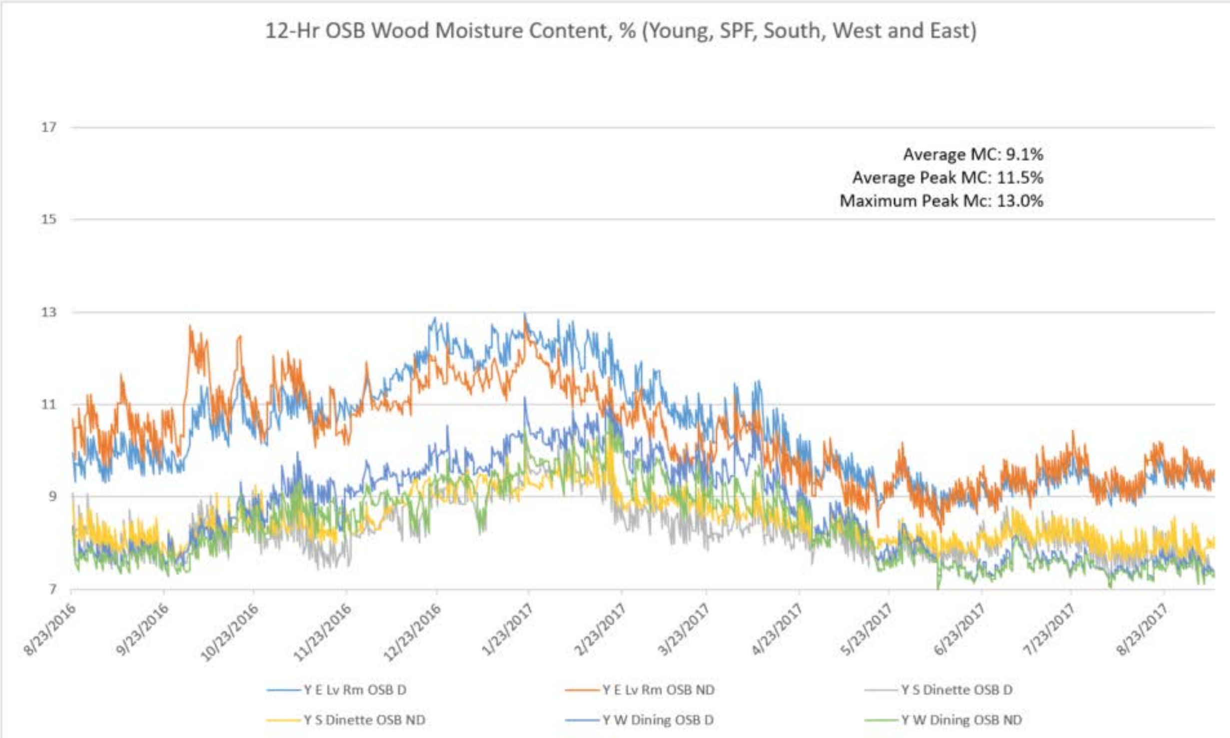


Figure 34. Moisture content for OSB in EP&B walls with ccSPF and blown fiberglass, non-north orientations, House 2

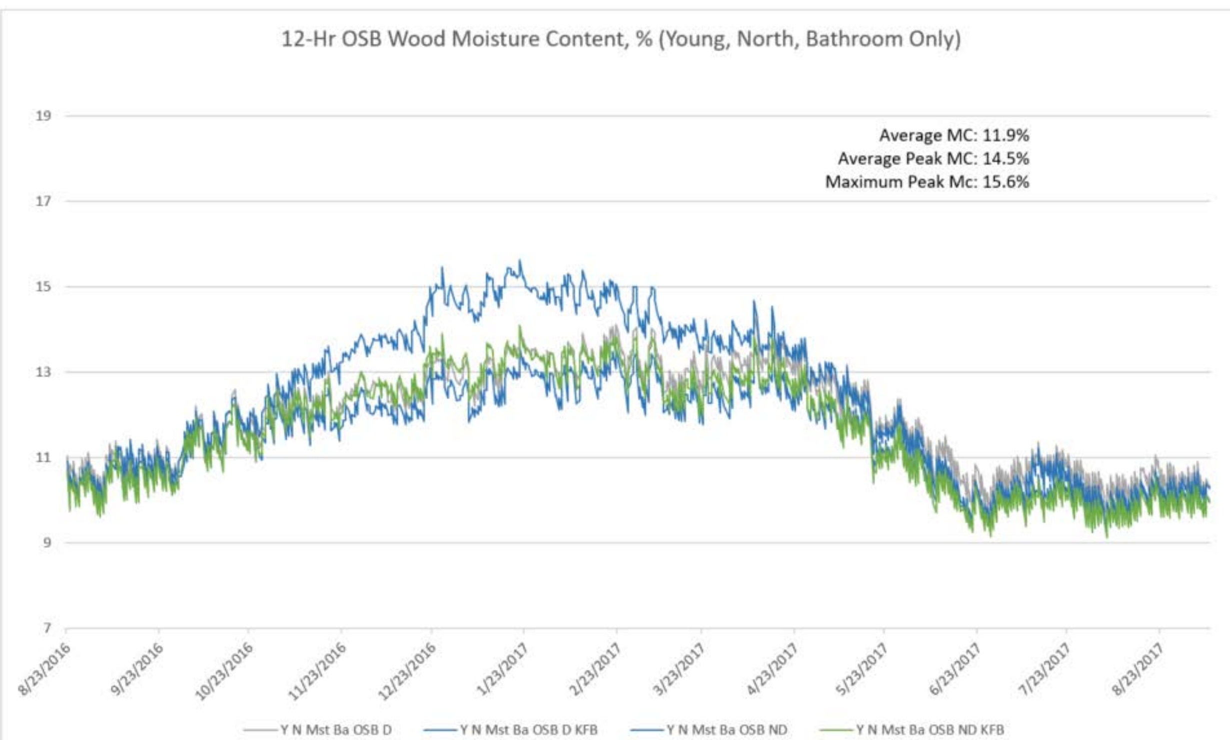


Figure 35. Moisture content for OSB in EP&B bathroom walls, north orientation only, House 2

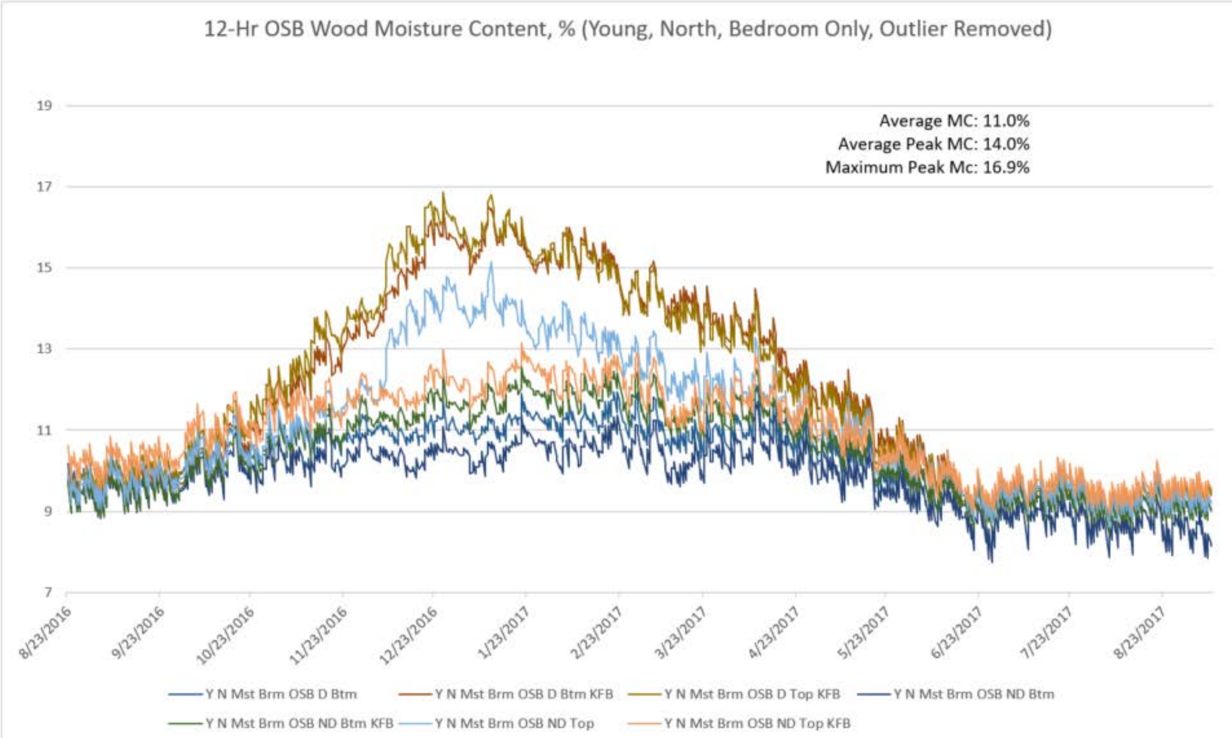


Figure 36. Moisture content for OSB in EP&B non-bathroom walls, north orientation only, House 2

2.5.4.6 House 2 Lumber Moisture Results

All sensors monitoring studs, plates, and rim in House 2 exhibited excellent moisture performance—less than 16%—well below the percentage generally considered to indicate moisture durability risk. Sensors exhibit very little variation because of orientation, either of the two air-sealing methods, the two insulation materials, or seasonal psychrometric variations. The rim MC and the bottom plate MC are noticeably on the low end of all monitored lumber. See Figure 37.

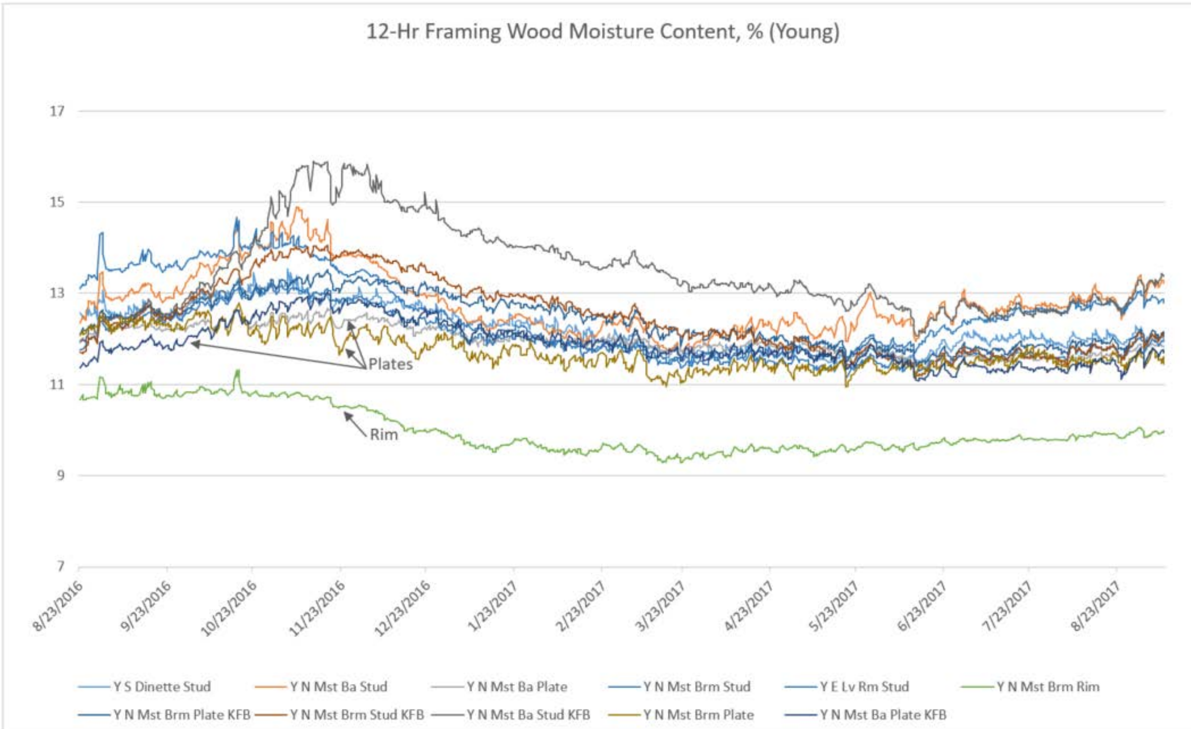


Figure 37. Stable moisture content for framing lumber in all EP&B studs, plates, and rim, House 2

Compared to OSB, studs, plates, and rims in EP&B walls in House 2 exhibited lower peak MC, a narrower range of MC, and less variation in MC in nearly all cases, though a slightly higher average MC.

Also, unlike with OSB, the cardinal orientation of the walls did not appear to significantly affect the MC of framing lumber in EP&B walls. This more stable result is expected with greater density and volume, which allow the material to behave as a moisture sink to buffer short-term changes.

Framing lumber in walls with ccSPF air sealing and blown-fiberglass (SPF/fiberglass) exhibited somewhat lower overall MC readings compared to framing lumber in walls with acrylic caulk air sealing and Kraft-faced batts.

The following summary describes the MC for framing lumber in House 2's walls for the full 12-month monitoring period of the field test:

- Sensors embedded in framing lumber recorded 12.1% average MC, 13.5% average peak MC, and 15.9% maximum peak MC for all walls. Subsets of predominantly north-facing walls and predominantly non-north-facing walls did not vary significantly in their MC behavior from the overall average.
- Sensors monitoring bays with ccSPF and blown-fiberglass insulation exhibited slightly lower average, average peak MC, and 14.9% maximum peak MC for north-facing walls, lower (better) than the Kraft-faced batt insulation bays, and slightly lower than the overall averages
- One stud (Y N Mst Ba Stud Kraft-faced batt insulation) in a bathroom on a north-facing wall could be considered an outlier, with a maximum MC reading of 15.9%. The sensor in this stud measured the highest MC from mid-November through mid-June, after which it dried to below 13%, similar to the overall grouping. The other stud in that bathroom wall (Y N Mst Ba Stud) exhibited MC slightly above average for the same time period, also drying out well by mid-June.
- Plates exhibited somewhat lower MC than studs; the rim exhibited the lowest MC.

- All lumber exhibited the expected seasonal trends: higher MC during winter, lower during summer, though the MC amplitude was dampened in comparison to OSB.

2.5.5 WUFI Simulation: Methodology

Computer simulations were used to calculate the heat and moisture transiency in various EP&B wall configurations using software developed by The Fraunhofer Institute for Building Physics: Wärme Und Feuchte Instationär (WUFI, German for “transient heat and moisture”). The software computations are both accurate and precise enough to mimic real-world moisture performance when all inputs include the proper material and construction characteristics.

The simulations were performed in three phases: (1) initial simulations of EP&B with typical materials choices in climate zones predicted to be the optimum locations for the technology, (2) modified simulations based on detailed information such as climate zone, infiltration rate, indoor conditions, insulation materials, and permeability of paint and WRB to correlate to the field-test results and calibrate the model, and (3) blind predictive simulations for extrapolating to other climate zones and untested construction materials combinations.

WUFI simulations were used to duplicate the insulation methods of the Grand Rapids test houses for one-to-one comparisons, including inputting the actual interior ambient conditions resulting from occupancy during the test period. The objective of customized WUFI simulations is to evaluate the potential predictive ability of simulated models when compared to in-field performance if select material properties and boundary conditions are known. Close correspondence between the modeled moisture performance and the actual moisture performance indicates that the WUFI simulation may be relied upon to accurately predict real-world performance of the EP&B wall.

The ambient outdoor temperature and humidity readings from both houses matched the typical meteorological year (TMY) data in the WUFI library fairly well, so the library data was used for climate inputs because it includes additional factors such as cloud index, wind-driven rain, and solar irradiance, which were not measured at the field-test sites. The interior bathroom and non-bathroom ambient temperature and humidity readings from House 2 were used to replace the WUFI library for interior conditions to ensure close correspondence.

Once the WUFI simulations were corroborated as reflecting actual performance, a matrix of standard EP&B constructions was tested for various climate zones. A standard construction 2x4/2x6 EP&B wall in Climate Zone 5 with XPS rigid insulation and R-13 fiberglass batt cavity insulation established a baseline. Several components were then varied to determine the limits of use and to develop construction recommendations for various material choices and climate zones.

2.5.6 WUFI Simulation: Results

2.5.6.1 Simulation versus Actual

WUFI simulation results for the EP&B walls duplicating the configurations of the Grand Rapids test houses indicate good correspondence with actual moisture performance.

Table 11 shows the detailed characteristics of the walls in the Grand Rapids demonstration houses and the WUFI inputs used to mimic the test house walls for direct comparison.

Table 11. Comparison of Actual and Simulated EP&B Test Walls, Configurations 1 and 2

Component	Test House	WUFI Simulation
Climate Zone	Climate Zone 5	Climate Zone 5
Interior air conditions	As recorded, Figure 14 and Figure 15	RH (%) and T (°F) data as recorded
Exterior air conditions	As recorded, Figure 16 and Figure 17	RH (%) and T (°F) data as recorded
EP&B framing	2x4/2x6	2x4/2x6
#1 air sealing	Flash coat of ccSPF (~1 in.)	1-in. ccSPF
#1 cavity insulation	Sprayed fiberglass	Sprayed fiberglass
#2 air sealing	Caulked at all transitions: House 1: 1.05 ACH50; House 2: 1.27 ACH50	Standard
#2 cavity insulation	Kraft-faced batts, R-15	Kraft-faced batts, R-15
Foam sheathing	R-10 2-in. XPS	R-10 2-in. XPS
WSP	½-in. OSB	½-in. OSB
WRB	Nonperforated, ~50 perm	50 perm
Monitoring period	August 2016–September 2017	August 2016–September 2017

The following is a summary of observations comparing actual monitoring data to the WUFI moisture simulation results for the OSB in north-facing walls using both bathroom and non-bathroom interior conditions. See Figure 38 and Figure 39.

- For walls with ccSPF flash coat with blown fiberglass insulation, the WUFI model prediction for peak OSB MC was very near to the recorded values.
- For walls with R-15 Kraft-faced batt fiberglass insulation, the WUFI model underpredicted actual peak OSB MC by 1.5 to 2 percentage points.
- For both insulation methods and both houses, MC under actual conditions peaked several months sooner than the WUFI simulation predicted.
- For both insulation methods and both houses, OSB dried out during the summertime to average MC very similar to the WUFI model prediction (between 9% and 10%).
- The bathroom conditions caused wintertime MC peaks in bathrooms that were slightly higher than non-bathroom peaks by less than 0.5% and lows that were higher than non-bathroom lows by less than 0.5%. These values are too small to be significant for WUFI.

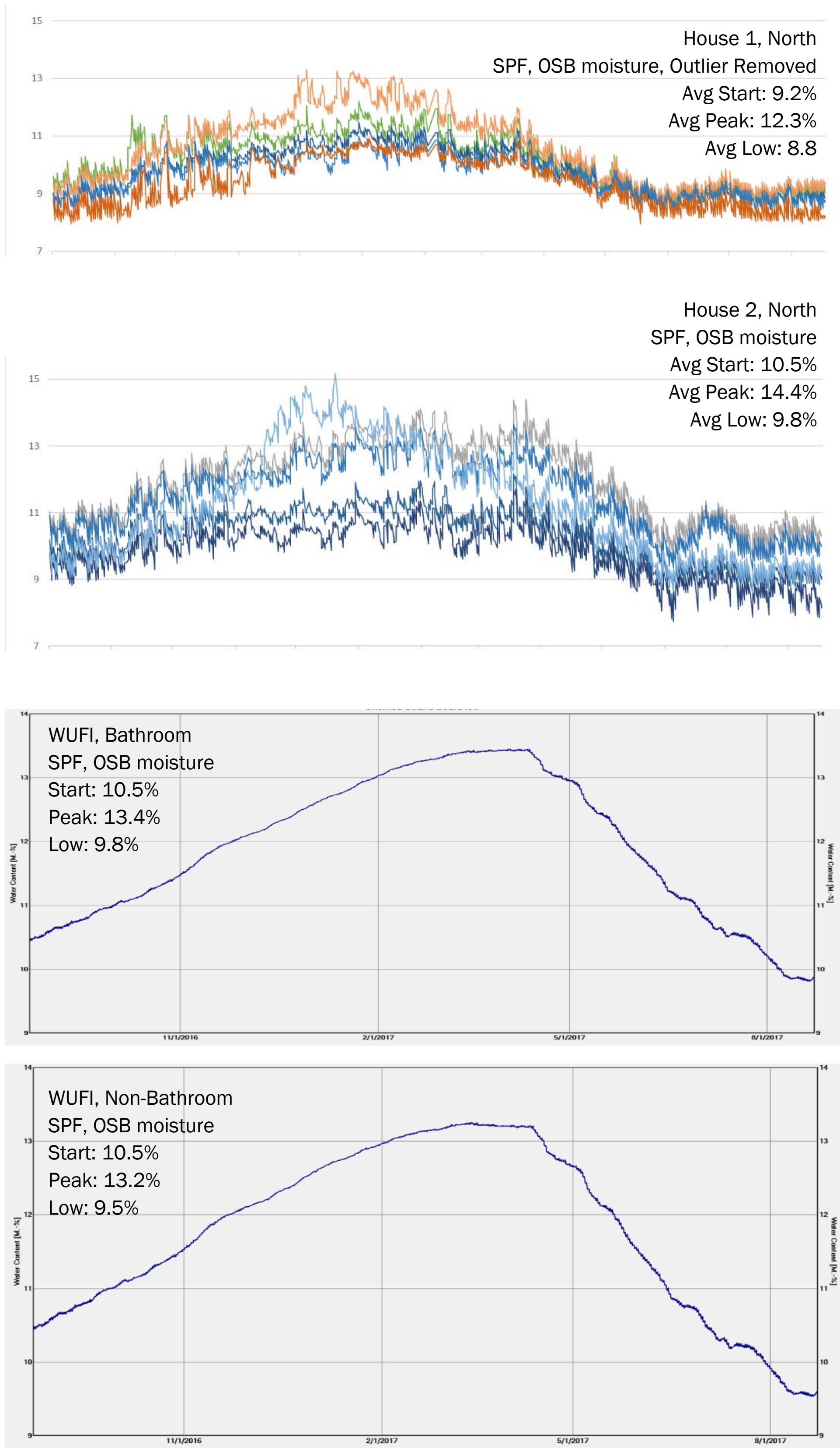


Figure 38. Comparing actual OSB MC to WUFI simulation, Grand Rapids test houses, spruce-pine-fur

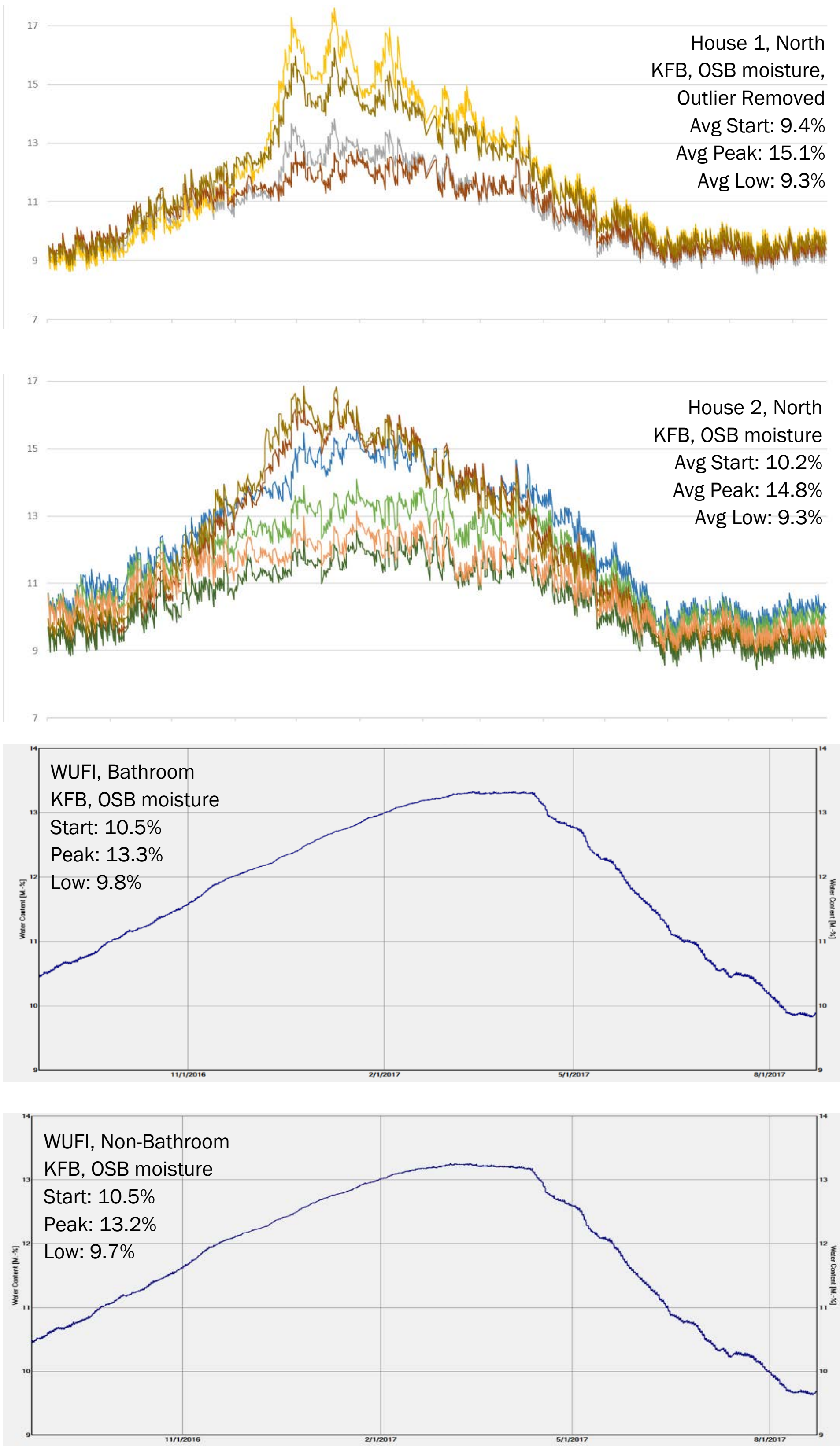


Figure 39. Comparing actual OSB MC to WUFI simulation, Grand Rapids test houses, Kraft-faced batt insulation

Simulations over four years using TMY3 data show settling by Year 3, with MC peaks below 13%, and end-of-summer minimums of around 9.5%. See Figure 40.

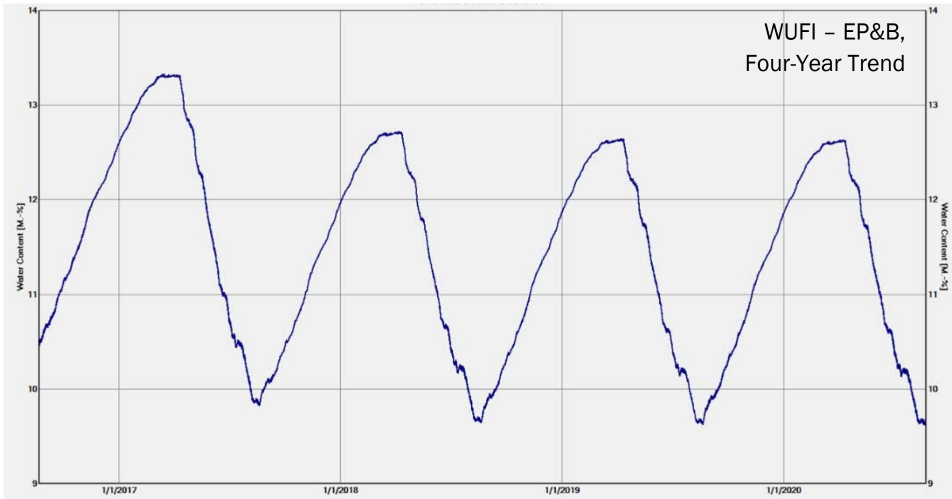


Figure 40. WUFI simulation, four years: peak and trend line settled by Year 3

2.5.6.2 WUFI Test Matrix

The WUFI computer simulations indicate that the EP&B wall system may confidently be used in nearly all typical combinations of insulation and cladding from climate zones 4–8. Variations in the matrix also highlighted characteristics of interior vapor retarder and WRB that reliably improve the moisture performance of the wall system and thus warrant additional construction recommendations. Only north-facing walls were simulated, representing the most vulnerable orientation.

Per the calibration exercise against the two test houses, WUFI is expected to closely predict the moisture performance of walls with ccSPF flash coat with blown fiberglass insulation and slightly underpredict actual peak OSB MC for Kraft-faced batt insulation fiberglass insulated walls by one to two percentage points. For both insulation methods, the WUFI model is expected to accurately predict end-of-summer drying levels.

The EP&B 2x4/2x6 configuration with R-13 fiberglass batt in the stud cavities and 2 in. of XPS (R-10) is simulated for reference in Climate Zone 4 and Climate Zone 8, bookending the conditions under which EP&B meets 2015 IECC minimum prescriptive requirements. A Class II vapor retarder would be required by code in Climate Zone 8, but the intention here was to stress the wall to mimic a common installation error (omission of code-required interior vapor retarder). Even in this last case, the worst peak MC in actual use is likely to be 17% or less, well within moisture good performance range.

The EP&B WUFI test matrix with results is shown in Table 12. Bold outlines highlight comparison groups.

Table 12. WUFI Test Matrix and Simulation Results for EP&B Walls

#	Cladding	WRB	Exterior Insulation	Cavity Insulation	Interior Vapor Retarder	Climate Zone	MC Range (%)	MC Peak (%)
Ref 1	Vinyl	W5	XPS	R-13 fiberglass	None	4	8–12	12
Ref 2	Vinyl	W5	XPS	R-13 fiberglass	None	8	12–15	15
1	Vinyl	W5	XPS	R-15 fiberglass	None	4	8–12	12.0
2	Vinyl	W5	XPS	R-15 fiberglass	None	5	10–14	14.0
3	Vinyl	W5	XPS	R-15 fiberglass	None	6	10–14	14.0
4	Vinyl	W5	EPS	R-13 fiberglass	None	4	10–16	16.0
5	Vinyl	W5	EPS, faced	R-13 fiberglass	None	4	8–11	11.0
6	Vinyl	Taped foam	PIC	R-13 fiberglass	None	4	9–11	11.0
7	Vinyl	W5	EPS	R-13 fiberglass	None	5	10–21	21.0
8	Vinyl	W5	EPS, faced	R-13 fiberglass	None	5	9–11.5	11.5
9	Vinyl	Taped foam	PIC	R-13 fiberglass	None	5	9–11.5	11.5
10	Vinyl	W5	XPS	Dense-packed cellulose	None	4	9–12	12.0
11	Vinyl	W5	XPS	Dense-packed cellulose	None	8	11–13.5	13.5
12	Vinyl	W5	XPS	R-15 fiberglass	Kraft	7	11–13	13.0
13	Vinyl	W5	XPS	R-15 fiberglass	Smart	7	10.5–13.5	13.5
14	Vinyl	W5	XPS	R-15 fiberglass	None	7	11–14	14.0
15	Vinyl	W5	XPS	R-15 fiberglass	None	8	12–14	14.0
16	Vinyl	W50	XPS	R-15 fiberglass	None	8	12–14	14.0
17	Vinyl	W5	XPS	R-15 fiberglass	Kraft	8	12–14	14.0
18	Vinyl	W50	XPS	R-15 fiberglass	Kraft	8	12–14	14.0
19	Fiber cement	W5	XPS	R-15 fiberglass	None	4	7–10.5	10.5
20	Fiber cement/ furring	W5	XPS	R-15 fiberglass	None	4	7–10.5	10.5
21	Brick cladding	W5	XPS	R-15 fiberglass	None	4	8–11	11.0
22	Fiber cement	W5	XPS	R-15 fiberglass	None	5	8–11	11.0
23	Fiber cement/ furring	W5	XPS	R-15 fiberglass	None	5	8–11	11.0
24	Brick cladding	W5	XPS	R-15 fiberglass	None	5	8–11.5	11.5
25	Fiber cement	W5	XPS	R-15 fiberglass	None	6	8–12	12.0
26	Fiber cement/ furring	W5	XPS	R-15 fiberglass	None	6	8–12	12.0
27	Brick cladding	W5	XPS	R-15 fiberglass	None	6	8–11.5	11.5
28	Fiber cement	W5	XPS	R-15 fiberglass	None	7	8–12.5	12.5
29	Fiber cement/ furring	W5	XPS	R-15 fiberglass	None	7	8–12	12.0
30	Brick cladding	W5	XPS	R-15 fiberglass	None	7	10–12	12.0

#	Cladding	WRB	Exterior Insulation	Cavity Insulation	Interior Vapor Retarder	Climat e Zone	MC Range (%)	MC Peak (%)
31	Fiber cement	W5	XPS	R-15 fiberglass	None	8	8–12.5	12.5
32	Fiber cement/ furring	W5	XPS	R-15 fiberglass	None	8	8–12	12.0
33	Brick cladding	W5	XPS	R-15 fiberglass	None	8	10–12	12.0
34	Vinyl	W50	XPS	R-21 fiberglass 2x6/2x7.5	Kraft	8	12–13.5	13.5

The following observations summarize some of the most important results of the WUFI simulation matrix

- EP&B with R-15 cavity insulation is tested most frequently in higher climate zones (13–32) because it is conservative: the lower proportion of rigid foam's contribution to the wall's overall thermal resistance goes down, decreasing the winter temperature in the OSB (a more challenging condition). EP&B performed well with a variety of rigid foam materials, claddings, WRBs, and interior vapor retarder choices.
- Even in Climate Zone 8 with no interior vapor retarder, a low-permeance WRB and R-15 cavity insulation (#14), the EP&B wall can still be expected to perform well, with MC in the OSB not exceeding approximately 16% (adding 2% for possible underprediction). This provides a reasonable safety factor.
- Rigid foam materials other than XPS are compared for Climate Zone 5 (4, 5, 6) and Climate Zone 6 (7, 8, 9). Because of its high native permeance, unfaced expanded polystyrene (EPS) foam (4, 7) is not a good candidate for the EP&B wall. Adding a low-perm facing to the interior face of the EPS is necessary (5, 8); it produces moisture performance similar to that of PIC (6, 9), which typically has a foil facing.
- The permeability of XPS is low enough without an adhered facing to perform well in the EP&B wall in various construction material combinations.
- Claddings that are denser (fiber cement) and much denser (brick) than vinyl siding perform well with EP&B, especially when ventilated (19–33).
- The usefulness of an interior vapor retarder is illustrated in tests 12–14. The EP&B wall is simulated in Climate Zone 7 with three different conditions: the Kraft-facing results in the lowest OSB moisture (13% peak), followed by "smart" vapor retarder (13.5% peak), and, finally, no vapor retarder at the interior wall plane behind the gypsum finish (14% peak). Simulating the worst-case scenario (no vapor retarder, low-perm WRB, R-15 batt) in the most challenging climate zone (Climate Zone 8) still yields good OSB moisture performance (15).
- Tests 15–18 were intended to test the usefulness of a high-perm WRB and/or interior vapor retarder. All simulated combinations produced OSB MC of approximately 14% peak. Although the WUFI simulation indicates that neither component is required for good performance under ideal circumstances, both a high-perm WRB and Kraft-paper interior vapor retarder are recommended as "belt-and suspenders" approaches in climate zones 5–8 to reduce risk. The WRB adds protection against wind-driven rain or a physical breach of the wall that allows liquid moisture to saturate the OSB. The interior vapor retarder is required by code in climate zones 6–8 and adds a degree of protection in Climate Zone 5 and Marine 4 when outward vapor drive is high. Specific recommendations are itemized in the *EP&B Construction Guide*.

- Even when WUFI simulations were run with 16% initial MC (higher than typical, and higher than the test houses), the wood dried to 12% at the end of the first summer season.

As expected, an interior vapor retarder provides increased protection in colder climate zones, where the outward vapor drive in winter is expected to be greater because of the larger temperature differential.

Also as expected, low-perm WRBs are adequate with ventilated siding and the low surface vapor drive of warmer climate zones (climate zones 3 and 4), but high-perm WRBs can provide additional protection in colder climate zones (climate zones 5–8).

The natural characteristics of the EP&B wall system configuration—high total thermal resistance with a low-perm, centrally located vapor plane—are expected to produce good moisture performance in climate zones 3–8 when installed according to Home Innovation's construction recommendations.

3 Discussion and Evaluation

3.1 Constructability

3.1.1 Framing

The builder and the framer for the demonstration houses in Grand Rapids, Michigan, determined that the EP&B wall system is constructible and generally cost-effective as an alternative to several other high-R wall types. The manager of the plant where the NYSERDA panelized test house EP&B walls were manufactured and the framer managing the crew that erected the walls at the site agreed that the construction requirements of the EP&B wall system were achievable and reasonable.

This field test of the EP&B wall system has prompted a change from the original framing design (that extended the bottom and second top plates only), resulting in a final recommendation of all three wall plates one lumber dimension wider than the studs. This calculates to an approximately R-1 reduction compared to a traditional exterior continuous insulation wall, but it offers the following construction advantages:

1. Simplifies lumber ordering and sorting. All 2x4s can be precut stud lengths, and all 2x6s will be framing lumber lengths, reducing the likelihood of mistaking studs for general framing lumber, which can be time-consuming and costly.
2. Provides more nailing area at the top of the wall for nail embedment and adjusting sheathing coverage and ensuring the required OSB gap
3. Provides more support at partition wall tie-ins
4. Provides more support below gable-end trusses.

3.1.2 Fastening Schedule

Framers involved in all field-test projects cited in this study commented on the cost and availability of longer nails and the larger nail guns required to shoot them. The new recommended fastening schedule is 3.5-in. nails in a 3/6 edge/field pattern, and it provides the following advantages:

1. 3.5-in. nails are ubiquitous on job sites, readily available at local supply stores, and reasonably priced.
2. 3.5-in. nails fit most standard framing guns without modification.
3. 3.5-in nails are appropriate substitutes for many framing connections, allowing the same tool to bridge several tasks.
4. The 3/6 perimeter/field fastener schedule is familiar to framers because it is a common stapling specification.
5. It potentially reduces nailing “misses” at vertical OSB joints.

3.1.3 Panel Construction and Erection

The framing and fastening schedule adjustments described above will improve the efficiency for factory panelization. Two other improvements to the construction process could reduce production time at the panel plant:

1. Rigid foam available from the manufacturer to match typical stud lengths to reduce the number of cuts
2. Full-depth router bits with self-sinking tips to cut window and door openings in the OSB and rigid foam in a single step. Note that this solution would also work well for field-framed EP&B projects.

Air sealing is a challenge for any wall system, but it can often be combined with standard water management detailing. Whether panelized or field-framed, best practice sealing techniques should be employed:

1. Plates: gaskets, caulk, spray foam, or a combination
2. Lumber and sheathing connections: WRB tape, caulk, liquid-applied sealant, or a combination
3. Envelope: detail the WRB as an air barrier by shingling the layers, taping at all seams and penetrations, and sealing at the top and bottom edges to the structure
4. Wall interior: a flash coat of ccSPF or spray-applied sealant can be an effective air seal in the wall cavity.

The best practice for connecting field-framed walls includes planning for staggered vertical seams of OSB and rigid foam; that is, ensuring that rigid foam seams are not coincident with OSB seams. Sometimes this requires leaving a section of WSP for installation after the wall has been erected and connected to its neighbor.

3.2 Cost and Marketability

3.2.1 Field framing

Previous research (Home Innovation Research Labs 2015a) developed detailed materials and labor pricing information that concludes that depending on geographic location and insulation choices, EP&B walls can cost approximately $0.55/ft^2 to $1.00/ft^2 of wall less to build than comparable walls with similar performance. A 200-ft^2 sample wall with typical cladding, windows, moisture, and air detailing was used to develop this comparison. Builders field-framing the EP&B wall will purchase rigid foam insulation, wider top and bottom plates, and will pay slightly more for longer and more numerous nails. The EP&B wall requires additional materials (WRB and 2x6 plates) compared to a continuous insulation wall, but the reduced installation complexity of windows, WRB, and siding—because of the nailing substrate provided by the exterior layer of the OSB sheathing—typically more than offsets those costs. The learning curve for framing crews erecting an EP&B wall for the first time is expected to be shallow and short.

3.2.2 Panelization

Building component manufacturers should expect to invest approximately $500 in training and tooling, and it may require additional time for the first two to three EP&B projects to accommodate the learning curve. After this the additional time required for an EP&B project is estimated to be less than 15% compared to a typical 2x4 framed wall panel without insulation. Construction time on task and materials costs are transferred from the site to the plant. Price premiums are later offset by on-site labor savings associated with reduced complexity for siding, WRB, and window installation, netting the builder a total savings up to $1.00/ft^2 compared to a conventional frame wall with 2-in. exterior continuous insulation

For a relatively low additional production expense, panelizers are now able to differentiate themselves in the market by offering EP&B as a high-performing, code-compliant wall that incorporates 2 in. of rigid foam in a nearly continuous layer. The suitability of EP&B walls to panelization represents a potential new product offering in the market for wall panelizers and an opportunity for framers to incorporate rigid foam as continuous insulation without adding risk or significantly changing their field practices.

3.3 Energy

Comparison of thermal attributes and previous energy modeling has confirmed that the EP&B wall system can contribute to a building envelope that meets or exceeds both prescriptive and performance energy code requirements and can aid in qualifying the home for voluntary energy-efficiency program certification. Two EP&B configurations and flexible insulation choices can provide a range of nominal R-values from 13+R-8 to 21+R-12, depending on choices for cavity insulation and rigid foam insulation (EPS, XPS, or PIC).

With the advent of stricter thermal performance requirements in the 2012 and 2015 IECC, builders who have been reluctant to transition to exterior continuous insulation, citing construction and detailing complexities, may be prompted to consider this alternative. The extended plates that are integral to the design of the EP&B wall constitute a small (<5%) thermal bridge and will result in a thermal performance penalty of approximately R-1 compared to a similar wall with fully exterior continuous insulation; however, many builders are likely to consider this a reasonable trade-off for the EP&B wall's simplicity, durability, and flexibility.

3.4 Durability

Moisture monitoring and WUFI simulations confirm that the basic 2x4/2x6 EP&B configuration can perform reliably in all climate zones, with average peak OSB MC less than 15%, well below accepted levels of risk. Follow all code requirements and typical best practices for WRB, moisture detailing, and air sealing.

The rigid foam insulation layer between the framing and the wood structural sheathing in an EP&B wall behaves as a centrally located vapor plane; wall materials should be allowed to dry both inward and outward from that plane. For Climate Zone 5 and colder, a Class II interior vapor retarder such as Kraft paper or a "smart" vapor retarder may be recommended to prevent moisture buildup within the wall cavity because of high outward vapor drive during cold conditions. A higher perm WRB is also recommended to support outward drying of the WSP.

3.5 Structural Performance

Based on laboratory testing per AC269.1, the EP&B wall meets the performance requirements of both IRC continuously braced walls and IRC intermittently braced walls. EP&B walls can be expected to perform equivalently to 2x4 IRC continuously sheathed WSP walls for both applications for typical residential one- and two-story structures.

AC269.2 procedures were used to determine the engineered shear value of 256 lbs/ft for EP&B with 3½-in. nails in a 3/6 attachment schedule; this value may be used by structural engineers of record to develop an engineered design, if necessary. Builders are encouraged to follow all construction requirements of the local authority having jurisdiction. The performance results from this study will form the basis for an IRC code change proposal to submit EP&B as an alternate prescriptive method for braced walls.

4 Conclusions

The successful field-test demonstration of the EP&B wall system has provided positive results to the main research objectives:

- Laboratory testing has demonstrated IRC braced wall equivalency; data will be used to support a code proposal and Evaluation Service reports. Already builders in Massachusetts, Idaho, and Montana have expressed interest in EP&B based on the lab test results and the calculated allowable design racking shear load value for EP&B walls: 256 plf (lbs/ft).
- Construction observation of the demonstration houses yielded valuable data regarding implementation, which have been used to optimize the EP&B fastening schedule and framing configuration.
- The sensors monitoring conditions within the walls verify good thermal and moisture performance, providing confidence to builders considering transitioning to the system.
- The EP&B *Construction Guide* is being published concurrently with this research report. Key benefits and learning curves are documented in the guide as well as rationale for performance and cost-effectiveness, empirical results, construction tips and tricks, and recommendations for use of the wall in all appropriate climate zones.
- Moisture and temperature data from the demonstration homes were used to fine-tune WUFI simulations, which then yielded valuable information confirming the thermal and moisture performance of a variety of materials and construction choices for EP&B walls to fine-tune recommendations for use and assembly in all climate zones.

The location of the rigid foam layer in an EP&B wall is a deliberate choice to reduce construction complexities, improve cost-effectiveness, and spur adoption in the market, helping more builders transition to high-performance wall assemblies that provide better than code thermal performance. Its suitability for factory panelization makes it attractive for wall panelizers and builders wishing to distinguish themselves in the market.

The companion publication, *Extended Plate and Beam Construction Guide*, includes instructions and final recommendations for the EP&B wall system. When properly planned and detailed for the local climate, EP&B is a straightforward and constructible wall system that provides good value, airtightness, moisture resilience, and structural performance that meets IRC requirements.

As a nonproprietary system with an incremental R-value expansion opportunity and proven performance, EP&B provides the builder with the flexibility, control, and confidence to meet and exceed IECC energy requirements for above-grade walls.

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Appendix A: Extended Plate and Beam Construction Details

Nailing pattern:

- 3½-in. L, 0.131-in. diameter nails at 6-in. on-center (o.c.) in field
- 3½-in. L, 0.131-in. diameter nails at 3-in. o.c. in edges

Wall framing:

- Bottom and both top plates extended
- Standard configuration: 2x4 studs with 2x6 plates
- Alternate 1: 2x6 studs with 2x7.5* plates (*denotes actual dimension achieved by ripping down 2x10s)
- Alternate 2: 2x6 studs with 2x8 plates with 1-3/4-in. rigid foam (typically two layers—stagger joints)

Rim construction:

- Double rim joists can be installed flush to exterior face of wall or inset by 1 in. for installation of 1-in. rigid foam continuous installation.
- Single rim joist must be inset 1 in.
- Rim joist(s) may be inset up to 2 in. only if the wood structural panel (WSP) sheathing spans from the top plate all the way to the sill plate and is fastened to the sill plate at 3-in. o.c. with scheduled nails. The aspect ratio for braced wall panels in this case shall be based on the entire length of the WSP sheathing from the top plate to the sill. If the end bearing length for the floor joists is not adequate (per International Residential Code [IRC] or manufacturer's requirements, typically 1¾ in.), the joists must be supported with metal hangers.

Rim construction:

- As above, but joist hangers must be used for all floor joists over window and door openings.

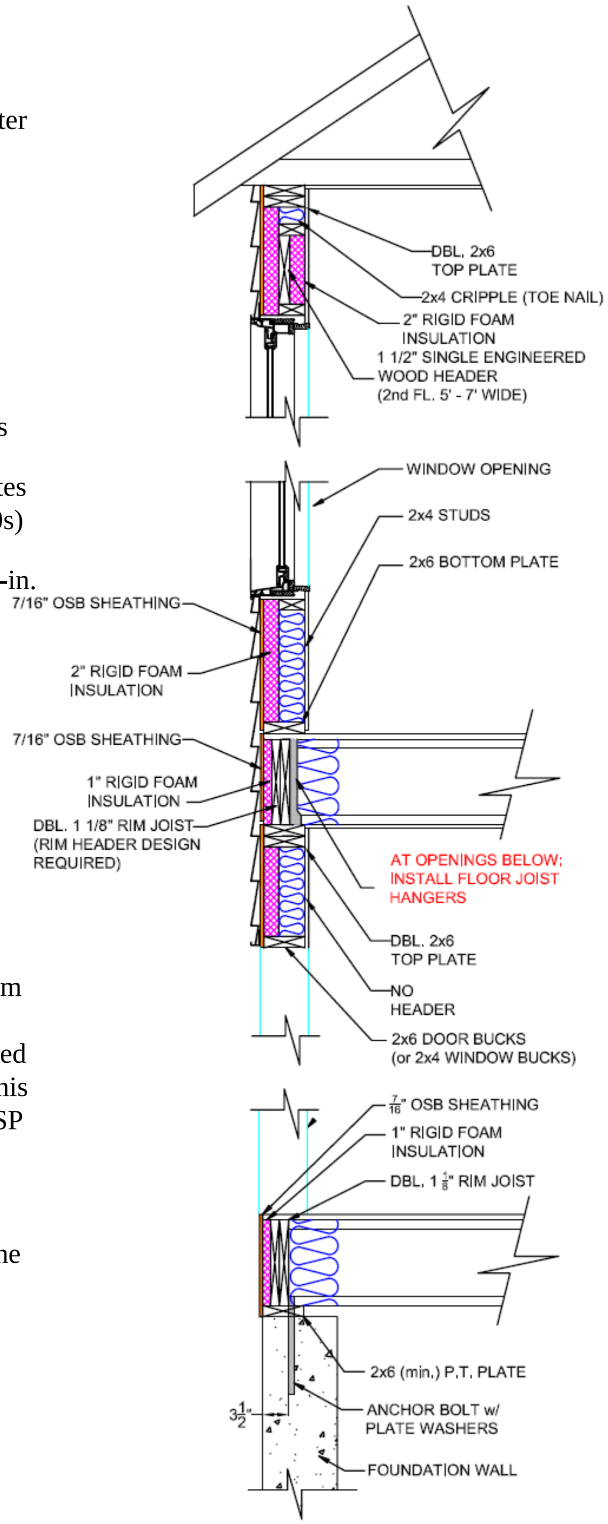


Figure 41. EP&B wall, section view

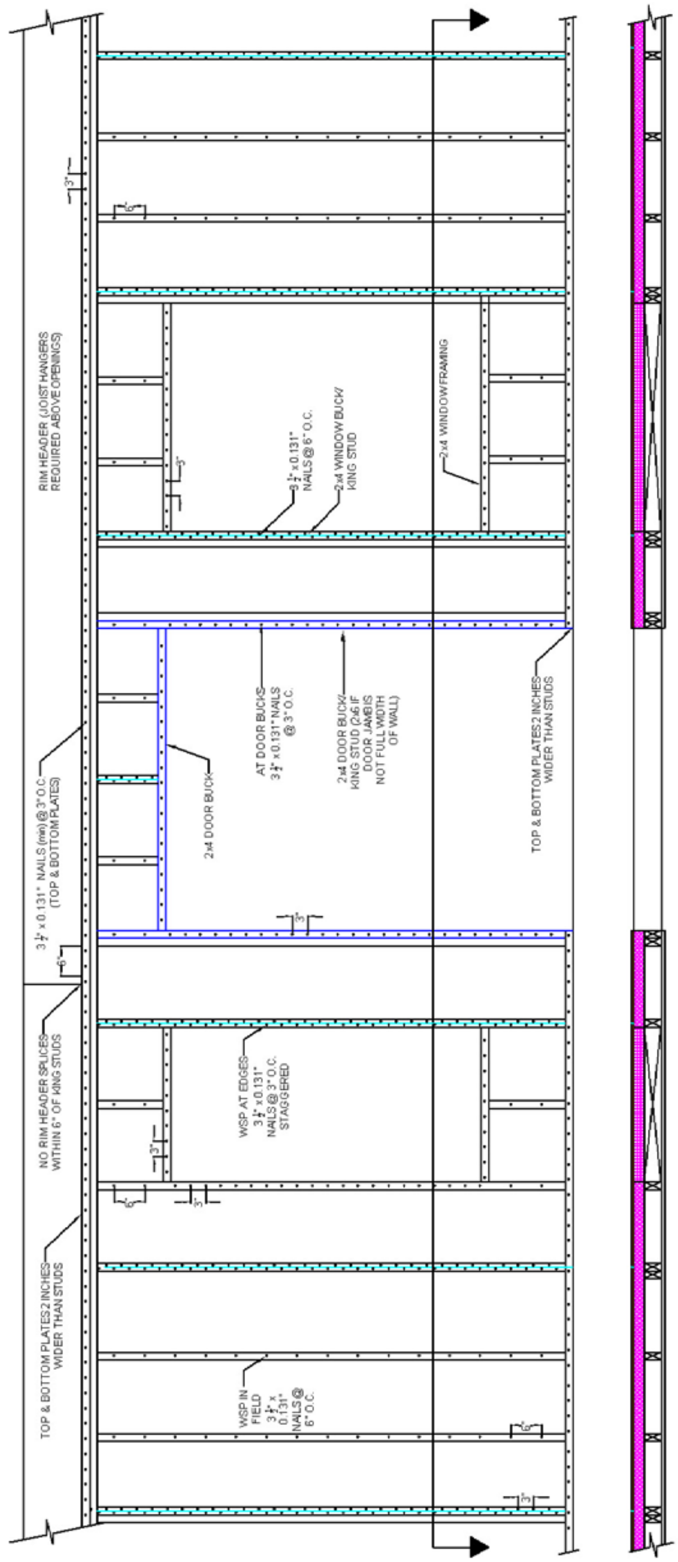


Figure 42. EP&B wall, interior elevation view

Appendix B: Laboratory Structural Testing

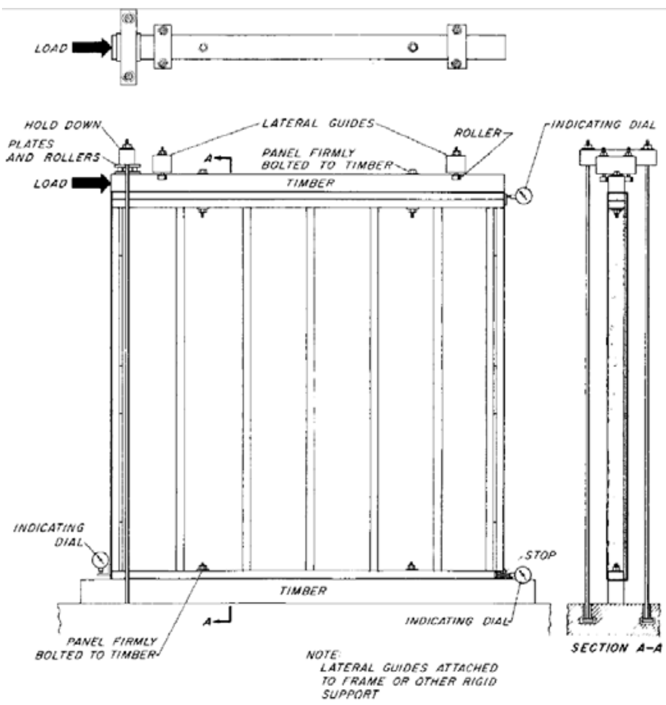
Equipment and Methodology

Table 13 itemizes the equipment used to perform the structural tests. All test equipment is calibrated in accordance with the Home Innovation procedures approved by the International Accreditation Service as part of the laboratory accreditation process.

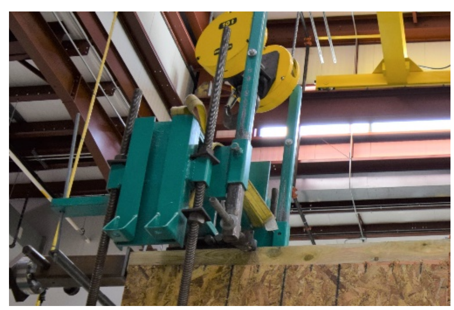
Table 13. Structural Test Equipment

Device	Manufacturer/Model	Measurement
Testing apparatus load cell	Omega LCH-50K	Load
Racker string pot	Unimeasure P1010-15-NJC-L15M	Deflection
Racker LVDTs	Macrosensor DC750-1000	Deflection
Racker LVDTs	Macrosensor DC750-2000	Deflection
Racker LVDTs	Macrosensor DC750-3000	Deflection
Handheld moisture meter	Delmhorst DB-10	Moisture content
Scale	Ohaus MCT500	Specific gravity
Oven	Despatch LBB1-43A-1	Specific gravity

Figure 43 and Figure 44 show the 2x6 IRC reference wall mounted in the racking shear test apparatus for the E72 test. Figure 45 shows an EP&B wall mounted in the racking shear test apparatus for an E564 test.



Note hold-down, rollers



Note hold-down, rollers

Figure 43. ASTM E72 Section 14.3.2 hold-down provisions, 2x6 standard reference wall in testing apparatus

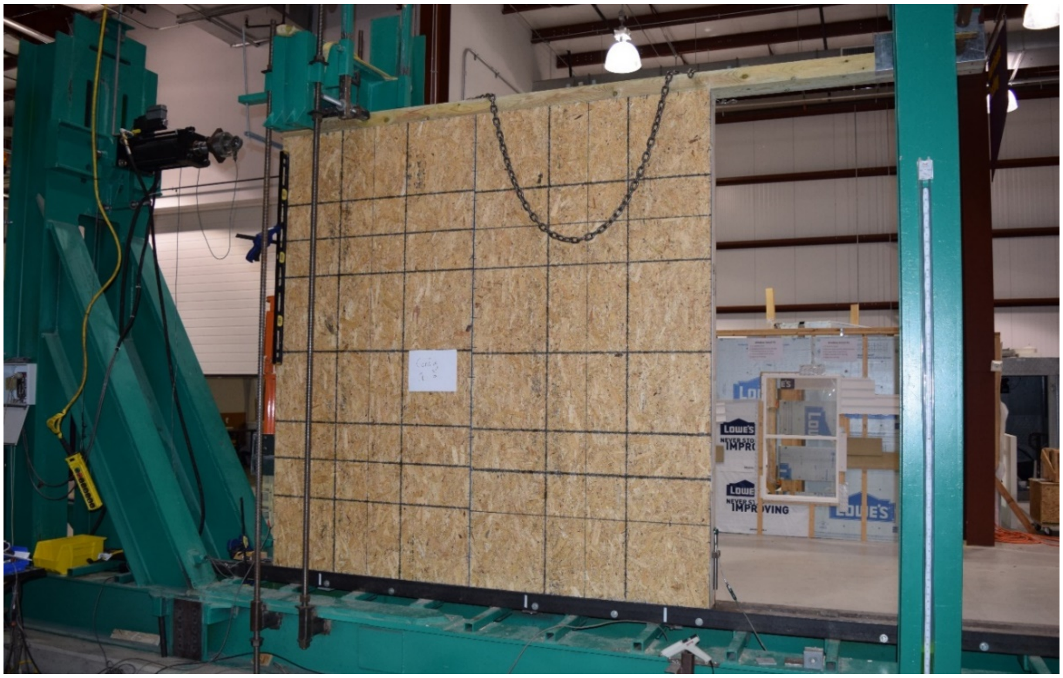
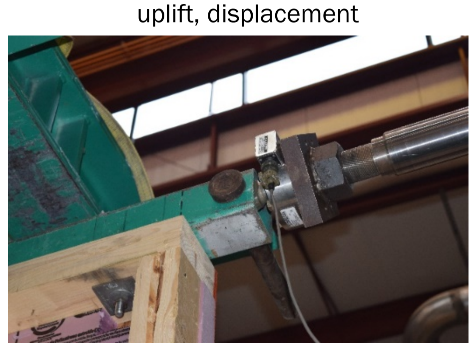


Figure 44. A 2x6 standard reference wall in testing apparatus prepared for ASTM 72 test

Section 4.2.3.2 overturning restraints for E564

String potentiometer for measuring uplift, displacement



Boundary conditions:
loading beam, plate anchors

Figure 45. EP&B specimen wall in testing apparatus prepared for AC269.1, E564 tests

Test Methods and Materials

AC269.1 Section 4.1.1.2 and Section 4.2.3 *Test Assembly Construction* specifies moisture content (MC) and specific gravity (oven-dry basis) for the lumber used to construct the specimen walls. Specific gravity (American Society for Testing and Materials [ASTM] D2395) and MC (ASTM D4442-07) for samples from each lumber shipment were measured following delivery of the lumber to confirm the range. Lumber was stored in a climate-controlled room between delivery and specimen construction; tests were conducted within two days of construction of the test wall. MC of framing was verified with a handheld electric moisture meter (Method A, ASTM Standard D 4444) before each test to verify that it was within the required range.

Table 14 shows average MC and specific gravity of the tested wall specimens.

Table 14. Average Specific Gravity of Lumber

Specimen Set	Test	Wood Species	Average Specific Gravity (lbs/f^3)
2x6 IRC comparison walls	ASTM E72	Spruce-pine-fir	0.405
EP&B 3/6 walls	ASTM E72	Douglas fir-larch	0.517
EP&B 3/6 walls	ASTM E562	Spruce-pine-fir	0.444

Structural tests were conducted using a racking shear test apparatus controlled via a computer-based system. Instrument readings including load and deformation measurements were recorded using a computer-based data acquisition system.

The load was measured using an electronic load cell located between the cylinder and the distribution beam. The following deformations were measured using a string potentiometer and linear variable differential transformers (LVDTs):

1. Lateral displacement of the centerline of the top plate relative to the test apparatus frame
2. Lateral displacement of the centerline of the bottom plate relative to the test apparatus base
3. Vertical displacement (compression) at the specimen corner compression stud relative to the test apparatus base
4. Vertical displacement (uplift) at the specimen corner tension stud relative to the test apparatus base
5. Vertical displacement (compression or uplift) inside doorways and full-height openings for compression and tension jack studs relative to the test apparatus base (as applicable for ASTM E564 wall configurations).

Table 15 summarizes key material and construction details for all testing phases.

Table 15. Average Specific Gravity of Lumber

<table>
<tr><th>Component</th><th colspan="2">Specification</th></tr>
<tr><td>Framing lumber, walls</td><td>Phase I (E72)
Reference
2x6 SPF #2 grade plates
2x6 stud grade studs
EP&B:
2x6 DFL #2 grade plates
2x4 DFL stud grade studs</td><td>Phase II (E564)

2x6 SPF #2 grade plates
2x4 SPF stud grade studs</td></tr>
<tr><td>Stud spacing</td><td colspan="2">Max 16-in. o.c.</td></tr>
<tr><td>Wall sheathing</td><td colspan="2">7/16-in.-thick OSB</td></tr>
<tr><td>Wall sheathing fasteners</td><td colspan="2">D=0.113 in., L=2-3/8 in. (2x6 standard wall)
D=0.131 in.; L=3-1/2 in. (EP&B)
Collated clipped head</td></tr>
<tr><td>Rigid foam</td><td colspan="2">2-in. thick XPS</td></tr>
<tr><td>Framing nails</td><td colspan="2">16d (D=0.131 in., L=3-1/2 in.)
Collated clipped head</td></tr>
<tr><td>Nailing distance from panel edge</td><td colspan="2">3/8-in. minimum</td></tr>
<tr><td>Panel joint gap</td><td colspan="2">1/8-in.</td></tr>
<tr><td>Hold-down: ASTM E72-13a</td><td colspan="2">Vertical rods, integral to testing apparatus</td></tr>
<tr><td>Hold-down:
AC269.1 Section 4.2 and ASTM E564</td><td colspan="2"><u>Simpson HTT4 with 16 qty 10d x 3 and 5/8-in. bolt</u>

This combination interpolated based on allowable tensile capacity ≤ 3,500 lbs:
<table><tr><th>Fasteners</th><th>Min. Wood Member Size (in.)</th><th>SPF/HF</th></tr><tr><td>18-10d x 1-1/2</td><td>1-1/2 x 5-1/2</td><td>2580</td></tr><tr><td>18-10d x 1-1/2</td><td>3 x 3-1/2</td><td>3105</td></tr><tr><td>18-16d x 2-1/2</td><td>3 x 3-1/2</td><td>3640</td></tr></table>(www.strongtie.com/products/connectors/LTT-HTT.asp?source=holdttcat)</td></tr>
<tr><td>Anchor bolts
(shear wall only)</td><td colspan="2">(3) ½-in. diameter bolts 3-in. x 3-in. plate washers (Phase 1)
(3) ½-in. diameter bolts with standard cut washers (Phase 2)</td></tr>
<tr><td>Interior sheathing</td><td colspan="2">None</td></tr>
</table>

Intermittent Braced Wall: Test Protocol

Table 16 lists the AC269.1/ASTM E72 qualification test matrix, including the two 2x6 standard IRC 8x8 wall specimens (for comparison only) and the three EP&B walls. Testing for intermittent braced walls follows Section 4.1 of AC269.1 2017 in accordance with ASTM E72 regarding specimen construction and loading protocol using the testing apparatus described below.

Table 16. AC269 4.1 (ASTM E72) Equivalency: IRC Intermittent Bracing Method

Wall	Replicates	Description	Sheathing Fastener	Notes
IRC Reference	2	Standard 2x6 IRC Continuously sheated WSP wall	2-3/8-in. L, 0.131-in. D @ 6-in. o.c. perimeter, 12-in. o.c. field	Provide reference—standard construction
EP&B-3/6	3	EP&B—2x4/2x6, three plates extended	3-1/2-in. L, 0.131-in. D @ 3-in. o.c. perimeter, 6-in. o.c. field	Establish EP&B equivalency

The hydraulic actuator motion was imposed on the specimen using a 4x6 (nominal) pressure-treated timber load beam bolted to the top plate of the EP&B specimen with (6) ½-in. diameter bolts with 3x3 plate washers on both the top and bottom. The bolts are installed off center to ensure that the bolts/plate washers do not interfere with the rigid foam and bear only on the framing. The out-of-plane deformations were restrained by a set of rollers located on the side of the load beam. The beam was centered on the wall plates; the bolts were centered relative to the 2x4 studs per typical construction practice.

Loading was applied as a compressive force by pushing on the end of the timber attached to the specimen's top plate, per Figure 46.

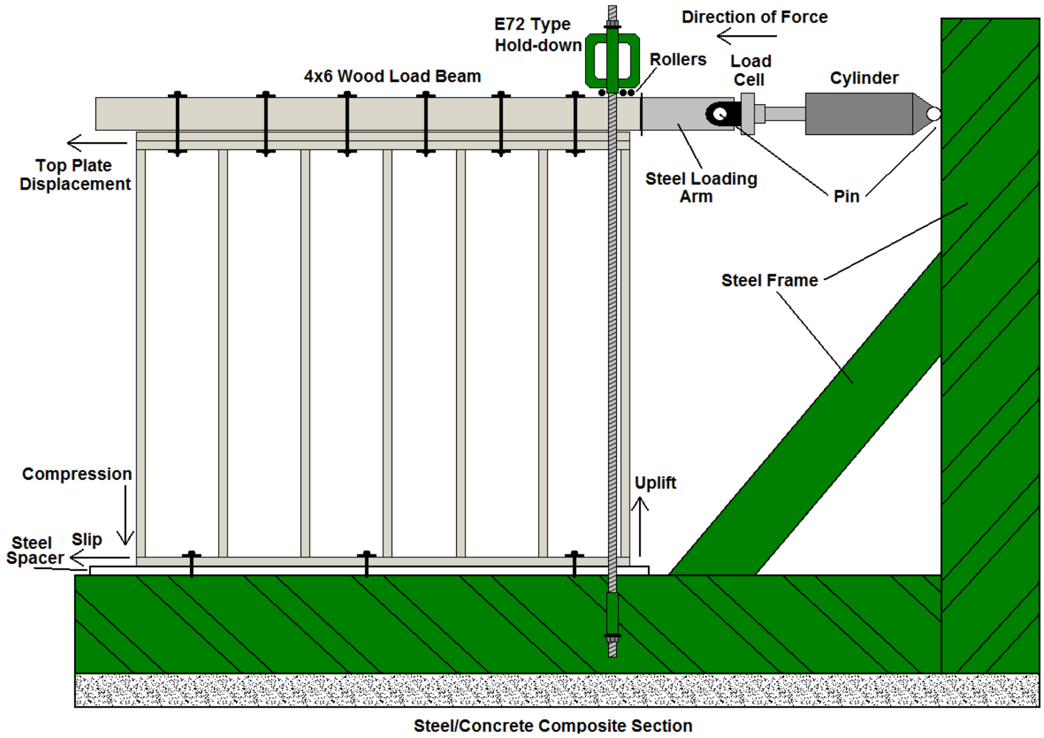


Figure 46. Test apparatus for AC269.1 Section 4.1, ASTM E72 tests

Loading for Phase I was applied in four phases in accordance with Section 14 of ASTM E72 at a constant displacement rate of 0.06 in./minute per phase. This rate was selected to meet the requirement of achieving 790 lbs in not less than 2 minutes. The same rate was applied for the all phases:

1. Load applied at 0.06 in./minute to 790
    A. Load removed at 0.6 in./minute to 0
    B. Hold at 0 for 5 minutes
2. Load applied at 0.06 in./minute to 1,570
    A. Load removed at 0.6 in./minute to 0
    B. Hold at 0 for 5 minutes
3. Load applied at 0.06 in./minute to 2,360
    A. Load removed at 0.6 in./minute to 0
    B. NO HOLD
4. Load applied at 0.06 in./minute until failure

The sample rate for data collection was 5 Hz. All walls were tested either to failure or to a minimum of 4-in. deflection.

E72 sections 14.1.1 and 14.1.2 direct that the sample walls should meet the goals of reproducibility and “replicate the behavior of the specimen over its entire range of use” in actual service. The configuration of the EP&B wall has been developed to optimize constructability and uniformity, and the fastener schedule was designed to meet the practical considerations of a residential construction site. A *Construction Guide* is being produced as a result of this project that will guide builders in duplicating the construction details as tested with these EP&B wall sections.

All test specimens were constructed in conformance with ASTM E72 using collated 3-1/2-in. clipped head nails for all framing connections of the EP&B specimen walls, as well as for attachment of the sheathing, providing direct comparison to the expected EP&B field construction methods. This included end nailing studs to plates, nailing double end studs, and nailing the second top plate to the top plate. A pneumatic nail gun was used because the EP&B wall is expected to be constructed in the field using a nail gun. Pneumatic pressure for the framing gun was chosen to drive the nail nearly flush with the OSB surface, and it was then replicated for all samples. Each nail was hand-driven the final length (as necessary) to avoid oversinking.

The 3/6-in. o.c. sheathing fastener schedule (3-in. o.c. perimeter/6-in. o.c. field) for the EP&B specimen walls was determined based on the requirements of the extended plate configuration and expected field practices. Nails were set back 3/8-in. from OSB panel edges, and a 1/8-in. gap was maintained between panels. EP&B specimen walls were constructed with Douglas fir-larch plate and stud lumber.

Standard 2x6 (spruce-pine-fir) IRC continuously sheathed WSP reference walls were constructed in conformance with ASTM E72 and tested for comparison only; these reference values are not required for AC269 equivalency. The 2x6 configuration was selected to match the framing material and finished wall thickness of the EP&B walls to allow for direct comparison. Sheathing for the 2x6 standard reference wall was attached using collated 2-3/8-in. clipped head nails with 6/12-in o.c. nail spacing. IRC reference walls were constructed with spruce-pine-fir lumber.

Continuous Braced Wall: Test Protocol

Based on E72 qualification, the E564 baseline tests were performed on EP&B wall samples for Type 1 (8-ft. baseline), Type 2 (12-ft. with corner return in lieu of hold-down), and types 3–7 (various perforated wall configurations, with one or multiple window and door openings).

Testing for continuously sheathed braced walls follows Section 4.2 of AC269.1 2017 regarding specimen construction, wall type test matrix, and loading protocol. The racking shear tests were conducted in accordance with ASTM E564. Loading for Phase II was applied in a single, continuous phase using the test apparatus described above.

The hydraulic actuator motion was imposed on the specimen using a 4x4 steel load beam bolted to the top plate of the EP&B specimen with (6) ½-in. diameter bolts with 3x3 plate washers on both the top and bottom. The beam and bolts/plate washers were installed to avoid interference with the rigid foam and bear only on the framing, allowing the sheathing to react during the test without interference. The out-of-plane deformations were restrained by a set of rollers located on the side of the load beam. The 2x6 top plates are 1½-in. wider than the 4-in. steel load beam, which is nearly centered over the wall at ½ in. from the sheathing side, 1 in. from the wall plane on the interior side to replicate actual construction and load conditions in the field.

Loading was applied as a tensile force by pulling on the end of the steel beam attached to the specimen’s top plate per Figure 47. The load was applied in a single, continuous motion at a constant displacement rate of 0.3 in./min. The sample rate for data collection was 5 Hz. All walls were tested either to failure or to a minimum of 4-in. deflection.

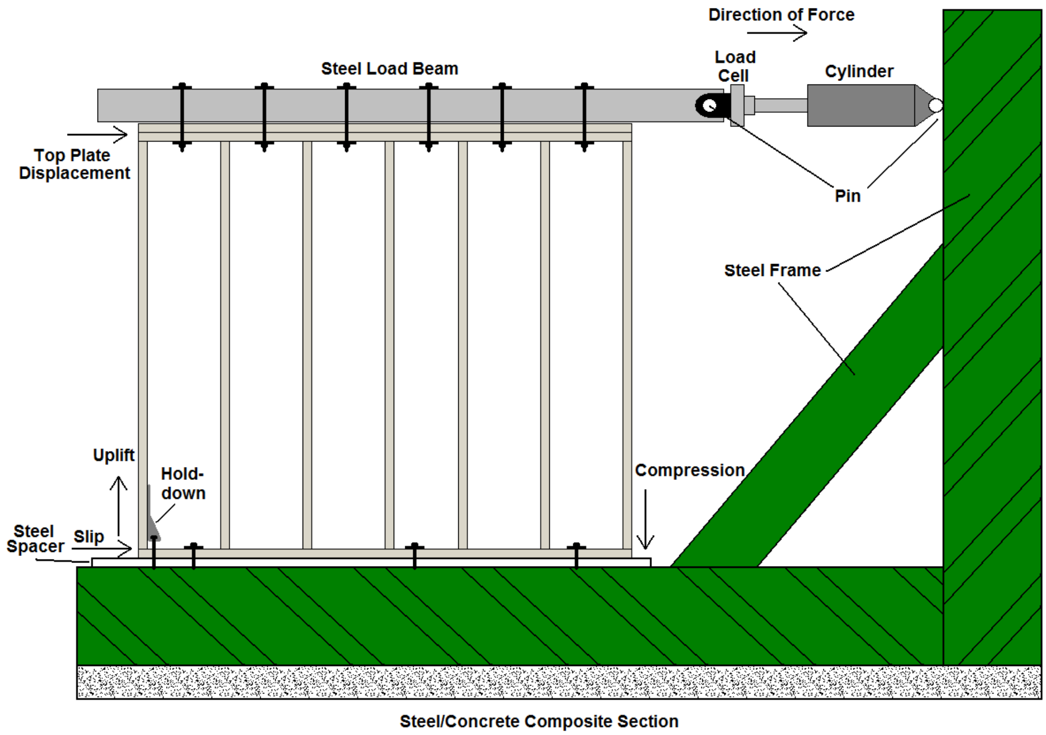
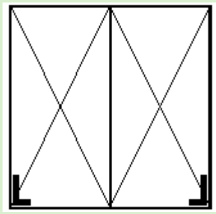
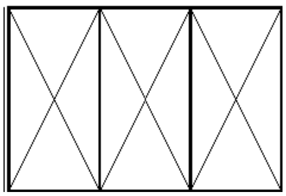
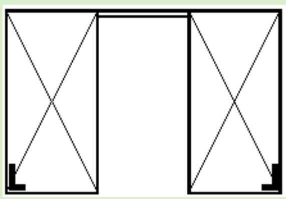
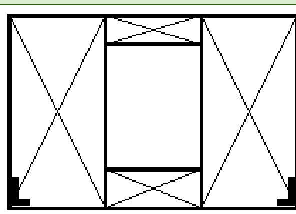
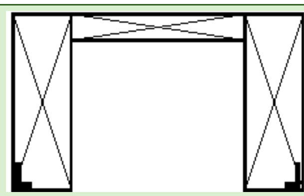
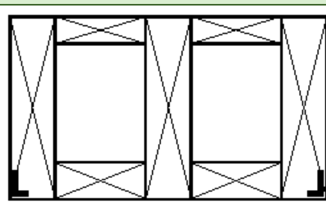
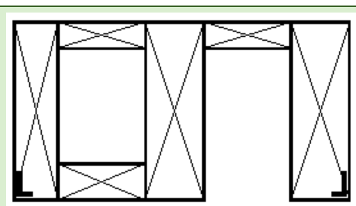


Figure 47. Testing apparatus for AC269.1 Section 4.2, E564 tests

The EP&B wall specimens for AC269 4.2 were constructed of spruce-pine-fur framing lumber according to the continuously sheathed wood structural panel bracing method (CS-WSP) of IRC Section R602.10.4, with geometries and hold-downs as itemized in ASTM E564, and matching the 3/6 fastening schedule from Phase I testing for wall Type 1 and wall types 2–7. Two specimens of wall Type 1 were built and tested; one specimen of each of wall types 2–7 were built and tested.

Per the E564 schematics, with panel joints parallel and coincident with the framing of openings, sheathing did not span across the corners of any openings, either above or below. Table 17 itemizes the details of all E564 test wall configurations.

Table 17. AC269 4.2 (ASTM E564) Equivalency: IRC Continuous Bracing Method

#	Configuration	Size (HxW), ft	Max Clear Opening Height, % of H	Reduction Factor	Types of Openings
1		8x8	n/a	n/a	None
2		8x12	n/a	0.79	None
3		8x12	100%	0.40	Full height, 4 feet wide
4		8x12	65%	0.51	Window, 4 feet wide
5		8x13.3	85%	0.21	Door, 8 feet wide
6		8x14	65%	0.29	Windows (2), 4 feet wide
7		8x15.3	65%, 85%	0.29	Window, Door, 4 feet wide

Appendix C: Construction Observations

Builder

Arn McIntyre is a builder and an engineer in Grand Rapids, Michigan. He owns and operates Performance Home Corporation, a building performance consulting and analysis firm. He often works with industry representatives and building researchers, conducts Home Energy Rating System Index and ENERGY STAR® ratings, and participates in educational sessions and building failure analysis. He is a frequent partner with Home Innovation.

McIntyre's typical envelope construction for Climate Zone 5 is 2x4 framing with sheathing of 1½-in. extruded polystyrene (XPS) rigid foam, employing let-in bracing for International Residential Code (IRC) shear requirements (no wood structural panel [WSP]). Insulation is generally an approximately 1-in. flash coat of closed-cell spray foam (ccSPF, ~R-6 per inch) followed by cavity fill insulation of blown fiberglass (~R-4.3 per inch.)

The extended plate and beam (EP&B) wall added approximately 1 in. of thickness to his typical wall (additional ½-in. XPS and 7/16-in. oriented strand board [OSB]) and increased nominal insulation by approximately R-3. McIntyre reported that the owners of the two test homes were both happy to "upgrade" to the EP&B wall system given his recommendation that it includes more insulation value than the wall promised in the contract.

McIntyre reported that he was pleased with the appearance of the EP&B wall and encouraged by the tested structural performance and monitored and simulated moisture performance. He noted that because jurisdictions in colder climate zones require better thermal performance, many builders have adopted either a 2x6 wall to incorporate more cavity insulation or are over-sheathing a typical 2x4 WSP-braced wall with foam to increase R-value. He considers both options to be susceptible to short- and long-term moisture issues. In the case of the 2x6 wall, in cold climates the temperature profile ensures below-dew point temperatures within the wall cavity, which can lead to condensation. In the case of foam over-sheathing, the OSB is trapped under the foam and susceptible to liquid water in the case of breech or construction error; damage and rot in this case is particularly difficult to locate and repair given the outer layer of rigid foam.

McIntyre pointed out that the greatest drawback to EP&B seems to be the degree of nailing accuracy required at OSB joints. He noted that the revised fastener schedule of 3.5-in. nails is likely to improve this situation (the field tests used 4-in. nails) but noted that any builder adopting EP&B should take special care to train the framing crew in the angle required for full framing engagement and set aside time for review and quality control until the crew can execute this step accurately and reliably.

Framer

The following comments resulted from conversations with Kevin L. Smith, owner of Kevin L. Smith Construction, and the other three crew members during the course of several days while they framed, wrapped, and installed windows in both houses.

1. For attaching OSB to framing, many carpenters use staples at double the frequency of nails. Because of the required length and the structural shear requirements, staples are not an acceptable substitute for nails in an EP&B wall. This should be strongly noted in instructions.

2. Nails at 4-in. length were expensive and needed to be special-ordered.

3. The nail gun for 4-in. nails is noticeably heavier than the standard framer's nail gun. If they had to use it frequently and for long periods in a horizontal position, especially on a ladder, this would be a burden. Because it is held vertically (aimed down) on walls lying horizontal on the deck, this is not a

problem. Note that the EP&B fastening schedule has since been modified to use 3½-in. nails, which are cheaper, more readily available, and fit into most (lighter) framing nail guns.

4. An 8-in. reciprocating saw blade is needed (6 in. is too short).

5. Noted that the OSB sections outboard of foam would be tricky at the last corner on the second level to ensure a complete thermal break (they need to work from outside the wall, on a ladder).

6. Smith guessed that it took approximately 30% additional time to frame compared to the typical McIntyre (foam sheathing only) wall. He estimated it would take the same or less time than a wall with continuous insulation over WSP (both have two layers of sheathing).

7. Additional time would be reduced for subsequent builds because of a relatively short learning curve.

8. The approach to air sealing of framing members is similar to the typical approach.

9. The WRB sheeting should be attached while walls are still laying on the deck. Fold the edges of the WRB out of the way for tip-up.

10. The EP&B fastener pattern was initially characterized as plates versus studs. There was some confusion about which nailing schedule to use at the window edges. Framers chose 6-in. intervals because the window would later be attached with long nails and would provide additional fasteners through both substrates. Note that the fastener schedule has since been changed to perimeter/field rather than plates/studs, reducing confusion. Fasteners around openings could still be reduced in anticipation of the nails used later to fasten the windows.

11. A 3-in. hand blade was kept available for manual foam cuts.

12. Extra time was required to plan for alternating vertical seams of OSB and rigid foam so that they are never coincident.

13. Once the walls were up, the crew checked from the inside for missed nails at studs. Angle is important—with the additional 2 in. of foam, it is easier to accidentally miss total embedment by overcorrecting, thus penetrating past the stud face on the opposite side. This straighter angle takes practice, and correction (re-nailing) can be time-consuming.

14. The WSP was re-nailed as necessary from outside (on a ladder), and the water-resistive barrier (WRB) was refolded into place. If the crew had to nail through the WRB, it was sealed with caulk at the nail head.

15. Cap nails are irritating to work with—they are thin, bend easily, leave a mess around the work site, and take up room in the pouch. Continuous insulation over WSP and foam plastic insulating sheathing (FPIS) as sheathing both require lots of cap nails. EP&B requires far fewer—that’s good. Plus, they end up being covered/held in place by OSB.

16. The crew also discussed other walls types, specifically FPIS-only with let-in bracing. Smith and his crew reported that when homeowners find out they have no wood sheathing they are often uncomfortable; they are surprised (and sometimes distressed) to learn that the exterior sheathing is only foam.

17. The crew agree that there is a major difference (noise, weight, feel) once spray foam is added to an FPIS-only sheathed wall. Similar improvements were seen with the EP&B wall compared to FPIS-only sheathing.

18. For houses with FPIS as the only sheathing, the crew always order doubled trusses for each gable end. This is not required for EP&B walls. The roof truss can bear on the extended 2x6 plates with the 2x4 vertical framing member below.

19. Joining wall sections requires standard attention to sealing details. When there is a gap between studs at an outside corner, do not simply force them together with a nail. Instead, fill with spray foam or gasket or caulk *first*, then connect and fasten tightly.

20. With the FPIS-only sheathing and exterior continuous insulation methods, the crew generally add a 1x6 sill at the bottom of each window opening to support window weight. This is not necessary with EP&B.

21. With the FPIS-only sheathing and exterior continuous insulation methods, some crews frame out the windows with 2x6 lumber. This is not necessary with EP&B.

22. In the typical foam-only sheathed wall, they install full sheets of the FPIS with the wall on the deck, but they cut the openings after the wall is tipped into place, from inside, which is a handy position both physically and for seeing the framing opening. Potentially this could also work for EP&B with a reciprocating saw but not with a circular saw or router. For the two field tests, the crew cut the openings while the walls were still laying on the deck, and in two passes—first for the foam and second for the OSB. They typically used a reciprocating saw for the foam and a circular saw for the OSB. This was time-consuming but relatively simple and straight-forward.

23. Bidding: A $500 premium was added because of the double sheathing effort (OSB in addition to rigid foam) and Tyvek (additional labor and materials for an approximate 1,200-ft^2 house).

24. The rigid foam was donated to the project. The crew noted that foam is expensive. The International Energy Conservation Code requires higher thermal performance, and continuous insulation is one way to get it: for a 28x46 single-story house, they would usually increase the bid by $1,000.

25. Speculation: if moisture gets behind the WRB in the EP&B wall, nails may pop (and there are a lot of them). Then the only solution is to destroy the wall to repair and replace—it is not easy to peel off a layer because the foam is behind the OSB. However, a water problem behind continuous insulation rigid foam over WSP would probably also compromise the OSB, and it would need to be removed regardless. Only the comparison FPIS-only wall is easily replaced in a water-intrusion situation.

26. Smith anticipates that locals are more likely to choose 16-in. o.c. 2x6 framing, with an additional 1 in. or 1½ in. of FPIS continuous insulation installed as sheathing, supported with let-in bracing.

27. Nailing was the biggest issue—frequency and angle. Smith considers EP&B to be a somewhat unforgiving system with respect to fasteners, which are demanding of precision.

28. Siding installation is not in the framer's scope of work; however, Smith speculated that there may not be a major advantage to EP&B related to the OSB as a nailing substrate. "In this area, siding is generally hand-nailed, and you can feel whether or not you've engaged the framing." However, for a builder transitioning from hand-nailing to attaching cladding with a nail gun, this may represent time savings.

29. Score lines make the rigid foam susceptible to accidental breakage. "No one snaps 2-in. foam." Choose unscored, if possible.

Panelizer: Grand Rapids, Michigan

The manager of the Zeeland Truss & Components panelization plant in Grand Rapids, Dean DeHoog, felt that Zeeland had successfully exploited a sector of the local market using a named product that bears a certain cachet. He indicated that he was unlikely to change unless his customers demanded something not deliverable by the proprietary system. Zeeland's current association with the manufacturer has developed a loyal, local, somewhat high-end following for a product with dependable, repeatable results.

In the case of the EP&B wall, DeHoog speculated that in the Zeeland production plant any initial savings resulting from lower costs for nonproprietary materials might be offset by additional time to install the OSB and rigid foam in two steps—the rigid foam of the proprietary panels comes laminated to the OSB. DeHoog also felt the local crews who had already erected dozens of these panelized buildings had mastered the taping required for air and moisture sealing so that the EP&B advantage of using traditional WRB sheet goods also might not represent savings. Regarding structural uplift, shear, and diaphragm loading, Zeeland has worked in concert with local architects and builders to address the design requirements for the building types that most frequently employ the proprietary wall panels, so there are no immediate savings to be gained from the EP&B's potential as an alternate IRC prescriptive braced wall.

Figure 48 through Figure 50 illustrate the Zeeland wall panel production plant.

Figure 48. Bridge nailer, Zeeland Truss & Components

Figure 49. Laser sight bridge nailer

Figure 50. Wall panel bundles ready for shipment

NYSERDA Panel Project

In 2015–2016, the New York State Energy Research & Development Authority (NYSERDA) sponsored a research project on a demonstration house built with EP&B wall panels produced at a building components plant in Whitesboro, New York. The design used 2x4 lumber for the studs and first top plate and 2x6 lumber for the bottom and second top plates, with 2-in. XPS R-10 rigid foam, 7/16-in. OSB exterior structural sheathing, and 3.5 in. of R-15 unfaced fiberglass batts in the wall cavity.

The EP&B wall system was evaluated as part of a panelized construction process where the walls are fabricated in a controlled factory environment and delivered to the site for assembly. The EP&B system provides an opportunity for panelizers to integrate thermal insulation into their fabrication process. It is standard practice for panelizers around the country not to install any insulation, neither cavity nor exterior, at the factory. In fact, the panelizer involved in this study had never installed insulation at their facility in the 50-year history of the company. The purpose of this project was to use the EP&B innovation to demonstrate a path for panelizers to add the energy-efficiency component of continuous insulation to the traditionally structure-only product and to participate in the high-performance construction market.

Figure 51 shows the front view of the completed home, and Figure 52 shows the floor plan of the test house.

Figure 51. NYSERDA EP&B test home front view

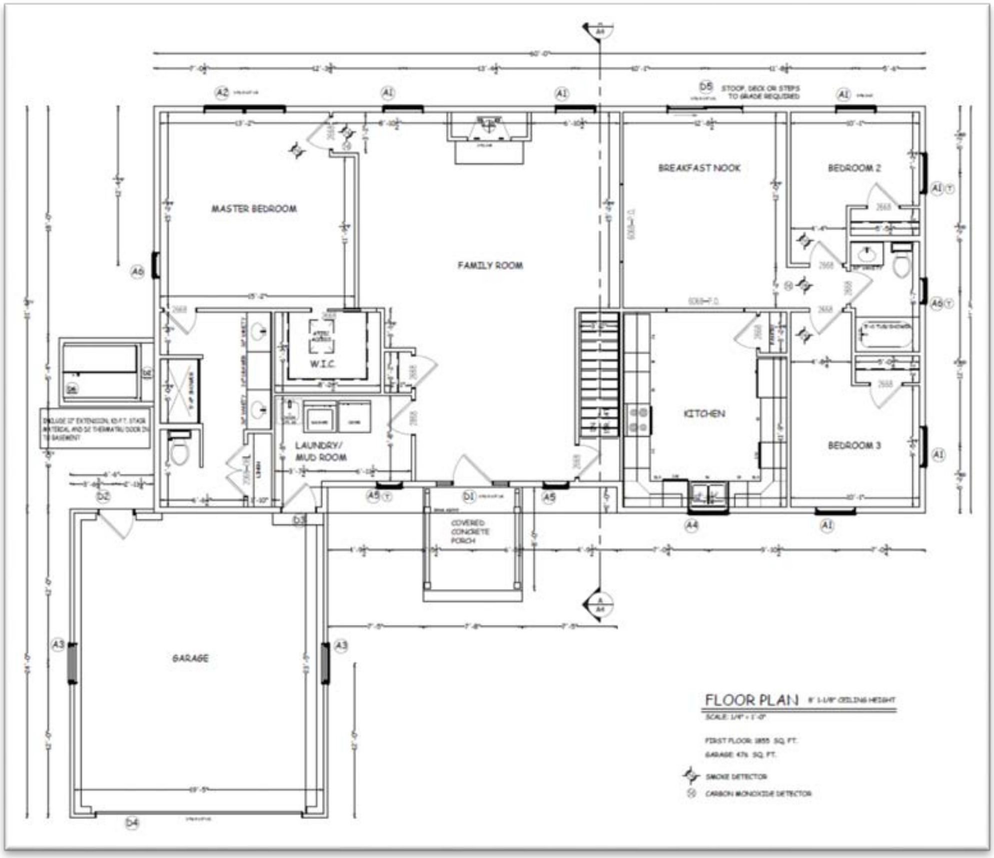
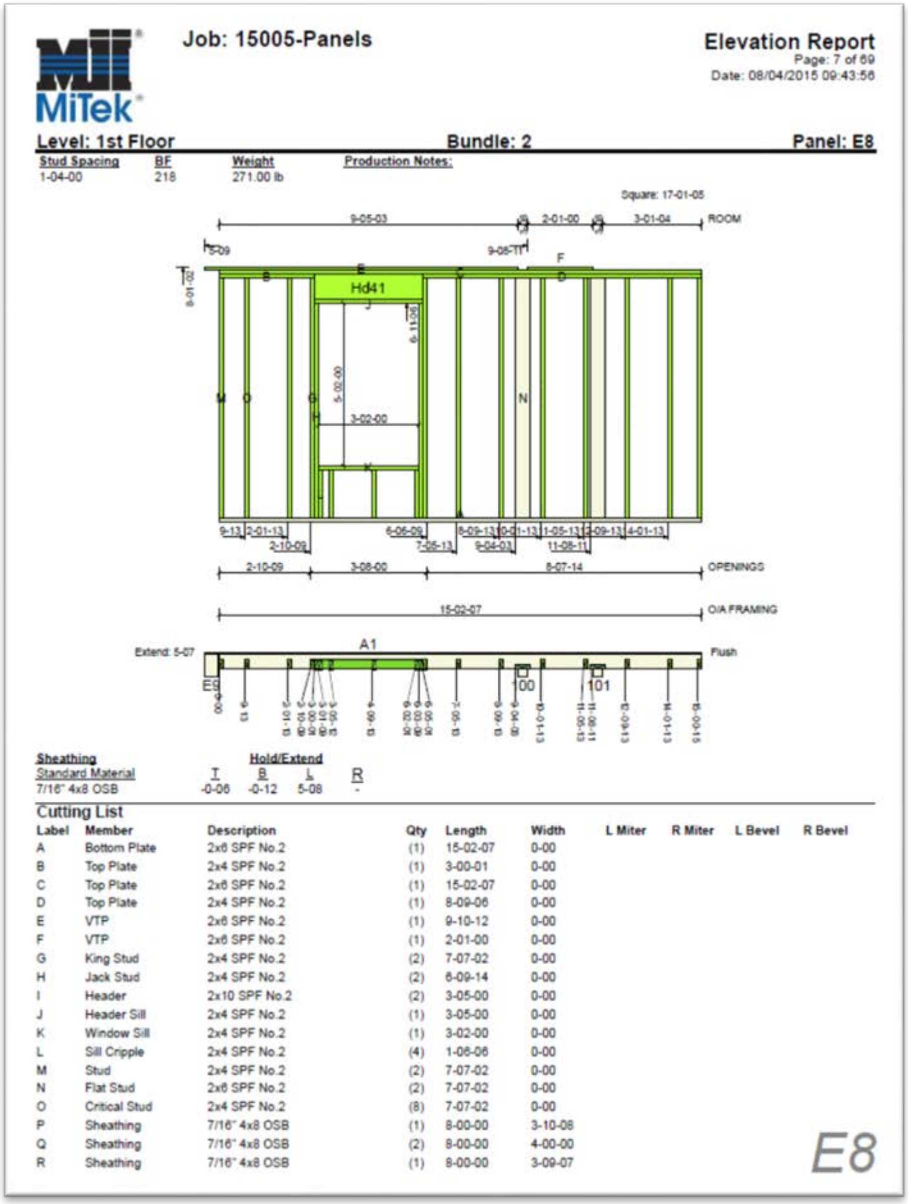


Figure 52. EP&B test home floor plan

Panelizer: Whitesboro, New York

Whitesboro plant manager Dan Webb stated that the project was outside of this Stark Truss facility's ordinary assembly work process. This plant was started as a wall panel fabrication plant, but recently it had been producing more trusses than wall components. The crew had no experience with the EP&B configuration nor with rigid foam sheathing.

The computer-aided design designer developed a complete set of shop drawings for all walls, including corners and window and door openings, according to their standard practice. Webb reported no difficulties in drafting the EP&B wall system. Figure 53 and Figure 54 are representative examples of the schematics provided to the shop crew for assembling the panels and bundling and marking them for shipment to the project site.



Job: 15005-Panels

Elevation Report
Page: 7 of 69
Date: 08/04/2015 09:43:56

Level: 1st Floor   Bundle: 2   Panel: E8

Stud Spacing	BF	Weight	Production Notes:
1-04-00	218	271.00 lb	

Sheathing	Hold/Extend			
Standard Material	T	B	L	R
7/16" 4x8 OSB	-0-06	-0-12	5-08	-

Cutting List

Label	Member	Description	Qty	Length	Width	L Miter	R Miter	L Bevel	R Bevel
A	Bottom Plate	2x6 SPF No.2	(1)	15-02-07	0-00				
B	Top Plate	2x4 SPF No.2	(1)	3-00-01	0-00				
C	Top Plate	2x6 SPF No.2	(1)	15-02-07	0-00				
D	Top Plate	2x4 SPF No.2	(1)	8-09-06	0-00				
E	VTP	2x6 SPF No.2	(1)	9-10-12	0-00				
F	VTP	2x6 SPF No.2	(1)	2-01-00	0-00				
G	King Stud	2x4 SPF No.2	(2)	7-07-02	0-00				
H	Jack Stud	2x4 SPF No.2	(2)	6-09-14	0-00				
I	Header	2x10 SPF No.2	(2)	3-05-00	0-00				
J	Header Sill	2x4 SPF No.2	(1)	3-05-00	0-00				
K	Window Sill	2x4 SPF No.2	(1)	3-02-00	0-00				
L	Sill Cripple	2x4 SPF No.2	(4)	1-06-06	0-00				
M	Stud	2x4 SPF No.2	(2)	7-07-02	0-00				
N	Flat Stud	2x6 SPF No.2	(2)	7-07-02	0-00				
O	Critical Stud	2x4 SPF No.2	(8)	7-07-02	0-00				
P	Sheathing	7/16" 4x8 OSB	(1)	8-00-00	3-10-06				
Q	Sheathing	7/16" 4x8 OSB	(2)	8-00-00	4-00-00				
R	Sheathing	7/16" 4x8 OSB	(1)	8-00-00	3-09-07				

E8

Figure 53. Example of construction drawing for manufacture of EP&B wall panel

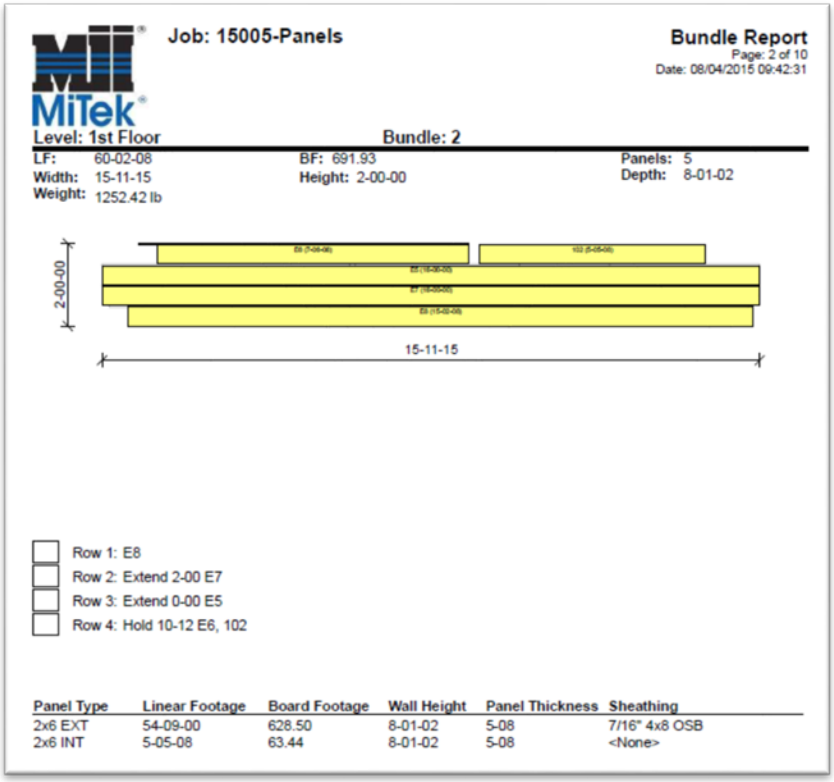


Figure 54. Example of construction drawing for bundling EP&B wall panels

Webb said that the addition of the rigid foam board accounted for the largest change to the team's typical process. Experimenting with various tools to cut the XPS took additional time; measuring and installing the foam required a change in workflow. A table saw was used to make long rips in both the OSB and foam prior to delivering the proper dimensions to the line. To cut the ends of the foam, the crew initially considered hot wire cutters, but they did not have the tool or the training. They also worried that melting the XPS might be a health hazard. Cutting the foam proved to be the most time-consuming aspect of EP&B wall construction, both during the initial hours when the crew was experimenting to find solutions and during the actual construction of the panels.

For window and door openings on the line, the crew initially used a handsaw for XPS and a circular saw for OSB. Because the XPS was placed on top of the framing early in the process, there was no circular saw available to use on the foam at that point in the line. The OSB was installed over the top of the foam later along the line.

Typically, a router bit is used when only OSB must be cut for window and door openings. These bits are too short to include the foam layer, so initially the crew cut the two layers independently. The production team was eventually able to locate a router bit that was long enough to span the combined depth of the 2-in. foam and 7/16-in. OSB. This allowed the crew to cut window and door openings at the typical location in the production line, after the foam had been installed over the studs and the OSB had been placed and fastened. Ideally, the bit would include a self-starting tip that can plunge through the OSB and foam into a known opening area and with enough length to guide the cut along the framing of the opening the full depth of both materials—roughly 2¾ in. to 3 in. (Figure 55). The tool they found had the necessary length but not the self-driving tip, so a pilot hole had to be drilled separately; however, once this extra step was accounted for, the router made the cut for each window or door opening in about the same time it would have taken for the OSB without the foam. With that process solved, end-cutting the foam panels was the step that the manager felt was least optimized. Note that rigid foam was originally developed to be installed on the exterior of building walls. The typical 8-ft length spans across the combined widths of the three plates plus the length of the studs, and it requires shortening to fit between top and bottom plates for the EP&B configuration.

Source: CMT Tools (used with permission)

Figure 55. “Pilot panel bit” for cutting OSB and foam together

The initial EP&B design used extended plates for only the bottom and second top plate; the first top plate was 2x4. Two different lumber sizes for framing required adjustment and planning, and this added complexity to the materials staging scheme. Assembly workers found it challenging to ensure that the face of the stud would be flush with the interior face of the plate to provide a good substrate for later drywall installation. The two different widths of the double top plate meant that the OSB could be fastened only to the second top plate. Atypically, a third top plate was incorporated in the design for tying the panels together in the field. These very top plates were designed, cut, and included in the package delivered to the site.

The 4-in. nails and framing gun required for fastening the OSB to the studs through the foam proved to be a challenge. Neither are typical and had to be special ordered. Both the nails and framing gun worked well, but Webb felt that this requirement might prove to be insurmountable for some crews or plants.

The plant work took two full 10-hour days for a crew of five (excluding supervision and management). This included the EP&B exterior walls and the standard interior partitions. The plant manager and research project field representative both reported that the learning curve appeared to be short, considering that three of the five crew members were new to the job, none had experience working with rigid insulation, and the available tools were not designed for the specific tasks.

The plant manager noted that it is difficult to compare to a typical job because the major difference was the cost of the foam, which was donated in this research project. He also did not have to source, compare prices, and order the foam, tasks that represent administrative time. Though the rigid foam is bulky, it is not heavy, and many plants have floor space to spare, including this one. The addition of the very top plate meant additional cost and further complicated the comparison of an EP&B system to a standard light-frame wood configuration.

Webb estimated that this one-off project required roughly 50%–60% additional time. With proper experience and tooling, Webb thought that the additional time required for an EP&B project would be 10%–15%, specifically for cutting and fitting the foam. This estimate was made prior to the recent system modifications of extending all top plates and using 3½-in. nails. In the future, he would plan to budget approximately another $500 to cover the necessary training and tooling changes to successfully bid and build EP&B wall panels. He predicted that with two or potentially three EP&B projects in close succession, any wall panel plant could optimize their processes so that little additional fee would be required, other than passing on the cost of the rigid foam. Gaps in time or personnel might lengthen this transition. He expressed willingness to do more EP&B projects in the future and stated that he would likely research and acquire the proper tools to solve the challenges described above if he knew that the EP&B system would be frequently requested. He noted that the ability to include insulation in the wall panel is a market differentiator.

Figure 56 through Figure 60 show various details of the EP&B wall panel production in the factory.

Figure 56. Studs nailed to bottom plate, with 2-in. gap for foam

Figure 57. Cutting XPS on a table saw

Figure 58. A wall panel with a window opening

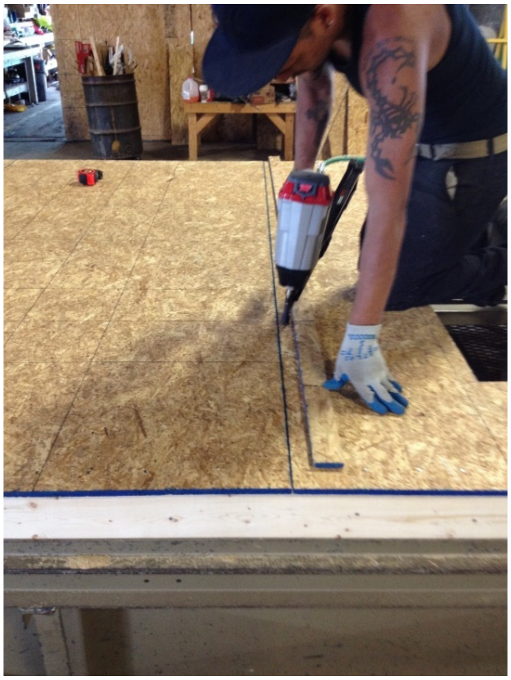


Figure 59. Using a guide to attach OSB to framing

Figure 60. Loading EP&B wall panels for delivery

Panel Erection On-Site: New York

The wall panels arrived on-site and were moved as required with no apparent damage.

Cody Warner, the framing foreman, had previous experience with a handful of panelized houses and reported that erection and joining the EP&B system took essentially the same time as any other panelized project, and the crew was able to use their standard tools and techniques. The 6-in. width of the EP&B walls was familiar to the crew because in that area of New York State the most common wall is 2x6 to accommodate code-mandated R-20 cavity fill insulation.

Warner reported only two potential quality issues with this EP&B project: detailing the air gap between neighboring panels (true for any panelized wall system) and nails at studs that missed framing (this appeared to be more problematic with EP&B than with other panelized wall systems). He noted that a bridge nailer at the panel plant would likely solve this problem. Warner noted that gaps between neighboring panels are common with any panelized project and not specific to EP&B. Air sealing was not within Warner's scope of work; he reported that the general contractor followed the framers and caulked each lumber connection, generally from the inside. This included the sill plate at the deck, the studs at neighboring wall sections, and the top plates.

Whether the wall panels are being constructed in a plant or on-site, nailing accuracy is difficult to determine until the walls are tipped up and examined from the cavity side. Unlike with hand nailing, the framing gun gives no indication of whether the lumber is engaged. A bridge nailer at the panel plant would likely solve this problem. Warner noted that quite a lot of renailing at studs was required on-site, which slowed the panel erection process to some degree.

Warner was asked to compare the EP&B configuration (rigid foam installed between the OSB and the stud framing) with the more common application of foam (continuous insulation exterior to the OSB of traditionally framed 2x4 light-frame wall). He has previous experience with exterior continuous insulation and feels comfortable with the necessary adjustments to his construction processes to accommodate the foam layer exterior to the wood sheathing. He does not consider the longer nails for window and siding installation and the addition of framing around window and door openings to be obstacles to using continuous insulation exterior FPIS, and he did not initially see the EP&B system as an advantage.

Warner noted there is some advantage to siding and window installation with EP&B because shorter nails can be used and less framing is required. He said he would be very willing to accept EP&B projects in the future and would not likely bid or staff the project any differently with respect to labor. For any panelized project, whether standard or EP&B, he recommended care with air sealing, especially where wall panels meet. Warner has used a flash coat of closed-cell spray foam on other projects and suggested that it would also be a good solution for air sealing the EP&B wall system.

Appendix D: Moisture Monitoring

Data Type and Interpretation

The data collected from the sensors include the local temperature and relative humidity (RH) and the moisture content (MC) of the wood to which it is attached.

Table 18 lists the accuracy and features of the monitoring equipment used in the project. Figure 31 (a) and (b) show the sensor and data logging devices.

Table 18. Omnisense Testing and Monitoring Equipment

Function	Range/Accuracy/Details	Equipment/Features
Temperature	T-40 to 185°F /±0.8°F, 3.6°F max	• S-1-3.5 wireless sensor • plastic casing ~ 2.5-in. wide, 1.5-in. high, and 1-in. deep • Lithium battery
RH	0 to 100%/ ±3.5%, ±5% max	
MC	Percentage by weight; measures elec. Resistance between the two screws embedded in the material	
Data logger	Stores data to bridge power outage	G-3-C-VZW cellular gateway

The data logger is set to collect data at approximately 15-minute intervals. Data are uploaded continuously to a website for data storage; battery backup allows temporary local storage in the event of a power interruption. The Omnisense acquisition protocol processes this raw data to calculate the dew point and grains of moisture based on the temperature and RH. The MC data are calibrated to a standard wood MC percentage based on the temperature at the wood surface.

The data set stored on the website have been downloaded on a monthly basis and averaged on several different time intervals (hourly to daily) for further analysis and charting. Twelve-hour averages are used in the graphs in this report.

The American Society for Testing and Materials (ASTM) D4444 Standard Test Method for Laboratory Standardization and Calibration of Hand-Held Moisture Meters was used as a guide for calibrating the Omnisense S-1 pin type (resistance) sensors. The accuracy of the Omnisense MC readings was determined by comparing recorded sensor measurements to gravimetric measurements of oriented strand board (OSB) samples of target wood species mixes using ASTM D4442 Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials for the same samples. Multiple samples in a variety of combinations of the following conditions were tested:

- Temperature was held constant at 25°C (77°F).
- RH ranged from 40% to 90%.
- MC ranged from 7% to 25%.
- The conditioned specimens were considered stable when the difference in mass during a 24-hour period was less than 0.04 grams.
- All specimens were weighed on a balance with a precision of 0.01 grams.
- Spruce-pine-fir framing lumber was also tested (the sensors are factory calibrated to Douglas fir).

The sensors record temperature simultaneously with RH. The sensor measures the resistance across the sensor pins (the tips of the screws) to determine MC and automatically corrects for temperature (because the conductivity of wood increases with increasing temperature).

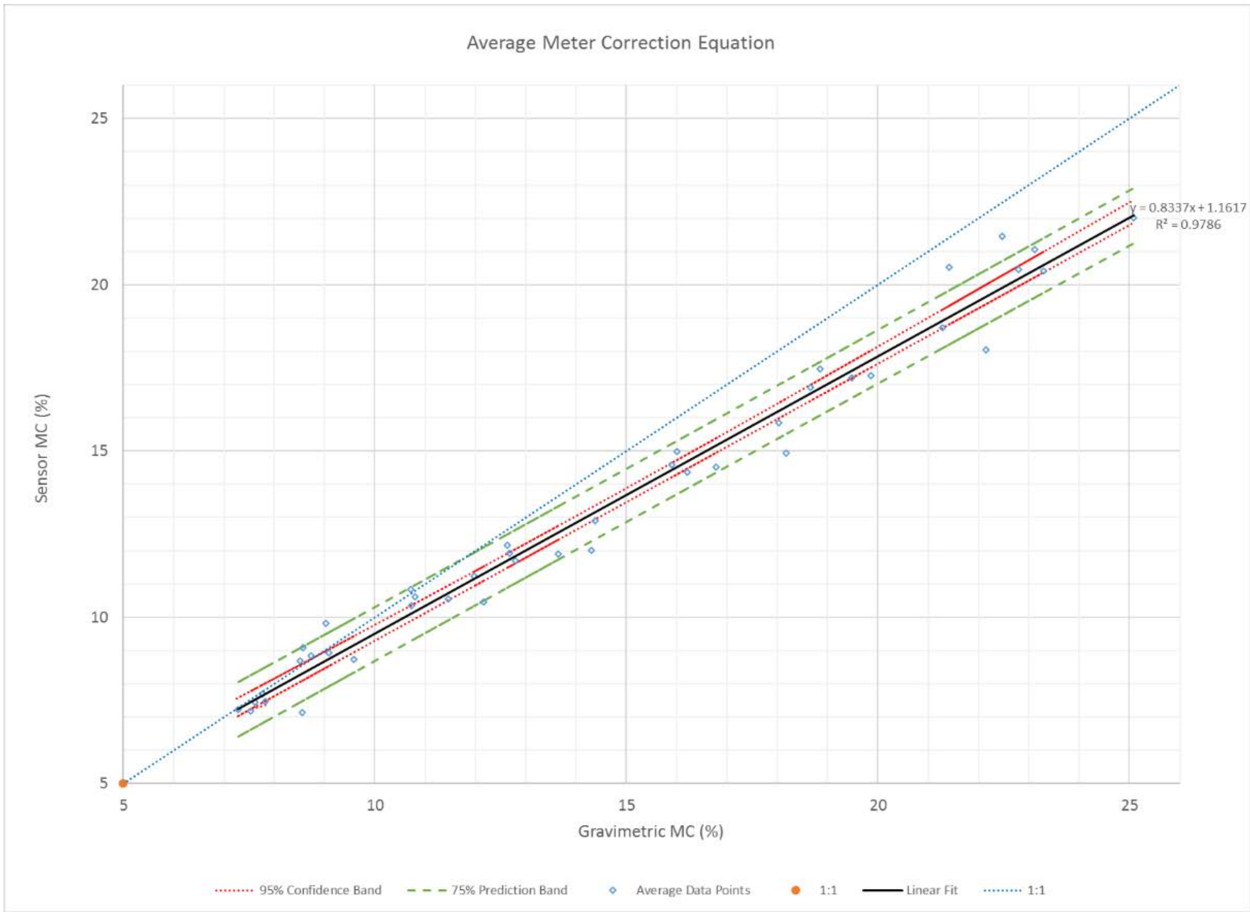


Figure 61. Curve fit chart for MC sensor calibration for all OSB data points

Figure 61 shows the data and curve fit result for OSB, for example. All wood MC values in this report for OSB, studs and plates, and rims have been corrected according to the following equations, based on laboratory calibration of each type:

$$OSB: MC_{actual} = 0.83\ x\ MC_{recorded} + 1.16$$

$$Lumber\ studs\ and\ plates: MC_{actual} = 1.22\ x\ MC_{recorded} + 0.23$$

$$Rims\ (engineered\ lumber): MC_{actual} = 0.77\ x\ MC_{recorded} + 2.20$$

Sensor Placement in Building and Walls

See Table 19 and Table 20 for a summary of the purpose and coverage of each sensor placed in the two Grand Rapids demonstration houses.

Table 19. Sensors, House 1

Sensor Qty	% of total	DESCRIPTION
36	100%	Total House 1 sensors
9	25%	Foam drilled and removed below sensor eye (D)
27	75%	Foam not drilled and removed below sensor eye (ND)
20	56%	Sensor monitoring OSB parameters
16	44%	Sensor monitoring non-OSB parameters
8	22%	Bays with acrylic caulk air seal and Kraft-faced batt insulation
28	78%	Bays with spray foam air sealing and blown-in fiberglass insulation (spruce-pine-fur)
4	11%	Ambient sensors
32	89%	Sensors embedded within or between construction materials
23	64%	North
13	36%	Not North

Table 20. Sensors, House 2

Sensor Qty	% of total	DESCRIPTION
33	100%	Total House 2 sensors
5	15%	Foam drilled and removed below sensor eye (D)
28	85%	Foam not drilled and removed below sensor eye (ND)
18	55%	Sensor monitoring OSB parameters
15	45%	Sensor monitoring non-OSB parameters
10	30%	Bays with acrylic caulk air seal and Kraft-faced batt insulation
23	70%	Bays with spray foam air sealing and blown-in fiberglass insulation (spruce-pine-fur)
2	6%	Ambient sensors
31	94%	Sensors embedded within or between construction materials
21	64%	North
12	36%	Not North

Table 21 and Table 22 list sensor identification information and show the final monitoring locations for each demonstration house.

Table 21. Sensor Details, House 1

Sensor Id	Name	Type	Direction	Location	VB	D/ND
1EE70039	B 2nd Ba ND OSB right	OSB	North	Bath	SPF	ND
1EE70192	B 2nd Ba D OSB left	OSB	North	Bath	SPF	D
1EE7019E	B Mstr Brm ND OSB Rleft	OSB	North	Bedroom	SPF	ND
1EE701B3	B Dining D OSB right	OSB	South	Dining	SPF	D
1EE701C0	B Mstr Brm ND OSB KFBR	OSB	North	Bedroom	KFB	ND
1EE701C4	B Dining ND OSB left	OSB	South	Dining	SPF	ND
1EE701DD	B Mstr Brm Stud left	Stud	North	Bedroom	SPF	
1EE701F0	B Gr Rm ND OSB Left Bay	OSB	North	Great room	SPF	ND
1EE7021A	B Mstr Brm ND OSB KFBL	OSB	North	Bedroom	KFB	ND
1EE7021B	B Mstr Brm ND OSB Lleft	OSB	North	Bedroom	SPF	ND
1EE7021C	B Gr Rm ND OSB Right KFB	OSB	North	Great room	KFB	ND
1EE70223	B 2nd Ba D OSB right	OSB	North	Bath	SPF	D
1EE70365	B Mstr Brm D OSB Rleft	OSB	North	Bedroom	SPF	D
1EE70388	B Gr Rm Interior Ambient	Ambient	Ambient	Great room		
1EE70375	B Mstr Ba D OSB left	OSB	West	Bath	SPF	D
1EE70395	B 2nd Ba ND OSB left	OSB	North	Bath	SPF	ND
1EE7039A	B Mstr Brm D OSB KFBR	OSB	North	Bedroom	KFB	D
1EE703D5	B Mstr Brm D OSB KFBL	OSB	North	Bedroom	KFB	D
1EE703EF	B Mstr Ba Stud left	Stud	West	Bath	SPF	
1EE703F4	B Mstr Brm Rim	Rim	North	Bedroom	SPF	
1EE7038B	B Mstr Ba D OSB right	OSB	West	Bath	SPF	D
1EE703F6	B Mstr Brm D OSB Lleft	OSB	North	Bedroom	SPF	D
1F650033	B Dining Stud	Stud	South	Dining	SPF	
1F650046	B Mstr Ba Stud right	Stud	West	Bath	SPF	
1F6500FD	B Mstr Brm Plate left	Plate	North	Bedroom	SPF	
1F650163	B 2nd Ba Stud right	Stud	North	Bath	SPF	
1F650199	B Exterior Ambient under deck	Ambient	Ambient	Exterior		
1F6501B6	B Mstr Brm Plate right KFB	Plate	North	Bedroom	KFB	
1F650207	B Gr Rm Stud Left Bay	Stud	North	Great room	SPF	
1F650208	B Mstr Brm Stud right KFB	Stud	North	Bedroom	KFB	
1F6502D7	B 2nd Ba Stud left	Stud	North	Bath	SPF	
1F65032E	B Gr Rm Stud Right KFB	Stud	North	Great room	KFB	
1F650392	B 2nd Ba Interior Ambient	Ambient	Ambient	Bath		
1F650153	B Mstr Ba Interior Ambient	Ambient	Ambient	Bath		
1EE70390	B Mstr Ba ND OSB left	OSB	West	Bath	SPF	ND
1EE703F5	B Mstr Ba ND OSB right	OSB	West	Bath	SPF	ND

Table 22. Sensor Details, House 2

Sensor Id	Name	Type	Direction	Location	VB	D/ND
206F01F3	Y E Lv Rm OSB D	OSB	East	Exterior	SPF	D
206F024D	Y E Lv Rm OSB ND	OSB	East	Exterior	SPF	ND
1F6501DC	Y E Lv Rm Stud	Stud	East	Exterior	SPF	
1F650152	Y Exterior Below Deck	Ambient	Ambient	Exterior		
1F6501B7	Y Int Dining Ambient	Ambient	Ambient	Dining		
1F650228	Y Int Mst Ba Ambient	Ambient	Ambient	Bath		
206F03FF	Y N Mst Ba OSB D	OSB	North	Bath	SPF	D
206F02F7	Y N Mst Ba OSB D KFB	OSB	North	Bath	KFB	D
206F02F3	Y N Mst Ba OSB ND	OSB	North	Bath	SPF	ND
206F0000	Y N Mst Ba OSB ND KFB	OSB	North	Bath	KFB	ND
1EE703A3	Y N Mst Ba Plate	Plate	North	Bath	SPF	
206F0319	Y N Mst Ba Plate KFB	Plate	North	Bath	KFB	
1EE70392	Y N Mst Ba Stud	Stud	North	Bath	SPF	
1F6503B8	Y N Mst Ba Stud KFB	Stud	North	Bath	KFB	
206F0049	Y N Mst Brm OSB D Btm	OSB	North	Bedroom	SPF	D
206F02BA	Y N Mst Brm OSB D Btm KFB	OSB	North	Bedroom	KFB	D
206F020F	Y N Mst Brm OSB D Top	OSB	North	Bedroom	SPF	D
206F0074	Y N Mst Brm OSB D Top KFB	OSB	North	Bedroom	KFB	D
206F02FF	Y N Mst Brm OSB ND Btm	OSB	North	Bedroom	SPF	ND
206F005D	Y N Mst Brm OSB ND Btm KFB	OSB	North	Bedroom	KFB	ND
206F013F	Y N Mst Brm OSB ND Top	OSB	North	Bedroom	SPF	ND
206F039E	Y N Mst Brm OSB ND Top KFB	OSB	North	Bedroom	KFB	ND
206F0280	Y N Mst Brm Plate	Plate	North	Bedroom	SPF	
1F6502D0	Y N Mst Brm Plate KFB	Plate	North	Bedroom	KFB	
1F6502BB	Y N Mst Brm Rim	Rim	North	Bedroom	SPF	
1F650005	Y N Mst Brm Stud	Stud	North	Bedroom	SPF	
1F6502D3	Y N Mst Brm Stud KFB	Stud	North	Bedroom	KFB	
206F03F5	Y S Dinette OSB D	OSB	South	Exterior	SPF	D
206F018F	Y S Dinette OSB ND	OSB	South	Exterior	SPF	ND
1EE70226	Y S Dinette Stud	Stud	South	Exterior	SPF	
206F0105	Y W Dining OSB D	OSB	West	Dining	SPF	D
206F0247	Y W Dining OSB ND	OSB	West	Dining	SPF	ND
1F6500A6	Y W Dining Stud D	Stud	West	Dining	SPF	D
206F01F3	Y E Lv Rm OSB D	OSB	East	Exterior	SPF	D
206F024D	Y E Lv Rm OSB ND	OSB	East	Exterior	SPF	ND
1EE703F5	B Mstr Ba ND OSB right	OSB	West	Bath	SPF	ND

Moisture Data Results and Analysis: Relative Humidity

RH recorded by stud sensors can be used to indicate moisture risk within the wall cavity. Figure 62 and Figure 63 show the RH readings for all wall cavities in both test houses. The following summary describes the 12-hour averaged RH readings in the wall cavities of both houses for the full 12-month monitoring period of the field test:

- All wall cavities in both houses performed well, never approaching 100% RH conditions which indicate condensation: local RH never rose above 82%
- North-facing wall cavities: local RH never rose above 82%
- North-facing wall cavities in non-bathrooms: local RH never rose above 78%
- North-facing wall cavities in non-bathrooms with SPF flash coat: local RH never rose above 76%

- East-facing wall cavities (non-bathroom): local RH never rose above 70%
- West-facing wall cavities in bathrooms: local RH never rose above 78%
- West-facing wall cavities in non-bathrooms: local RH never rose above 66%
- South-facing wall cavities (all non-bathrooms): local RH never rose above 68%
- North-facing bathroom and bedroom wall cavities exhibited slightly different results for the two field test houses:
    - In House 1, the overall highest peak (78% RH) and the overall highest average (71% RH) occurred in north-facing *bedroom* wall cavities
    - In House 2, the overall highest peak (72% RH) and the overall highest average (68% RH) occurred in north-facing *bathroom* wall cavities.

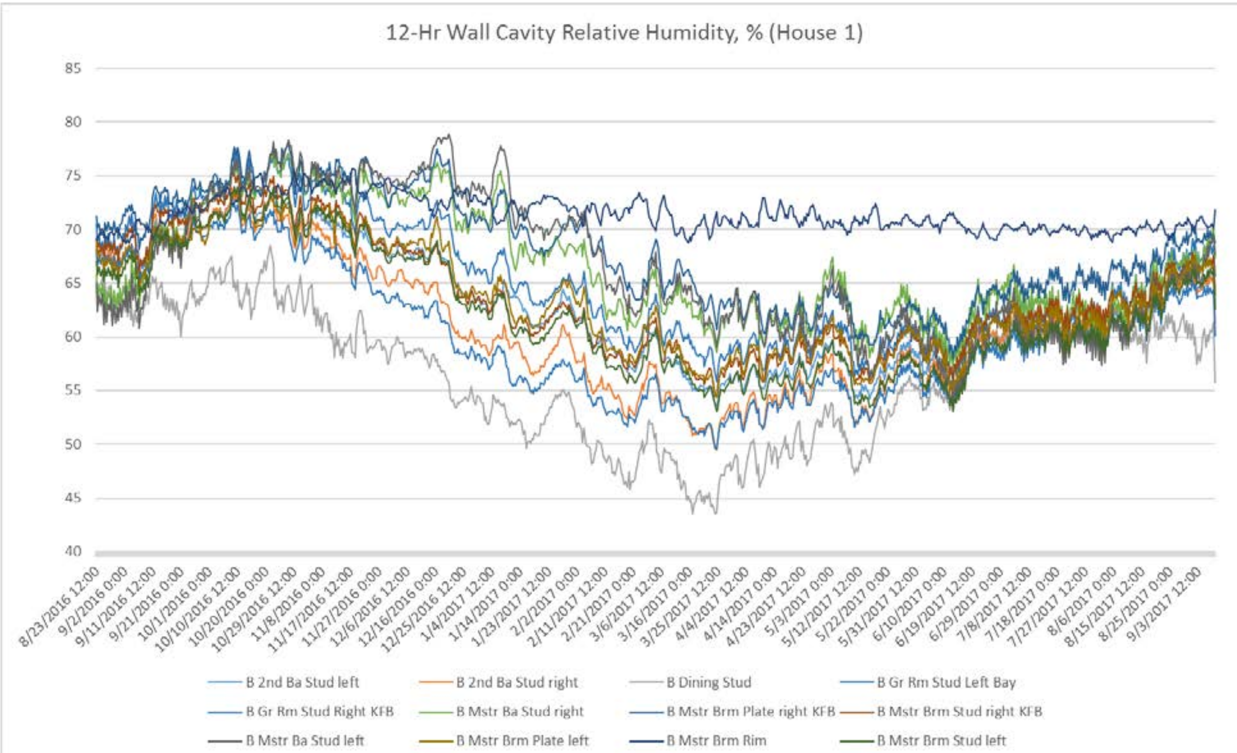


Figure 62. Wall cavity RH, House 1

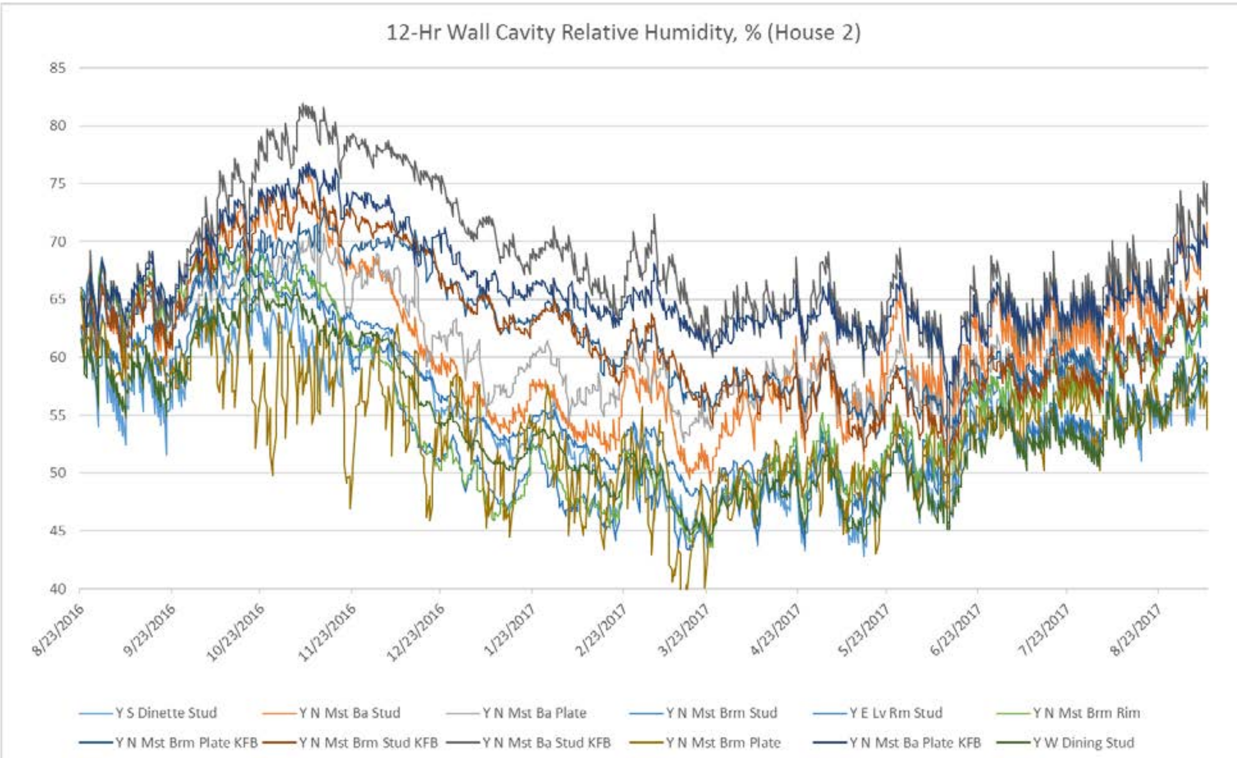


Figure 63. Wall cavity RH, House 2

Moisture Data Results and Analysis: Outlier Sensor

In House 1, MC recorded by all but one OSB sensor is well below the fiber saturation point, as well as the threshold for potential moisture concerns, indicating excellent moisture performance (Figure 64). The stud bay with the highest recorded OSB MC readings is a north-facing wall in the master bedroom, two stud bays away from a window, in an area with acrylic caulk air sealing and Kraft-faced fiberglass batt insulation. See Figure 65 and Figure 66. Note that the water-resistive barrier (WRB) covering the stud and plate sensors (Figure 66) was removed after the application of spray foam and before the installation of cavity insulation to ensure that the recorded dry bulb and dew point temperatures would reflect conditions within the cavity. Sensors in this bay were chosen before the bay was assigned to received Kraft-faced fiberglass batt insulation.

This bay had a high level of monitoring redundancy, with four OSB sensors all within an 18-inch radius. Data from three of the four sensors indicate very good moisture performance. It is presumed that this single outlier is because of some unique detail of the installation or sensor and not indicative of general behavior for the extended plate and beam (EP&B) walls. Although this location experienced peak MC for a short period of time above what would normally be considered the fiber saturation point for OSB, it dried out by the end of summer nearly as well as the uncompromised locations. Both Grand Rapids test houses will be monitored for a second full year, which may provide additional insight into the cause and repercussions.

Further exploration and discussion with the builder has not identified a reason for these results, but the possibilities include:

- The OSB in the area of one or both sensor screw tips may have been damaged or breached as a result of subsequent construction activities.
- A cladding fastener may have been embedded in the OSB near or in contact with one or both sensor screw tips, creating a thermal bridge and/or a path for moisture wicking.

- The WRB tape used to seal the sensor cabinet to the rigid foam may be imperfect, allowing moisture migration between inside and outside.
- Removal of the foam core below the sensor eye, if over-drilled, may have damaged the OSB, allowing moisture to enter from behind the cladding.

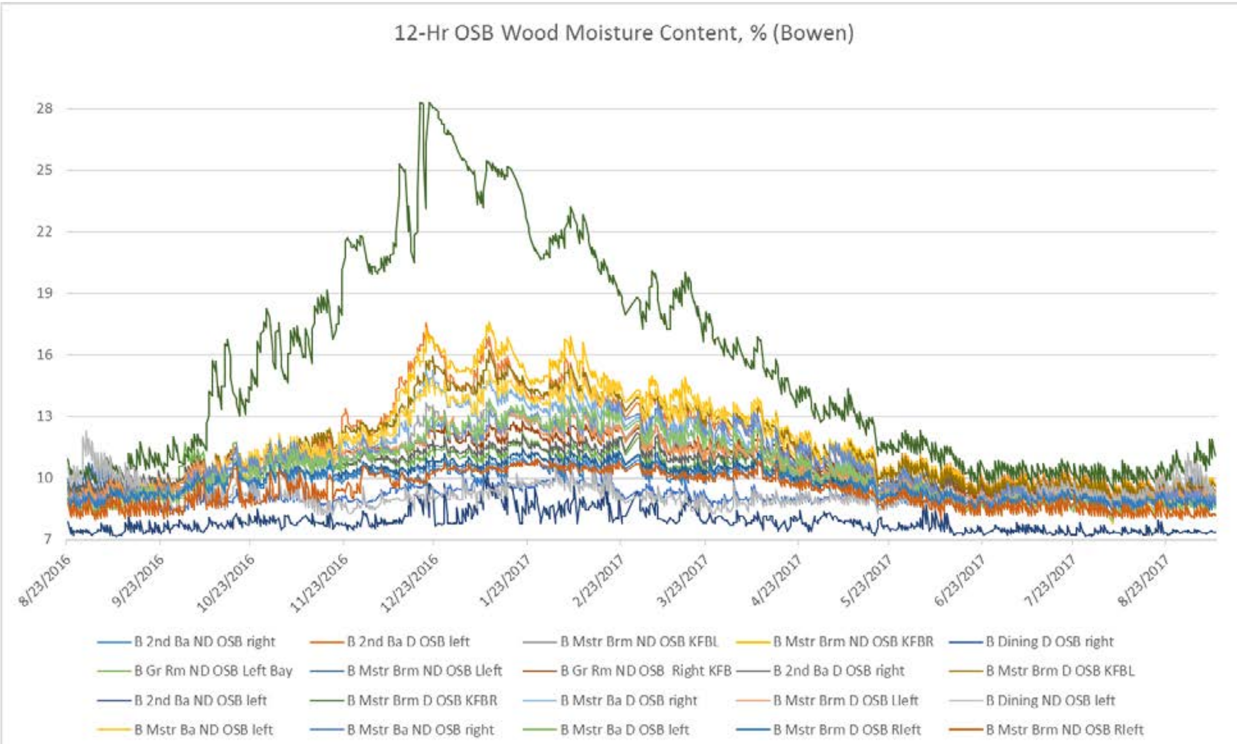


Figure 64. MC for OSB in all EP&B walls, House 1

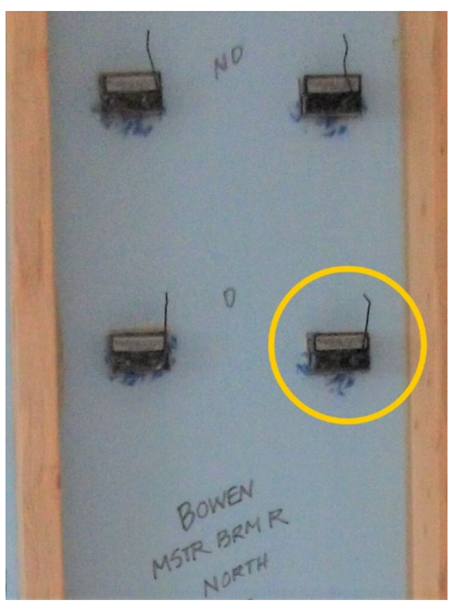


Figure 65. Bay containing outlier OSB sensor, House 1

Figure 66. Bay containing outlier OSB sensor, House 1

On the north side of House 2, a single sensor (Y N Mst Brm OSB D Top) in a bay with ccSPF air sealing and blown-in fiberglass insulation recorded a maximum peak of 19.1% MC and a one-year average of 12.8%. See Figure 68 and Figure 69. This sensor may be considered an outlier because three other OSB sensors in the same stud bay and within a distance of 18 in. had a combined average of 11.0% MC and respective maximums of 11.7, 12.2, and 15.2% MC. In the same room and on the same wall, but two stud bays east, is a test bay with acrylic caulk air sealing and Kraft-faced batt insulation. The four OSB sensors in this bay had a combined average of 11.4% MC and respective maximums of 12.6, 13.2, 16.5, and 16.9% MC, somewhat higher than the overall peaks and averages for the entire set of OSB sensors in House 2 and only slightly higher than recorded in the subset of north-facing walls. Speculation regarding the cause of this outlier is the same as for House 1.

Figure 30 shows 12-horr averaged MC readings for all sensors monitoring OSB in House 2 for a 12-month period starting in August 2016.

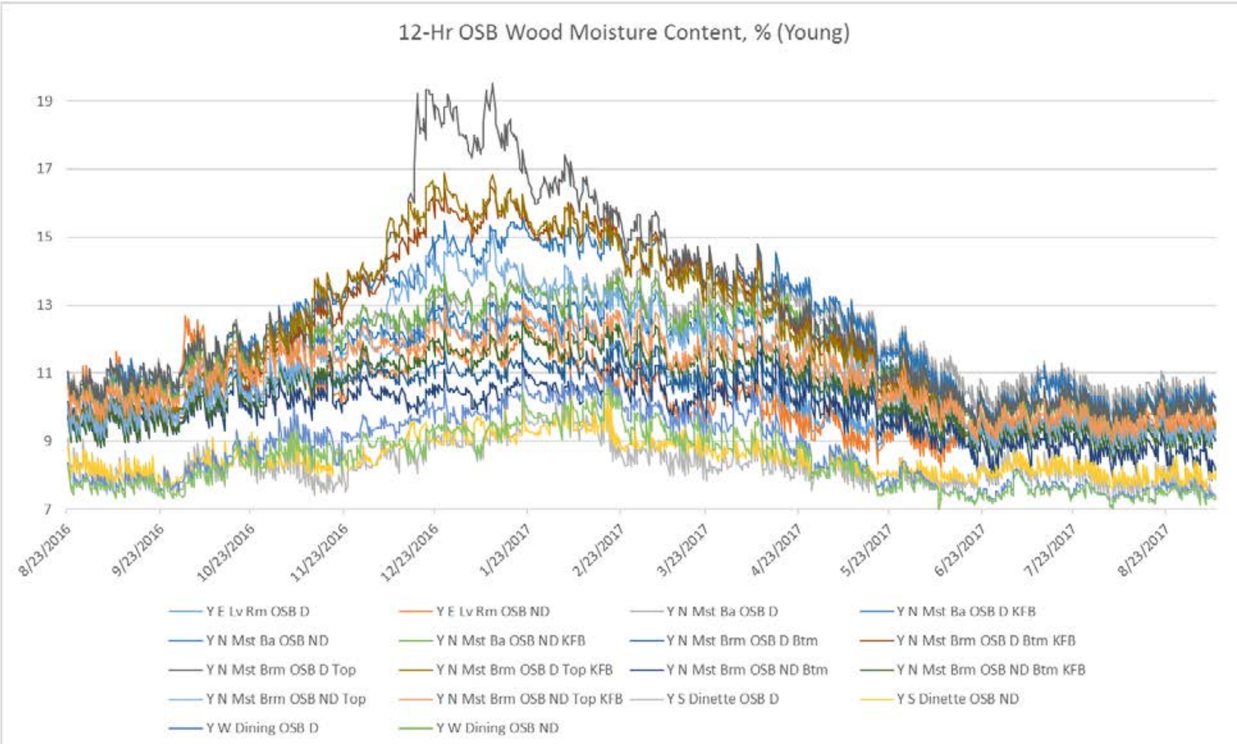


Figure 67. MC for OSB in all EP&B walls, House 2

Figure 68. Wall containing outlier OSB sensor, House 2

Figure 69. Detail of outlier OSB sensor, House 2

Moisture Data Results and Analysis: Adjustment of Sensor Data

The EP&B wall's unique materials ordering includes rigid foam sheet insulation installed exterior to the framing but interior to the OSB sheathing. In a previous field demonstration, a small cube of the rigid foam was removed to allow installation of the sensors directly against the OSB sheathing on the interior side. The foam cube was reinstalled over the top of the sensor, yet several of these sensors failed during the first winter of monitoring. The failures occurred when the combination of high moisture and low temperatures indicated the existence of ice. The problem appeared to be related to inadequate air sealing at the edges of the opening, which presumably allowed moisture migration. In response to this issue, a high level of redundancy was applied to the sensor layout for both Grand Rapids demonstration houses, and two different installation methods were employed to ensure data recovery.

Figure 70. A jig ensures that the sensor's legs can be embedded in the 2-in. rigid foam layer without gaps.

Figure 71. A spacer ensures proper embedment depth into the OSB.

Figure 72. Sensor cabinets are protected from intrusion of moisture and debris with WRB tape

Because the MC is calculated internally by the sensor based on the resistance across the pins (screw legs) and the local temperature, two configurations were used: drilled (D) configurations have a cylindrical channel bored orthogonally through the rigid foam directly below the sensor eye to allow direct measurement of temperature at the OSB surface; non-Drilled (ND) configurations have no cored access for the sensor eye. Figure 70, Figure 71, and Figure 72 show the steps for OSB sensor installation. WRB tape was applied to seal the sensor cabinet against the interior face of the rigid foam to protect from spray foam and to ensure an air and moisture seal at the central plane. WRB paper protected stud sensors prior to application of the ccSP) and was later removed for installation of cavity insulation.

OSB sensors were installed with ample redundancy in two different configurations to protect them from ice damage and ensure data availability. The recorded temperature readings of sensors in the drilled configuration were found to be almost identical to those in the non-drilled configuration compared on a bay-by-bay basis. This likely indicates that the sensor is not designed to accurately read temperature at a distance of several inches and that the columnar void within the foam maintains a temperature gradient, preventing this method (drilled) from accurately sensing the actual OSB surface temperature.

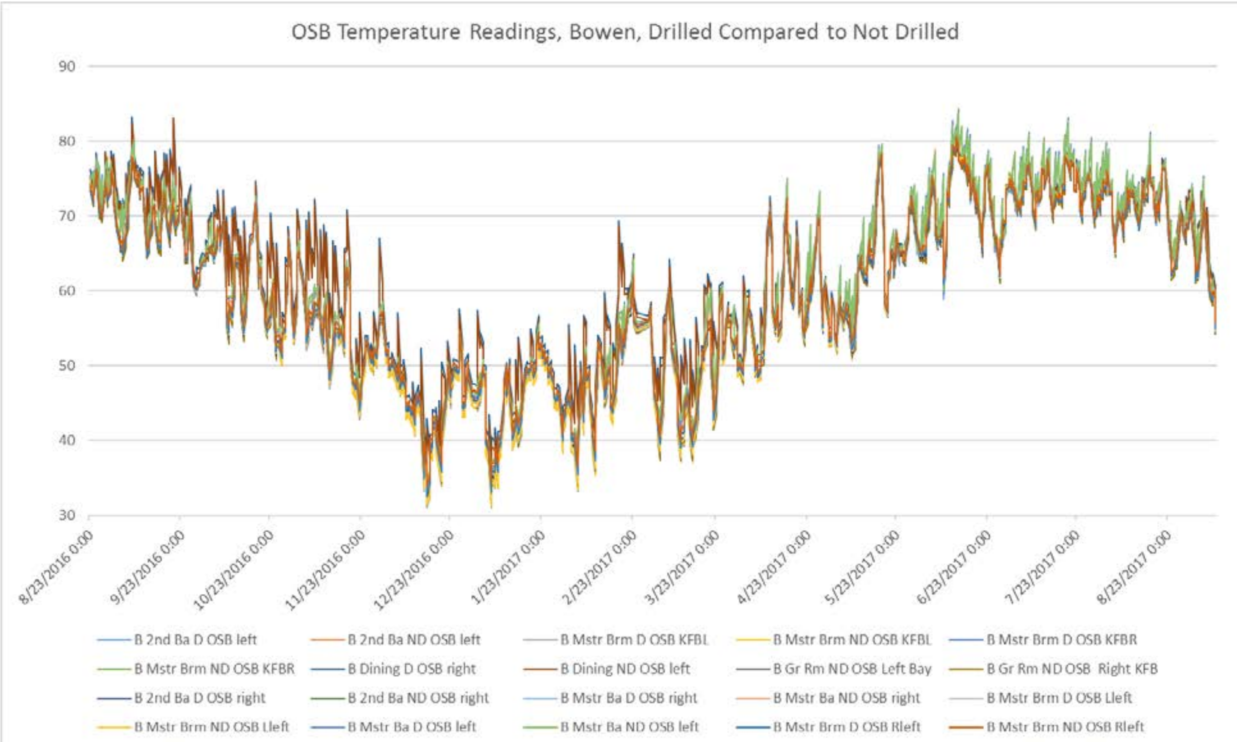


Figure 73. Comparing recorded temperatures, D and ND, House 1

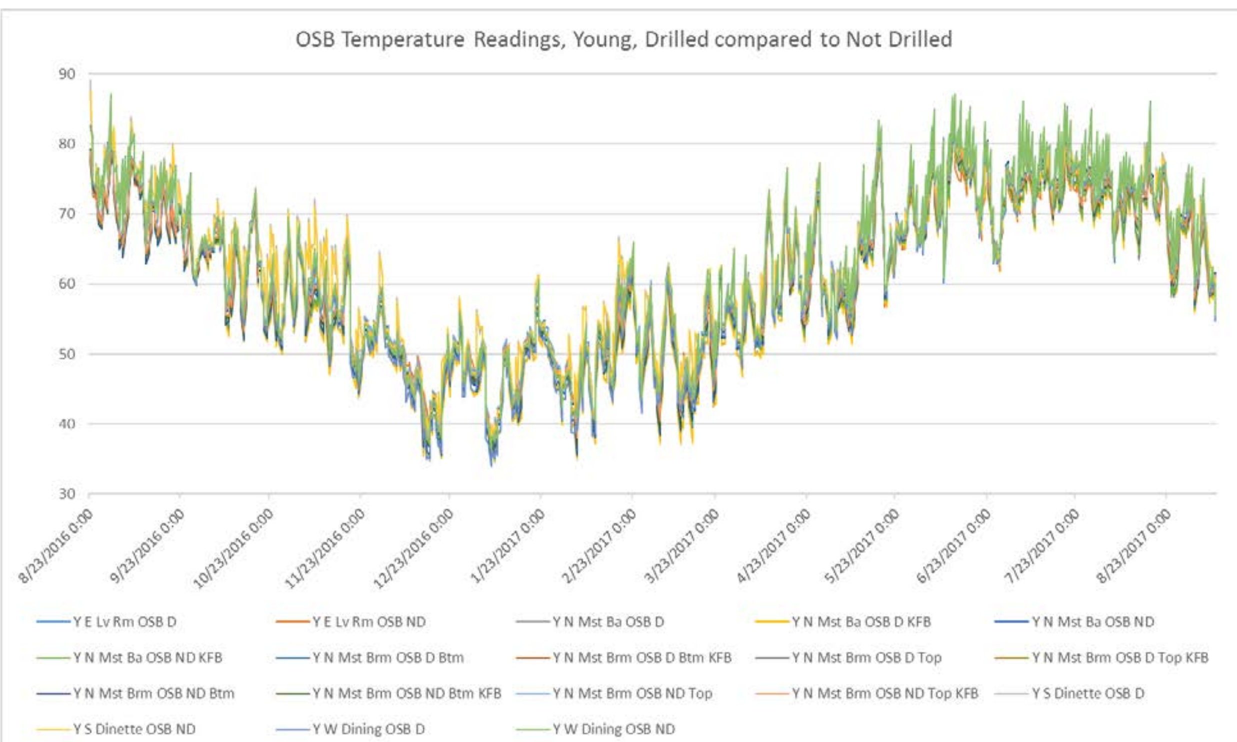


Figure 74. Comparing recorded temperatures, D and ND, House 2

Given that the temperature differences between the two installation methods (D and ND) on average varied by less than 1°F and by only about 1.5% for paired sensors sharing the same bays, all recorded OSB temperatures were adjusted (T_{adj}) to the resultant OSB temperature using the ASHRAE parallel path method and interpolating according the theoretical temperature gradient of the EP&B wall configuration based on material thermal resistances and two-dimensional layering.

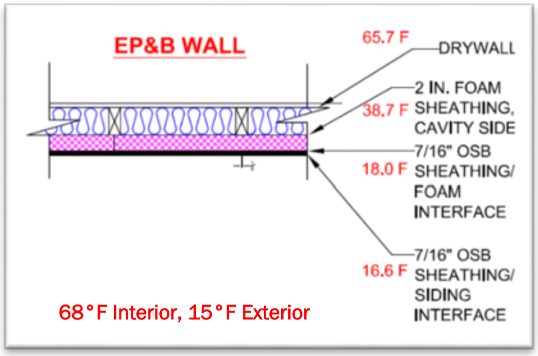


Figure 75. Thermal resistance of materials layers dictates intermediate temperatures

Each wall type in the two Grand Rapids demonstration houses was modeled using the ASHRAE parallel path method to determine the theoretical relationship between the temperatures at the interior plane of the rigid foam insulation and at the OSB holding interior ambient temperature constant at 68°F and varying T_{out} from 0°F to 80°F. See Figure 76 for the SPF/blown fiberglass example. A table was developed using bins of 5°F T_{out}, and the data points were plotted to develop an equation to adjust OSB sensors' temperature data to account for the actual temperature within the sheathing. See Figure 78. The temperature difference between that recorded by the sensor (remote—at foam insulation) and the actual OSB temperature (calculated by relationship) was then used to correct the recorded percentage MC for the OSB, conservatively using the worst-case value for recorded MCs between 7% and 20% for each 10-degree T_{foam} temperature bin. Only one sensor recorded MC above 20%, and it was adjusted for 20%–30% MC in each 10-degree temperature bin as well as 30% + MC for each 10-degree temperature bin. See Figure 81. The conservatism of the approach is compounded because both the drilled and not-drilled configurations were corrected.

All OSB MC graphs shown in the body of this report use these adjusted values according to the appropriate insulation type.

	Wall U-value calculation	W, in.	Nominal	Actual						
	1-in. ccSPF + Spider	Stud	2" x 4"	3.5						
		Plate	2" x 6"	5.5			Winter Temperature Profile			
		Layer R-value	Path 1 Cavity	Path 2 Framing	Path 3 Insul Gr	Path 4 Plate	Tin (°F) =	68 Cavity	Framing	Cantilever
IN	Int. film resistance	0.68	0.68	0.68	0.68	0.68		68.00	68.0	68.0
int. wall	Gyp drywall, 1/2"	0.45	0.45	0.45	0.45	0.45		67.17	66.6	65.6
cavity	1-in. SPF+Spider	4.57	16.0		16.0			66.61	65.7	64.0
framing	Lumber, SPF	1.25		4.38		6.88	condensing surf=>	46.97	65.7	64.0
EP&B c.i.	XPS, 2"	10	10.00	10.00	10.00	0.00	Step 1	46.97	56.8	39.7
ext. sheathing	OSB, 7/16"	0.62	0.62	0.62	0.62	0.62		34.69	36.5	39.7
EXT c.i.	None	0	0.00	0.00	0.00	0.00		33.93	35.2	37.5
airspace	Airspace (worst-case ext.)	1.12	1.12	1.12	1.12	1.12		33.93	35.2	37.5
cladding	Siding - fiber cement	0.28	0.28	0.28	0.28	0.28		32.55	32.9	33.6
OUT	Ext. film resistance (winter)	0.17	0.17	0.17	0.17	0.17		32.21	32.3	32.6
	PARALLEL PATH / nominal	29.25					Tout (°F) =	32		
	Path Thermal Resistance, R		29.32	17.70	29.32	10.20	F = Foam	2.7	O-Out delta (OSB vs Out)	
	Path Thermal Conductivity, U (1/R)		0.0341	0.0565	0.0341	0.0981	O = OSB	0.0747	O-Out temp diff vs in/out delta	
	Percent of Assembly	100.0%	73.6%	21.7%	0.0%	4.7%		12.3	F-O delta (OSB vs Foam)	
	Total Assembly U-value	0.041976	0.025102	0.012263	0	0.00461		0.3411	F-O temp diff vs in/out delta	
	Total Assembly R-value	23.82327								

Figure 76. Corresponding theoretical temperatures within the ccSPF EP&B wall were calculated.

	Wall U-value calculation	W, in.	Nominal	Actual						
	R-15 KFB	Stud	2" x 4"	3.5						
		Plate	2" x 6"	5.5			Winter Temperature Profile			
		Layer R-value	Path 1 Cavity	Path 2 Framing	Path 3 Insul Gr	Path 4 Cantilever	Tin (°F)	Cavity	Framing	Cantilever
IN	Int. film resistance	0.68	0.68	0.68	0.68	0.68	68	68.00	68.0	68.0
int. wall	Gyp drywall, 1/2"	0.45	0.45	0.45	0.45	0.45		67.21	66.7	4782.3
cavity	R-15 KFB	4.29	15.0		15.0			66.68	65.9	4068.8
framing	Lumber, SPF	1.25		4.38		6.88	ndensing surf=>	49.20	65.9	3254.3
EP&B c.i.	XPS, 2"	10	10.00	10.00	10.00	0.00	Step 1	49.20	57.7	2562.0
ext. sheathing	OSB, 7/16"	0.62	0.62	0.62	0.62	0.62		37.55	39.1	1914.1
EXT c.i.	None	0	0.00	0.00	0.00	0.00		36.83	37.9	1509.4
airspace	Airspace (worst-case ext.)	1.12	1.12	1.12	1.12	1.12		36.83	37.9	1132.8
cladding	Siding - fiber cement	0.28	0.28	0.28	0.28	0.28		35.52	35.8	732.4
OUT	Ext. film resistance (winter)	0.17	0.17	0.17	0.17	0.17		35.20	35.3	376.7
	PARALLEL PATH / nominal	29.25					Tout (°F) =	35		
	Path Thermal Resistance, R		28.34	17.70	28.34	10.20	F = Foam	2.6	O-Out delta (OSB vs Out)	
	Path Thermal Conductivity, U (1/R)		0.0353	0.0565	0.0353	0.0981	O = OSB	0.0773	O-Out temp diff vs in/out delta	
	Percent of Assembly		73.6%	21.7%	0.0%	4.7%		11.6	F-O delta (OSB vs Foam)	
	Total Assembly U-value	0.042848	0.025975	0.012263	0	0.00461		0.3529	F-O temp diff vs in/out delta	
	Total Assembly R-value	23.3381								

Figure 77. Corresponding theoretical temperatures within the Kraft-faced fiberglass batt insulation EP&B wall were calculated.

ccSPF	Temp in =	68	RATIO	
Temp out	Foam	OSB	dIF/dFO	deltaT
80	75.01	79.1	0.583	-4.09
75	72.09	74.48	0.584	-2.39
70	69.17	69.85	0.581	-0.68
65	66.25	65.22	0.589	1.03
60	63.33	60.6	0.585	2.73
55	60.4	55.97	0.583	4.43
50	57.48	51.34	0.584	6.14
45	54.56	46.72	0.583	7.84
40	51.64	42.09	0.584	9.55
35	48.72	37.46	0.584	11.26
30	45.8	32.84	0.584	12.96
25	42.88	28.21	0.584	14.67
20	39.96	23.59	0.584	16.37
15	37.04	18.96	0.584	18.08
10	34.11	14.33	0.584	19.78
5	31.19	9.71	0.584	21.48
0	28.27	5.08	0.584	23.19
		AVG	0.584	
	0.584 = (Tfoam - TOSB)/(68 - Tfoam)			
	Solve for OSB Temp			
Step 3	OSB Temp = 1.584*(Foam Temp)-39.712			

KFB	Temp in =	68	RATIO	
Temp out	Foam	OSB	dIF/dFO	deltaT
80	74.84	79.07	0.618	-4.23
75	71.99	74.46	0.619	-2.47
70	69.14	69.85	0.623	-0.71
65	66.29	65.23	0.620	1.06
60	63.44	60.62	0.618	2.82
55	60.59	56	0.619	4.59
50	57.74	51.39	0.619	6.35
45	54.89	46.78	0.619	8.11
40	52.05	42.16	0.620	9.89
35	49.2	37.55	0.620	11.65
30	46.35	32.94	0.619	13.41
25	43.5	28.32	0.620	15.18
20	40.65	23.71	0.619	16.94
15	37.8	19.1	0.619	18.70
10	34.95	14.48	0.619	20.47
5	32.1	9.87	0.619	22.23
0	29.25	5.26	0.619	23.99
		AVG	0.619	
	0.5619 = (Tfoam - TOSB)/(68 - Tfoam)			
	Solve for OSB Temp			
Step 3	OSB Temp = 1.619*(Foam Temp)-42.092			

Figure 78. An equation was developed to determine the resultant (actual) OSB temperature for each insulation type.

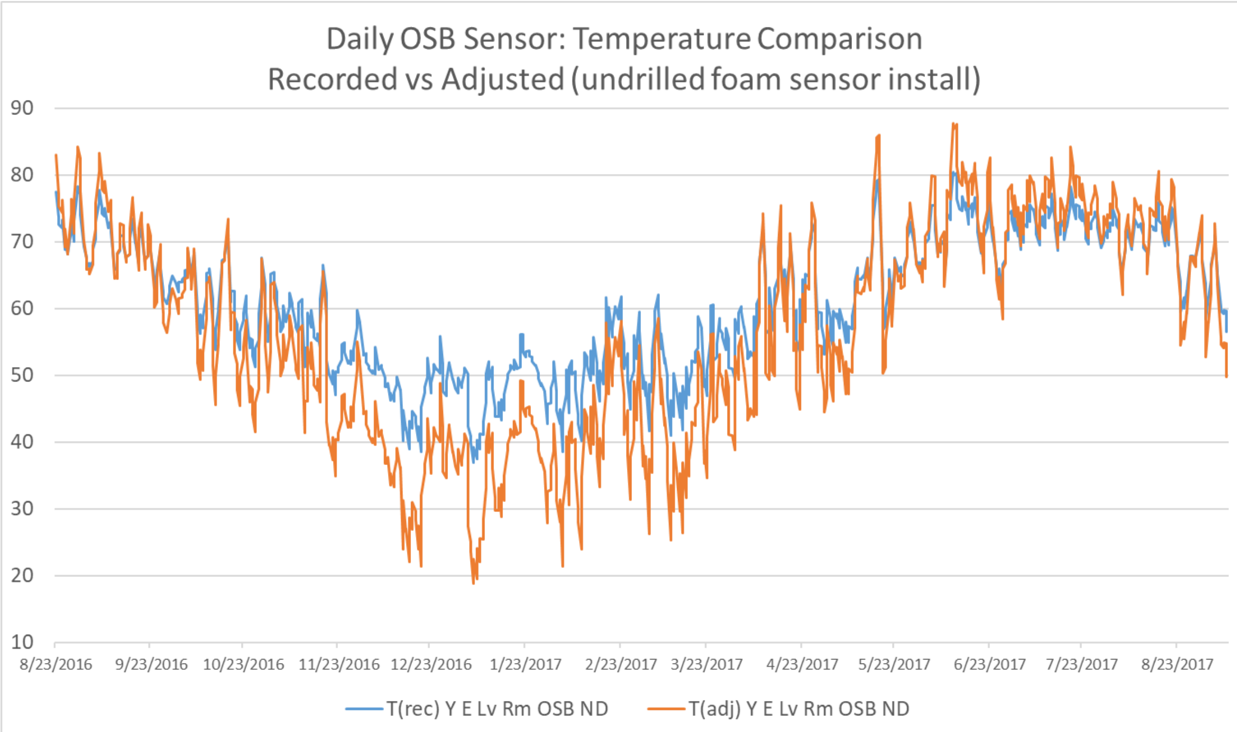


Figure 79. Example of OSB temperature adjustment to actual for sensor (undrilled foam)

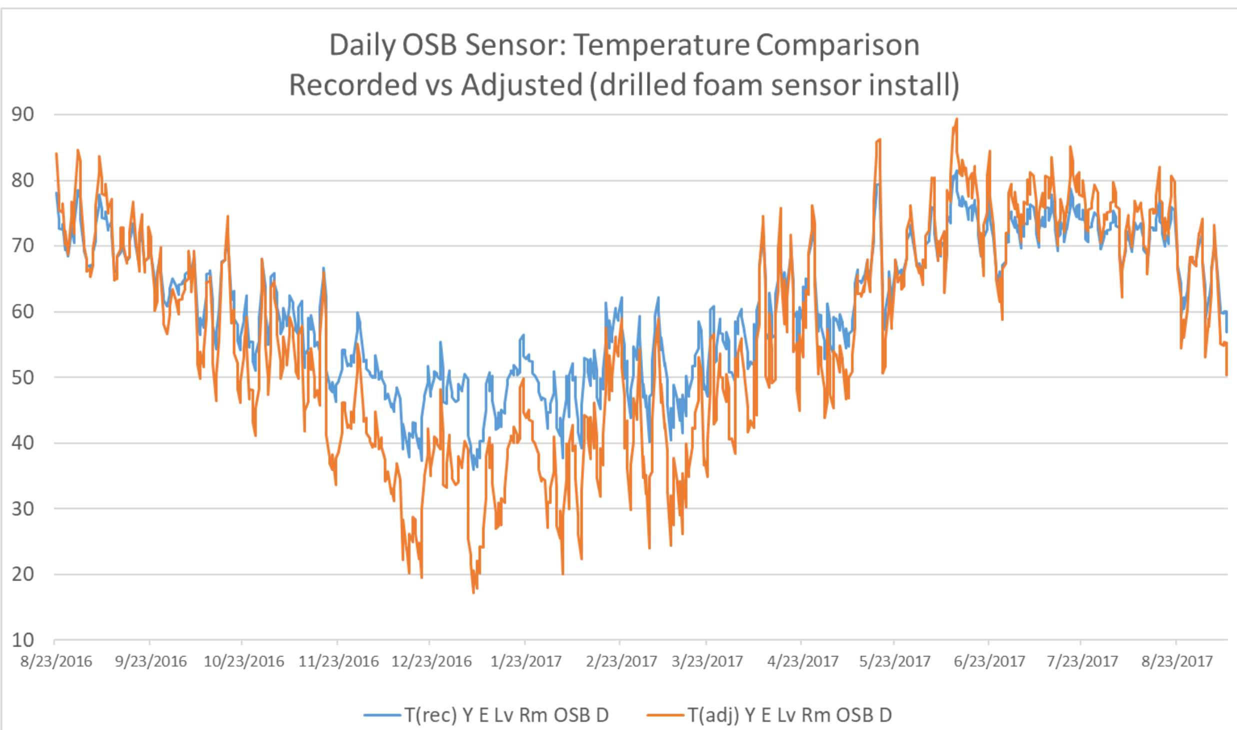


Figure 80. Example of OSB temperature adjustment to actual for sensor (drilled foam)

T, degF	CALC	At these ranges MC, adj rec'd MC% by this amt to derive OSB MC						Final ADJ		
Tfoam	Tosb	7	10	15	20	25	30	(typ)add	MC 20-30	MC 30+
30	7.8	1.6	1.6	2.3	3.9	4.0	5.2	2.3	4.0	5.2
40	23.6	1.75	1.75	1.75	3.5	3.5	3.5	1.8	3.5	3.5
50	39.5	0.5	0.5	1	1.5	1.5	2	1.0	1.5	2.0
60	55.3	-0.05	0.25	0.5	0.75	0.75	1	0.5	0.8	1.0
70	71.2	0	0	0	0	0	0	0.0	0.0	0.0
80	87.0	0	0	0	0	0	0	0.0	0.0	0.0

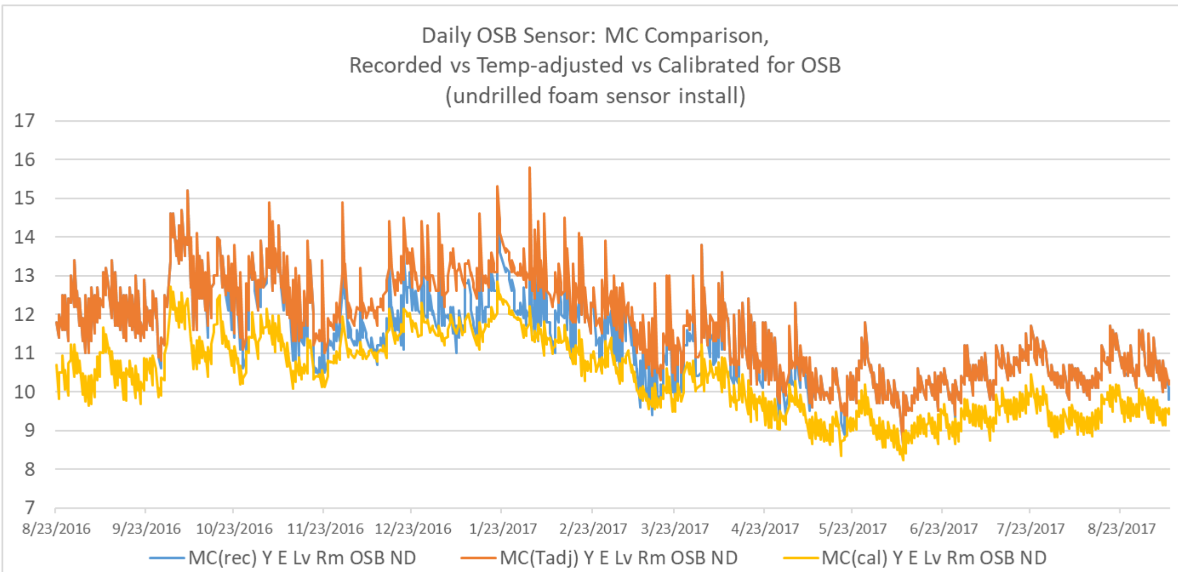


Figure 81. Example of MC adjustments for temperature and calibration (undrilled foam)

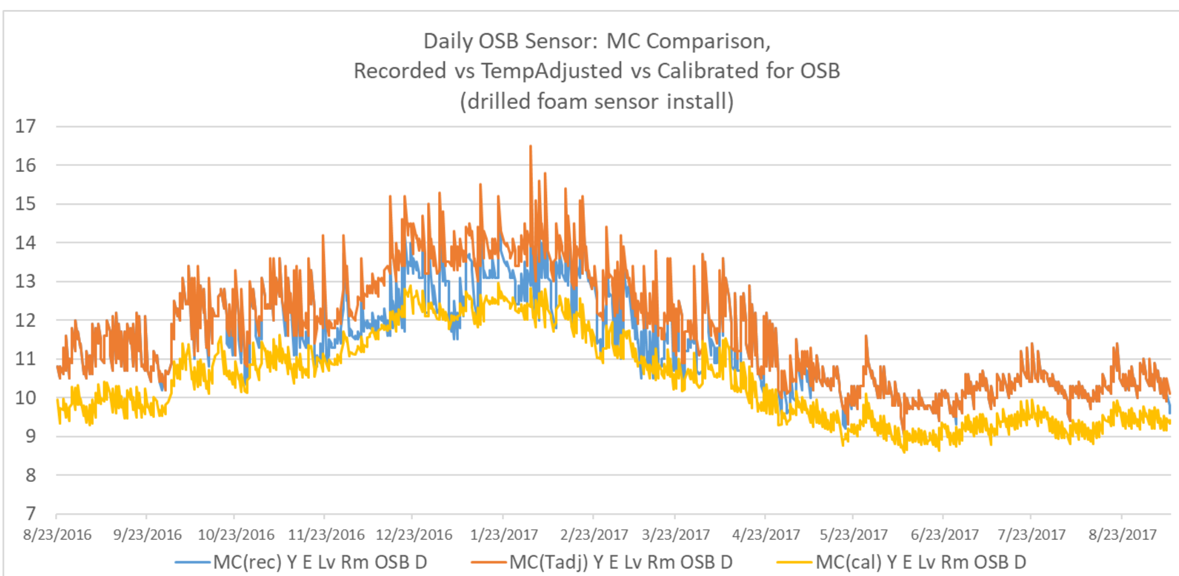


Figure 82. Example of MC adjustments for temperature and calibration (drilled foam)

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